UNIVERSITY OF PRETORIA

ATMOSPHERIC EMISSIONS AND ENERGY METRICS FROM SIMULATED CLAMP KILN TECHNOLOGY IN THE SOUTH AFRICAN CLAY BRICK INDUSTRY

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ATMOSPHERIC EMISSIONS AND ENERGY METRICS FROM SIMULATED CLAMP KILN TECHNOLOGY IN THE SOUTH AFRICAN CLAY BRICK INDUSTRY

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SYNOPSIS

Topic: Atmospheric Emissions and Energy Metrics from Simulated Clamp Kiln Technology in the South African Clay Brick Industry

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The quantification of atmospheric emissions from clamp kilns in the clay brick industry has met with limited success globally. The complex configuration of clamp kilns using coal or other carbonaceous fuels, as well as the uncertainty regarding kiln combustion conditions, has proven to be a hurdle in measurement of emissions and standardization of clamp kiln conditions.

To enable measurement and quantification of emission and energy metrics, a model kiln was designed to simulate operating conditions and configuration similar to a transverse slice of a typical full-scale clamp kiln, but with a lower capacity (20 000 – 35 000 bricks per firing cycle). The model kiln design ensures the adequate confinement and extraction of flue gases with the aid of a bifurcated fan forcing the draft through a horizontal extraction stack where monitoring occurs. The model kiln design, which comprise two adjacent sealed sides and two partially enclosing and sliding galvanized steel doors, provides adequate spacing for 'packing' and 'un-packing' of bricks and sufficient oxygen for combustion, while still ensuring minimum losses of emission via the semi-enclosed sides.

Concurrent firing and hourly monitoring of flue gases in the flue duct was conducted for fourteen batches of bricks over 8 – 14 days using varying brick products and energy inputs from eleven South African brick factories that utilizes clamp kiln as firing technology. The model kiln was tested for its suitability in firing bricks that are similar to conventional South African clamp kilns, as well as its effectiveness in the capturing and channelling of flue gases through to the stack vent where monitoring of the flue gases took place. Hourly readings are recorded for process parameters, SO_2, NO_x, NO, NO_2, CO and particulate matter (PM) concentrations in the extraction stack. PM size-segregated mass measurement was conducted to produce PM_1, $PM_{2.5}$, PM_4, PM_{10}, and PM_{15} fractions. SO_2 monitoring results were also compared to mass balance calculations, using the analysis of sulfur in the coal to indicate that the model kiln design is effective in capturing emissions and standardizing emission factors, as well as providing an effective energy analysis tool for clamp kilns.

A statistical mean efficiency for the model kiln emissions capturing and channelling capacity was calculated from sulfur mass balance results of the batches that lie within 95% confidence interval of the assumed true mean (100%) to give 84.2%. Therefore, 15.8% of emissions were considered to escape from underneath the semi-enclosed sides. Final emission factors (mean ± standard deviation) were quantified as 22.5 ± 18.8 g/brick for CO, 0.14 ± 0.1 g/brick

for NO, 0.0 g/brick for NO_2, 0.14 ± 0.1 g/brick for NO_x, 1.07 ± 0.7 g/brick for SO_2, 378 ± 223 g/brick for CO_2, 0.96 ± 0.5 g/brick for PM_{10}; as well as 1.53 g/brick for hydrocarbons (calibrated to propane emissions) and 0.96 g/brick for PM_{15}, PM_4, $PM_{2.5}$ and PM_1. Various kiln technologies were ranked from lowest to highest potential for atmospheric pollution based on available emission metrics as follows: Zig-zag < Vertical shaft < South African Clamps < US coal-fired < Fixed chimney Bull's trench < Tunnel < Asia Clamps < Down draft < Bull's trench.

Energy analyses indicate that a significant reduction of 0.9 MJ/kg (36%) in energy use could be achieved by the South African clamp kiln industry, thereby reducing cost of input, and significantly reducing the quantity of atmospheric emissions.

In addition, chemical reactions and thermodynamic processes occurring in the firing chamber of brick kilns were qualitatively linked to the amount and type of pollutant emissions released at different periods during a firing cycle. The sensitivity of brick kiln emission concentrations and process metrics to these reactions and processes was utilized to proffer emission control measures. These measures are aimed at reducing energy consumption; improving the clay material processing and drying technique; monitoring chemical constituents of input materials in order to eliminate less favourable options; monitoring firing temperature to modify firing process; as well as altering the combustion and firing process in order to favour chemical and thermodynamic processes that will result in the release of lower emissions.

Screening dispersion modelling results was additionally employed in recommending the extent of impact zones from the clamp kiln area for small kilns (500 m), medium kilns (1000 m) and large kilns (2000 m).

A general reduction in most pollutant emissions was observed when the external fuel (coal) was replaced with a locally available alternative, propane gas. CO, CO_2, NO_x/NO and PM_{10} indicated 87%, 7%, 41% and 10% reduction in emissions respectively, during propane gas firing. SO_2 emission, however, indicated a 19% increase, which may be attributed to lower energy consumption that alters the complex thermodynamic reactions in the model kiln. Only CO and NO_x/NO emissions provided significant reduction in emission rates to support the notion that substituting the external coal with propane gas will result in significant reduction in atmospheric emissions. PM_{10} and CO_2 emission rate do not provide significant reduction to validate this notion, while SO_2 emission rate analysis is inconclusive and may require further research.

Keywords: emission monitoring**;** clamp kiln; emission rate; emission factor; model kiln design; clay bricks; energy efficiency for clay bricks; alternative energy for clay bricks

DECLARATION

I, Oladapo B. Akinshipe, hereby declare that the work provided in this thesis is my own original work. Where the work of another has been used (whether from a printed or electronic source), due acknowledgement has been given and reference made in accordance with departmental guidelines. I also declare that this work has not been submitted to another institution in partial or whole fulfilment of another degree.

Oladapo Akinshipe

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Parts of this study have been submitted, published or presented in technical/specialist reports, conference proceedings and journal articles. These are listed below:

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"All that I am, and ever hope to be, I owe to God, to my family, and to mentors".

This work is dedicated:

Firstly, to my parents, Patrice and Damilola Akinshipe ...for your love and the seed of faith that grows in me daily;

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ABBREVIATIONS

ADMS	Atmospheric Dispersion Modelling System
AEL	Atmospheric Emission License
AIRPET	Asian Regional Air Pollution Research Network
APEIS	Asia-Pacific Environmental Innovation Strategies
BEE	Bureau of Energy Efficiency (India)
BIA	Brick Industry Association (USA)
BTK	Bull's trench kiln
CAI-ASIA	Clean Air Initiative for Asia Cities
Cape EAPrac	Cape EAPrac Environmental Assessment Practitioners
CBA	Clay Brick Association (South Africa)
CCAC	Climate and Clean Air Coalition
CDM	Clean Development Mechanism
CFA	Carbon fly ash
CIDB	Construction Industry Development Board (South Africa)
CPCB	Central Pollution Control Board (India)
CSE	Centre for Science and Environment (India)
DDK	Down-draught kiln
DEA	Department of Environmental Affairs (South Africa)
DMC	Development Management Support Centre (Nepal)
EEA	European Economic Area
EECB	Energy Efficient Clay Brick (South Africa)
EMEP	European Monitoring and Evaluation Programme
EMTIC	Emission Measurement Technical Information Centre (USA)
FAO	Food and Agriculture Organization
FCBTK	Fixed chimney Bull's trench kiln
GAINS	Greenhouse Gas and Air Pollution Interactions and Synergies
GATE	German Appropriate Technology Exchange
GMD	Geometric Mass Mean Diameter
GSD	Geometric Standard Deviation
HAPs	Hazardous Air Pollutants
IIASA	International Institute for Applied Systems Analysis
IIDFC	Industrial and Infrastructure Development Finance Company (Bangladesh)
ILO	International Labour Organization
MCBTK	Movable chimney Bull's trench kiln
MOE	Ministry of Environment (Nepal)

MRHP	Mwanza Rural Housing Programme (Tanzania)
NAAQS	National Ambient Air Quality Standards (South Africa)
NAPAP	National Acid Precipitation Assessment Program (USA)
NDIR	Nondispersive Infrared
NEM:AQA	National Environmental Management: Air Quality Act (South Africa)
NPI	National pollutant inventory (Australia)
NRMCA	National Ready Mixed Concrete Association (USA)
OECD	Organization for Economic Co-operation and Development (Europe)
PAHs	Polycyclic aromatic hydrocarbons
PCDD/F	Polychlorinated Dibenzo-p-dioxin and Dibenzofuran
PM	Particulate Matter
PM_1	Particles which pass through a size-selective inlet with a 50% efficiency cut-off at 1 µm aerodynamic diameter
PM_{10}	Particles which pass through a size-selective inlet with a 50% efficiency cut-off at 10 µm aerodynamic diameter
$PM_{2.5}$	Particles which pass through a size-selective inlet with a 50% efficiency cut-off at 2.5 µm aerodynamic diameter
PM_4	Particles which pass through a size-selective inlet with a 50% efficiency cut-off at 4 µm aerodynamic diameter
Total PM or PM_{Total}	Particles which pass through a size-selective inlet with a 50% efficiency cut-off at 15 µm aerodynamic diameter (based on TSI definition)
POPs	Persistent Organic Pollutants
RSPCB	Rajasthan State Pollution Control Board (India)
SABS	South African Bureau of Standards
SANS	South African National Standard
SD	Standard deviation
SEC	Specific energy consumption
SPM	Suspended particulate matter
TERI	The Energy and Resources Institute (India)
TOCs	Total Organic Compounds
TSP	Total Suspended Particulates
TVA	Transverse arch kiln
UNFCCC	United Nations Framework Convention on Climate Change
UNIDO	United Nations Industrial Development Organization
USEPA	United States Environmental Protection Agency
VOCs	Volatile organic compounds
VSBK	Vertical shaft brick kiln
WHO	World Health Organization

SYMBOLS, FORMULAE AND UNITS

α	Alpha
β	Beta
°C	Degree Celsius
µg	Microgram(s)
µg/m³	Micrograms per cubic meter
µm	Micrometer
Cd	Cadmium
CO	Carbon monoxide
CO_2	Carbon dioxide
Cr	Chromium
Cu	Copper
Fe	Iron
g/brick	gram per brick fired
g/kg	gram per kilogram
g/s	gram per second
g/s brick	gram per second per brick
GJ	Gigajoule
HF	Hydrogen Fluoride
kg/Mg	kilogram per megagram
kJ	Kilojoule
km	Kilometre
kN	Kilo newton
m/s	Metres per second
m^2	Metres squared
mg	Milligram(s)
mg/m³	Milligrams per cubic meter
mg/Nm³	Milligrams per normal cubic meter
MJ	Megajoule
mm	Millimetres
Mn	Manganese
MPa	Megapascal
Ni	Nickel
NO	Nitrogen oxide
NO_2	Nitrogen dioxide
NO_x	Oxides of nitrogen

O_3	Ozone
Pb	Lead
ppm	Parts per million
SO_2	Sulfur dioxide
SO_3	Sulfur trioxide
Zn	Zinc

CHAPTER ONE

1 INTRODUCTION

1.1 BACKGROUND AND RESEARCH RATIONALE

The global brick making industry has been identified as a significant source of air pollution and greenhouse gas emissions in most regions of the world, especially in east, central and south-west Asia; Africa; and Central America (Croitoru and Sarraf, 2012; World Bank, 1997; Lalchandani, 2012; Ferdausi *et al,* 2008; World Bank, 1998; FAO, 1999).

Clamp kiln technology, at an industrial scale, is the main technology used for firing bricks in South Africa, and is widely used in various regions of Asia and Central America. This is due to its relatively simple and affordable technological application during preparation, production and post-production phases of brick manufacturing – i.e. when compared to other brick firing technologies (Akinshipe, 2013; Maithel *et al,* 2012; Guttikunda *et al,* 2013; RSPCB, 2011).

The South African Clay Brick Association, (CBA, 2002) and Rajasthan State Pollution Control Board, (RSPCB, 2012) describe a clamp kiln as a temporary structure constructed with "green bricks" to be fired. The "green bricks" are packed in a pyramid-shaped formation on top of a foundation layer made of previously fired bricks, which also houses a portion of the fuel material (coal, coke, wood, cinder, waste etc.) A layer or two of previously fired bricks may be used to enclose the "green bricks", in order to reduce heat loss and conserve energy (Figure 1).

Clamp kiln technology has, however, been globally branded as a polluting, energy inefficient technology; and its usage has since been discontinued in most developed nations of the world (Akinshipe, 2013; Hashemi & Cruickshank, 2015b; Raut, 2003).

Figure 1: A typical clamp kiln at Nova Bricks, South Africa (NOTE: containment of emissions is not feasible)

The pollutants associated with brick making and particularly, clamp kiln technology, include particulate matter (PM), all PM passing into a sampler whose inlet has a median cut-off of 10 micrometres (PM_{10}), all PM passing into

a sampler whose inlet has a median cut-off of 2.5 micrometres ($PM_{2.5}$), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), nitrogen oxide (NO), carbon monoxide (CO), carbon dioxide (CO_2), ozone (O_3), metals, organic compounds (TOC) (including methane, ethane and other volatile organic compounds [VOCs], and some hazardous air pollutants [HAPs] such as hydrogen chloride (HCl) and hydrogen cyanide (HCN), as well as some fluorides (USEPA, 1997a; Akinshipe 2013; Assadi *et al,* 2011; Skinder *et al,* 2014b). These pollutants can cause severe health problems in humans and animals, as well as damage to agriculture, vegetation and land cover, etc.

In 2010, the South African Department of Environmental Affairs (DEA), identified clamp kiln technology as one of the activities that pose "negative environmental effects by impacting negatively on health, social, economic and ecological conditions". Thus, the mandatory application for an Atmospheric Emissions License (AEL) by clamp kiln operators was promulgated (DEA, 2010b; 2012).

The challenge associated with emissions from clamp kiln firing include the following: an uncontrollable firing process (due to the pseudo-enclosed nature of the firing chamber); inadequate abatement technology for mitigating emissions; as well as the localised effect of the emission on the immediate environment as a result of the lower height of release and limited buoyancy of the relatively cool emissions (i.e. if compared to other industrial processes) (DEA, 2012; Akinshipe, 2013; Irm, 2012).

In addition, the quantification of emissions from clamp kilns has proven to be globally unsuccessful, due to inadequate scientific methods for measuring or quantifying pollutant and process metrics from the kiln. These metrics include particulates and gas concentrations, flue gas temperature, flue gas velocity, combustion efficiency, emission rates, emission factors etc. The configuration of a clamp kiln and the mechanism of its firing process make it impracticable to capture and channel flue gases emanating from the kiln, without which measurements cannot be taken accurately and representatively. Any attempt to undertake measurements produces severely distorted results due to external environmental and climatic influences such as wind speed, wind direction, rain, humidity and ambient temperature, (Umlauf *et al,* 2011; Cardenas *et al,* 2009).

Furthermore, the contribution of external sources of pollution from the brick yard and from regional land use activities such as agriculture and other industries cannot be adequately quantified and apportioned due to the pseudo-enclosed nature of the clamp kiln firing chamber. Hence, measurement results, as well as dispersion simulations are mostly over estimated, since emissions from external sources cannot be excluded or adequately accounted for (Akinshipe, 2013; Akinshipe & Kornelius, 2017b).

As a result of these challenges, previous studies, policies and regulations involving clamp kiln technology around the world have been based on inferences and estimates, as well as assumptions drawn from similar firing technologies.

This thesis reports the outcome of the research work designed to address the afore-mentioned challenges in order to adequately measure atmospheric emissions from clamp kilns.

1.2 AIM, OBJECTIVES AND SCOPE OF STUDY

In light of the challenges discussed above, the aim of the study is to design a scientifically acceptable technique for capturing and confining emissions from a simulated clamp kiln in order to comprehensively measure and/or quantify emission metrics, emission factors, energy efficiency, as well as develop air quality management measures and practices for clamp kilns.

In order to achieve this aim, the following objectives were undertaken as scope of study:

- Design a model kiln with similar configuration and operation to a full scale clamp kiln that is capable of simulating the firing process in a full-scale clamp kiln;
- Design a single source stack configuration for the model kiln that is capable of capturing and channelling flue gases from the kiln through a sampling duct;
- Undertake a series of brick firing and stack monitoring campaigns on the model kiln (at the outlet stack) using varying firing inputs typically used by South African clamp kiln operations;
- Conduct laboratory and computational analyses of input data and measured results in order to generate clamp kiln emission rates, emission factors and other emission metrics;
- Evaluate the energy efficiency of clamp kilns based on analyses of fuel use;
- Compare emissions results from clamp kilns with those from previous literature, as well as results from similar brick firing technologies, in order to evaluate the extent of clamp kiln pollution relative to those firing technologies; and
- Develop and recommend air quality management measures and/or best industry practices for clamp kilns based on findings of the study.

1.3 POLLUTANTS AND METRICS OF INTEREST

Several gaseous and particulate air pollutants are emitted from brick kilns. Among these pollutants, the following are of greater significance to air quality and were investigated in this study: CO, NOx (including nitrogen dioxide, NO_2 and nitrogen oxide, NO), SO_2 and total PM, as well as various size fractions of PM. These pollutants are significant to air pollution studies in South Africa and globally as well. They have been shown by various studies (including World Bank, 1997; Maithel *et al,* 2012; DEA, 2009a; DEA, 2009b; DEA, 2010a; DEA, 2010b; DEA, 2012; DEA, 2013; Assadi *et al,* 2011; Skinder *et al,* 2014b; Ahmad *et al,* 2011) to be the pollutants with the highest impacts, both nationally and globally.

The measurement of atmospheric pollutant emissions is required to be recorded in relevant and useable formats and units. These units include concentrations, emission rates and emission factors. Pollutant concentrations are often expressed in mass per volume, while emission rates are often expressed as mass of pollutant released over specific time.

An emission factor (EF) is a quantity of a pollutant emitted relative to an activity metric (Weyant, 2014). It is a representative value that attempts to relate the quantity of a pollutant released to the atmosphere, with an activity associated with the release of that pollutant (USEPA, 1995). For instance, an EF for the release of NO_2 from combustion of coal would be expressed in grams (g) NO_2 emitted per kilogram (kg) of coal combusted. EFs are usually expressed as the weight of pollutant divided by a unit weight, volume, distance, or duration of the activity emitting the pollutant (USEPA, 1995).

Pollutant metrics applicable to this study include milligrams per cubic metre, mg/m^3 or micrograms per cubic metre, $\mu g/m^3$ (as concentration); grams per second, g/s or grams per second per brick, g/s brick (as emission rates); and grams per kilogram of fired bricks, g/kg or gram per brick fired, g/brick (as emission factors).

1.4 Significance of Research

The availability of emission rates, emission factors and associated metrics for specific industrial processes is a significant tool in air quality engineering and management worldwide. Hence, the determination of these metrics for clamp kiln technology will significantly improve air quality dispersion simulations, impact assessment studies, air quality planning and management around a clamp kiln facility.

The research outcome is expected to facilitate the formulation of scientifically informed policies and regulations in South Africa, India and other parts of south and Southeast Asia, Central America, and other nations of the world where clamp kilns are still widely in use.

1.5 Structure of Thesis

The following chapters are presented in this thesis:

- **Chapter 1 – Introduction:** This is the current chapter. It provides background information to the study and gives the aim, objectives, scope, interest and significance of the study.
- **Chapter 2 – Literature:** This chapter provides a detailed review of brick kiln firing, associated emissions as well as health and other adverse effects. A comprehensive description of various firing technologies as obtained from literature is included.
- **Chapter 3 – Model kiln design and monitoring methodology:** This chapter describes the design applied in the model kiln construction as well as the experimental procedure and equipment utilized in emissions monitoring.
- **Chapter 4 – Emissions results, discussion and emission factor calibration:** This chapter provides the results of monitoring, results of analysis, and calculation of emission rates and emission factors. Discussion is presented along with each result for clarity.

- **Chapter 5 – Energy analyses for clamp kilns:** This chapter evaluates the energy input utilized in the model kiln firing and how efficient the model kiln is fired per cycle.
- **Chapter 6 – Emissions Correction and management mechanisms:** In this chapter, the model kiln performance in capturing emissions is evaluated using sulfur mass balance analysis. Emission control, management measures and dispersion simulation are also presented and discussed.
- **Chapter 7 – Alternative energy use for clamp kilns:** A pilot study was conducted to substitute the external fuel with a locally available alternative in order to attempt improving the energy efficiency of the kiln and consequently evaluate any likely reduction in atmospheric emissions. The approach to the pilot study and outcome obtained are presented in this chapter.
- **Chapter 8 – Findings, conclusions and recommendations:** In this chapter, findings and conclusions are inferred from the results and discussions provided. Limitations, assumptions and knowledge gaps that are applicable to the study were also provided. Finally, recommendations are offered for clamp kiln air quality management, as well as for further research.
- **Chapter 9** provides the reference list while **Chapter 10** presents the Appendix section. A Glossary section is provided after the Appendix.

CHAPTER TWO

2 LITERATURE

2.1 CLAY BRICK FIRING

Clay bricks are fired in kilns, and they are one of the most widely used forms of building materials in the world (EcoSur, 2006; Lalchandani, 2012). The consistent popularity of fired bricks as building material is a result of flexibility in construction and design, cost effectiveness, adaptability in severe conditions and its relatively high plasticity (Warren, 1999; CBA, 2002; 2005 Majzoub, 1999; Kornmann *et al,* 2007; Handisyde *et al,* 1976).

According to the Climate and Clean Air Coalition, CCAC (2015) and Pradhan (2015), annual global brick production is estimated at about 1.5 trillion bricks, with Asia accounting for 89 - 90 % (1.35 trillion), as shown in Figure 2. The largest clay brick producing countries in the world are China (54 – 67 %), India (11 – 16 %), Pakistan (3 – 8 %), Bangladesh (1 – 4 %) and Vietnam (~2 %) (Pradhan, 2015; Baum, 2010; CCAC, 2015; Weyant *et al,* 2014). In South Africa, CBA (2005) estimates the annual brick production at 0.23 – 0.26 % of global production (3.5 – 4 billion bricks).

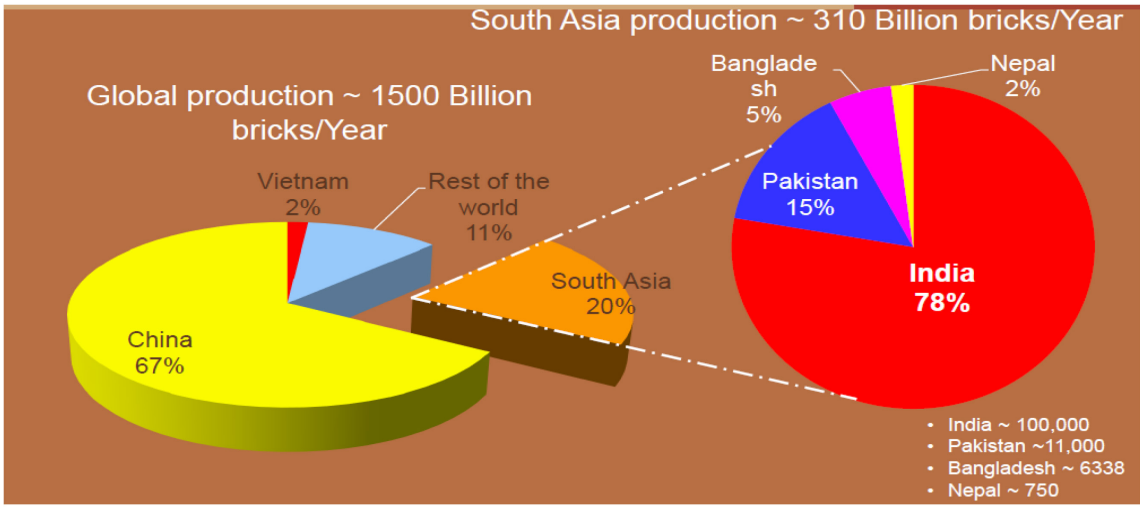


Figure 2: Annual global brick production distribution (Pradhan, 2015)

The clay brick firing process may be classified based on the structure of the firing system adopted – intermittent or continuous; and on the direction of flow of heat and flue gases – up-draught, down-draught and horizontal or cross-draught (Merschmeyer, 2000a; Baum, 2010; Brick Industry Association, BIA, 2006; USEPA, 1997a; Habla, 2016).

Intermittent or periodic kilns are either fully or partially enclosed structures that employ definite structural patterns in order to permit adequate circulation of heat, which is fed via fire holes in the kiln (BIA, 2006; USEPA, 1997a). According to Lopez *et al* (2012), intermittent kilns generally have low energy efficiencies when compared with

continuous kilns, since they require fresh energy for restarting the firing process in every cycle. In intermittent kilns, a steady temperature rise occurs within the kiln until the firing process is completed and the kiln is de-hacked (unpacked) after cooling down. Intermittent kilns include clamp kilns, scotch kilns, round kilns, annular kilns, zigzag kilns etc. (Habla, 2016; BIA, 2006; EcoSur, 2006; RSPCB, 2011; Merschmeyer, 2000a).

Continuous kilns, alternatively, are more sophisticated, employing continuous or constant feed of fuel into a structure in which either green bricks are passed steadily through a stationery firing zone; or a firing zone is passed through a stationery pack of green bricks (with the aid of a suction fan or chimney). Continuous kilns include tunnel kilns, vertical shaft brick kilns (VSBKs), Hoffmann kilns, Bull's trench kilns, fixed chimney kilns, high draught kilns etc. (Habla, 2016; RSPCB, 2011; EcoSur, 2006; Maithel *et al,* 2012).

Merschmeyer (2000a), Potgieter & Jansen (2010) and EMEP/EEA (2009) classify kilns into three types, based on the direction in which the heat flows, namely, up-draught firing, down-draught firing and horizontal or cross-draught firing. This is illustrated in Figure 3.

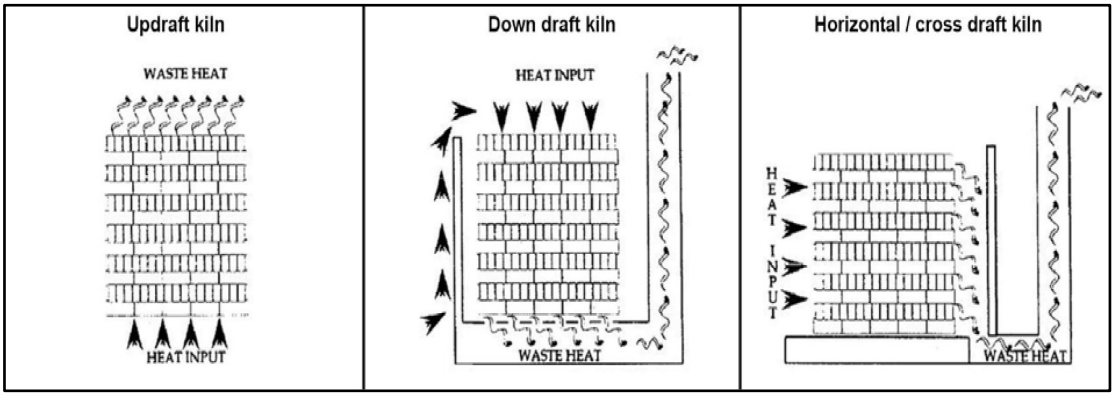


Figure 3: Classification of brick kilns based on flow of emissions (Potgieter & Jansen, 2010)

The up-draught firing system include the clamp kiln and VSBK; the down-draught firing system include the scotch kiln, round kiln, annular kiln and zigzag kiln (arch-less); while the horizontal or cross-draught firing system include the Hoffmann kiln, tunnel kiln, fixed chimney Bull's trench Kiln (FCBTK) and Bull's trench Kiln (Merschmeyer, 2000a; RSPCB, 2011; Maithel *et al,* 2012).

2.2 CHEMISTRY AND THERMODYNAMICS OF CLAY BRICK FIRING

Rowden (1964), Alfrey & Clark (2005), Mutsago (2002), Diop *et al* (2011), Velasco *et al* (2014), Bleininger (1917) and Oti & Kinuthia (2012) provide adequate background on the chemical properties of clay material utilized in brickmaking as well as the chemistry of clay brick firing. Clay bricks are formed from either carbonaceous clays and shales, or non-carbonaceous clays, the main chemical constituents being silica, alumina, iron oxide and often lime (Rowden, 1964; Velasco *et al,* 2014). The chemical compositions of clay materials used for brick making from different sources as published by Rowden (1964), Ahmari & Zhang (2012), Chou *et al* (2002), Aramide (2012), Diop & Grutzeck (2008) and Vieira *et al* (2008) are shown in Table 1.

Table 1: Chemical composition of various clays (Rowden, 1964; Ahmari & Zhang, 2012; Chou *et al,* 2002; Aramide, 2012; Diop & Grutzeck, 2008; Vieira *et al,* 2008)

	Clay types by source											
	England					Illinois, USA			Nigeria	Senegal	Rio de Janeiro, Brazil	
	Eturia	Weald	Keuper	Oxford	Shale	Fly ash	Clay	Shale	Ipetumodu	Bafoundou	Amarela	Preta
Constituent	%	%	%	%	%	%	%	%	%	%	%	%
Silica, SiO_2	60 – 62	55.0	42.7	44.0	49 – 62	49.0	57.1	63.3	63.4	69.7	43.9	44.8
Titanic Oxide, TiO_2	1.2 – 1.5	1.0	1.0	0.3	0.9 – 1.2	1.19	1.38	1.02	1.00	0.8	1.23	1.3
Alumina, Al_2O_3	17 – 20.5	18.4	16.3	17.5	18 – 23.0	22.5	25.0	16.7	32.58	13.3	27.5	34.0
Ferric oxide, Fe_2O_3	9 – 9.8	10.4	6.6	2.8	4.0 – 7.3	13.3	2.33	6.54	2.62	10.1	12.8	3.93
Ferric Sulfide,FeS_2	–	–	–	2.6	–	–	–	–	–	–	–	–
Lime, CaO	0.2 – 0.5	2.7	9.5	8.1	0.8 – 1.2	1.35	0.46	0.39	0.12	0.1	0.19	0.16
Magnesia, MgO	0.8 – 1.1	0.9	6.2	1.6	1.0 – 1.6	0.86	0.53	1.79	0.10	0.1	0.89	–
Potash, K_2O	0.9 – 1.7	3.2	3.6	2.7	1.9 – 3.7	2.36	1.42	3.14	0.09	1.3	1.5	–
Soda, Na_2O	0.1 – 0.5	0.5	0.8	0.7	0.2 – 1.2	1.50	0.02	0.92	–	0.6	–	–
Sulfur Trioxide, SO_3	–	–	–	1.3	–	–	–	–	–	–	–	–
Manganese(II) oxide, MnO	–	–	–	–	–	0.02	<0.01	0.07	–	–	–	–
Phosphorus(V) oxide, P_2O_5	–	–	–	–	–	0.19	0.07	0.12	–	0.03	–	–
Chromia, Cr_2O_3	–	–	–	–	–	0.03	0.03	0.02	–	–	–	–
Loss on Ignition (1000 ^oC)	5.8 – 7.2	7.7	13.6	18.5	6.6 – 14.9	6.64	8.84	4.49	11.3	4.0	11.6	14.7

The main mineral constituents of clay are expressed in the form of clay matter ($Al_2O_3.2SiO_2.2H_2O$), felspathic or micaceous matter ($K_2O.Al_2O_3.6SiO_2$), quartz (SiO_2), ferric oxide (Fe_2O_3) and Lime (CaO). The clay matter, when heated to a temperature ranging from 450 – 650 ^oC, is decomposed into its separate constituents, viz. silica, alumina and water. The water constituent in $Al_2O_3.2SiO_2.2H_2O$, known as "combined water", amounts to about 14 % of the weight of the clay matter, and does not form part of the "mechanical water", i.e. the water added into the clay mixture during processing. The mechanical water is steamed off mostly during drying, at temperatures ranging from 20 ^oC to 150 ^oC (Rowden, 1964; Alfrey & Clark, 2005; Mutsago, 2002; Vieira *et al,* 2008; Diop *et al,* 2011; Ahmari & Zhang, 2012; Oti & Kinuthia, 2012).

According to Vieira *et al* (2008) and Rowden (1964), when a "green brick" or dried brick is heated to extremely high temperatures (> 1000^oC), it loses weight, a term referred to as "loss-on-ignition". Loss-on-ignition is due to the following:

- The burning out of carbonaceous matter and combustible sulfur in the clay;
- The breakdown of carbonates present in the clay to give off carbon dioxide, CO_2; and
- The release of "combined water" from the clay.

Loss-on-ignition is therefore, an indicator of the amount of carbonaceous matter and carbonates present in the clay. For instance, a low loss-on-ignition indicates that the amount of carbonaceous matter and carbonates in the clay is low (Vieira *et al,* 2008; Rowden, 1964).

Carbonates found in clay are mostly magnesium, iron and calcium carbonates, which are often regarded as impurities (Bleininger, 1917; Rowden, 1964). These carbonates dissociate on heating to form oxides and CO_2 (shown in Equations 1, 2 and 3).

$$\mathbf{FeCO_3 \rightarrow FeO + CO_2\ (Temperature, 400 - 700\ ^oC)} \quad \text{Equation 1}$$

$$\mathbf{MgCO_3 \rightarrow MgO + CO_2\ (Temperature, 400 - 650\ ^oC)} \quad \text{Equation 2}$$

$$\mathbf{CaCO_3 \rightarrow CaO + CO_2\ (Temperature, 600 - 900\ ^oC)} \quad \text{Equation 3}$$

A high percentage of calcium carbonate in the clay material may cause lime flaking in the fired bricks, and/or produce a scum of white calcium sulphate on the exposed surfaces of the fired bricks, especially when a significant amount of SO_2 is released from the fuel during firing (Rowden, 1964).

Carbonaceous matter in clay starts to burn out at about 200 – 350 ^oC to form hydrocarbons and a more carbonaceous residue (Rowden, 1964). The carbonaceous residue will only be further dissociated to emit CO or CO_2 if the following favourable conditions, described by Rowden (1964), occur in the kiln:

- Availability of excess air in the combustion chamber to maintain an oxidising environment in the kiln;
- A high cross sectional area of the clay material being exposed to combustion, as well as adequate spacing employed when packing the bricks; and

- Uniformity in the rate of combustion, so as to ensure adequate penetration of the clay brick and ignition of the carbon in the core of the bricks.

According to Grim & Johns Jr. (1951) and Gredmaier *et al,* (2011), raw clay materials used in brick firing also contain **sulfur and calcium**, which are evenly distributed in trace amounts in the unfired bricks. The most likely compound to be formed during brick firing is calcium sulfate ($CaSO_4$), in a complex reaction proposed by Tourneret *et al,* (1990) as follows:

$$\mathbf{9CaCO_3(s) + 9SO_2\,(g) \rightarrow 6CaSO_4(s) + CaSO_3(s) + 2CaS\,(s) + 9CO_2\,(g)} \quad \text{Equation 4}$$

$$\mathbf{4CaSO_3(s) \rightarrow 3CaSO_4(s) + CaS\,(s)} \quad \text{Equation 5}$$

$$\mathbf{CaS\,(s) + 2O_2(g) \rightarrow CaSO_4(s)} \quad \text{Equation 6}$$

Equation 6 requires excess oxygen which is only abundant at the brick surface. An insufficient supply of oxygen could change the reaction in Equation 6 to become:

$$\mathbf{CaO\,(s) + SO_2\,(g) + 3CO\,(g) \rightarrow CaS\,(s) + 3CO_2\,(g)} \quad \text{Equation 7}$$

Tourneret *et al,* (1990) and Brownell (1949) opines that the major source of sulfur released during firing is from the oxidation of the pyrite component (FeS_2) in the clay material, as well as the sulfur present in the coal that is mixed with the clay material during brick processing.

In addition, it was established by Brownell (1949) that calcium sulfate is one of the most prominent and persistent salts that builds up during the firing process. This is due to the extreme temperatures required for calcium sulfates to dissociate and react with silicates; temperatures which may not be achieved at regular brick kiln temperatures (Gredmaier *et al,* 2011 and Brownell, 1960). A clear influence of the firing environment on the quantity of water soluble sulfate in bricks made from clay material containing pyrite component was discovered. According to these studies, clays that are fired in a reducing environment have the potential to retain more sulfates compared to clay fired in an oxidizing environment (Brosnan & Sanders, 2005; Klepetsanis *et al,* 1999).

According to Rowden (1964), Grim & Johns Jr. (1951) and Gredmaier *et al,* (2011), it is possible to have both oxidising and reducing conditions occurring within the firing chamber of a kiln. Whilst the excess air in the firing chamber favours oxidation conditions within the firing chamber, the release of a high temperature water vapour (combined water) at a temperature of 450 – 650 ^{o}C inside and around the bricks, may prevent oxygen from entering the core of the bricks. The carbon present in the core of the bricks reacts with the steam being released to produce strongly reducing gases; hydrogen and CO, which at high temperatures may permanently reduce the iron in the clay and produce varying degrees of colour.

Grim & Johns Jr. (1951) and Gredmaier *et al,* (2011) also describe the reaction in which heat is absorbed (endothermic reaction) into the clay material, which may be due to dehydration, destruction of lattice structure and change in crystal phase. Alternatively, heat release (exothermic reaction) from the clay material may be due to oxidation or the development of new crystalline phases.

The chemical composition of clay material, the firing temperature, as well as the oxidation or reduction condition in the kiln and/or within the bricks, impact on the colour and physical condition of fired bricks. Oxidation occurs when an adequate supply of air (oxygen) is circulated within the kiln, imparting a red or dark brown colour to the bricks. Reducing conditions occur when the oxygen supply within the kiln or within the bricks is limited, impacting an orange, yellow, blue or grey colour to the bricks (Rowden, 1964; Aramide, 2012; Cultronea *et al,* 2003; International Labour Organization, ILO, 1984; Monteiro & Vieira, 2004). Dark coloured spots of iron oxides have also been observed when a clay material that contains high amounts of iron carbonates is fired in a reducing environment (Rowden, 1964).

6 stages in the clay brick firing process have been identified as follows: evaporation, dehydration, oxidation, vitrification, flashing and cooling. Table 2 provides the temperature range and description for these six stages. According to Kornmann *et al,* (2007), Merschmeyer (2000a) and BIA (2006), the range of temperature required for firing at each stage is vital to the quality of bricks produced, while the temperature required depends on the type of clay material, the size and "coring" of the fired bricks.

Table 2: Temperature range for various stages of brick firing (Rowden, 1964; BIA 2006; USEPA, 1997a; 2003a; Grim & Johns Jr., 1951; Gredmaier *et al,* 2011)

Stages	Temperature Range (°C)	Description of Reactions during Firing
Evaporation	20 – 150	Water-smoking or slow heating stage where evaporation of "free or mechanical water" takes place. Mechanical water is the water that is added into the clay mixture during processing. It is essential at this stage to maintain gradual temperature rise so as to prevent cracking of the bricks, since the outer surface of the bricks will contract at a faster rate than inside the bricks, leading to cracking. An endothermic reaction is observed at this stage due to the loss of the mechanical water.
Dehydration	149 – 650	Burning out and breaking down of the carbonaceous matter and carbonates, as well as the "combined water", occur during the dehydration stage. The temperature at which the "combined water", carbonaceous matter and carbonates completely combust depends on the rate of heating. Rapid heating may cause an atmosphere of steam to persist around and within the bricks, resulting in reducing conditions (due to insufficient supply of oxygen within the bricks) that produces discolouration or dark coloured, cored and bloated bricks. An endothermic reaction is observed at this stage due to further release of water and carbonaceous matter.
Oxidation	300 – 982	Oxidation in the kiln may commence at temperatures as low as 300 °C and may extend as high as over 900 °C, depending on the rate of heating, the quantity of carbon present in the clay, the amount of excess air available in the combustion chamber, the density and area to volume ratio of the clay bricks. In order to produce quality bricks, it is essential that any residue carbonaceous matter be combusted and all iron residues oxidized to its oxides at this stage. This could be achieved by ensuring excess air of 50 % or more is circulated within the combustion chamber; holding the temperature at about oxidation 800 - 900 °C for a few days (3 - 4 days in some kilns); and keeping the CO_2 level in the flue gas at 10 - 12 %. An exothermic reaction is observed at this stage, and is due to the oxidation of organic compounds and subsequently, sulfide compounds in the clay material. This exothermic reaction is observed from 300 °C up to 450 °C, and then an endothermic reaction sets in. This is attributed to the loss of water from the crystal structure of the mineral and a change in crystalline phase of the quartz from α to β form. The loss of water is achieved without damage or shrinkage of the of the clay mineral lattice structure.
Vitrification	900 – 1316	Vitrification usually commences at about 900 °C, when all the carbonaceous matter has been fully oxidized, and extends up to the highest temperature the bricks can withstand without damage. The strength of the fired bricks is developed during vitrification, by sintering of clay particles and melting of the clay mass. The solid particles become coated with liquid which upon cooling solidifies mainly as a glass and binds the particles together. The strength of the fired bricks thus depends on the maximum temperature reached, the duration of the vitrification stage or maximum temperature, as well as amount of fluxes, such as potash, soda, magnesia, lime and ferrous oxide present in the clay. At this stage, a series of exothermic reaction are observed, due to the slow oxidation of sulfur compounds and possibly residual organic material, as well as formation of new crystalline phases.
Flashing	1150 – 1316	Holding the peak or finishing temperature for a period in order to impact the required colour to the bricks by the addition of “un-combusted fuel” to the kiln.
Cooling	1316 – 20	This is the decrease of kiln temperature from peak to ambient temperature, lasting a few days (4 – 5 days or more).

2.3 CLAY BRICK FIRING AND ATMOSPHERIC POLLUTION

Atmospheric emissions arising from brick manufacturing installations are a significant source of atmospheric pollution (FAO, 1993; Lalchandani, 2012; Brebbia & Pulselli, 2014). Brick kilns have been identified as one of the most significant source of atmospheric pollution, (and have gained international concern in recent years) due to its basic technology application, poor or inefficient combustion processes and the absence of adequate emission control required to capture and mitigate pollutants released to the atmosphere (Croitoru and Sarraf, 2012; World Bank, 1997; Lalchandani, 2012; Ferdausi *et al,* 2008; Akinshipe & Kornelius 2015; CAI-Asia, 2008; DEA, 2010a; DEA, 2013; Hashemi & Cruickshank, 2015b; Raut, 2003). The brick manufacturing industry is also considered to be one of the significant sources of greenhouse gas emissions in various regions of the world (World Bank, 1998; FAO, 1990; Alam, 2006; Abdalla *et al,* 2012).

Table 3 provides the percentage contribution of brick kilns to total pollutant emissions based on the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) Model, operated by the International Institute for Applied Systems Analysis (IIASA).

Table 3: Contribution of brick production to regional and global emissions of air pollutants in 2010, Source – GAINS Model (Klimont, 2012)

Region	% Contribution of Brick Kilns to Total Emissions				
	BC [1]	OC [2]	PM_1 [3]	SO_2	CO
Africa	0.3	0.1	0.1	0.1	0.1
East Asia & Pacific	8.2	5.1	2.3	6.5	2.3
Latin America & Caribbean	0.5	0.2	0.1	0.1	0.1
North America & Europe	0.2	0.1	0.2	<0.1	0.2
South-West-Central Asia	10.4	4.6	3.7	0.9	3.7
Global	**5.5**	**2.6**	**1.6**	**2.9**	**1.6**

NOTE

[1] BC is Black Carbon

[2] OC is Organic Carbon

[3] PM_1 is all PM passing into a sampler whose inlet has a median cut-off of 1 micrometre

The most abundant and harmful pollutants in brick production sites have been identified as SO_2, NOx, CO, ozone (O_3), hydrogen fluoride and heavy metals, as well as suspended PM (Assadi *et al,* 2011; Skinder *et al,* 2014b; Ahmad *et al,* 2011).

Various studies in Asia (including Ismail *et al,* 2012; Hassan *et al,* 2012; Pariyar *et al,* 2013; Bisht & Neupane, 2015; Skinder *et al,* 2014a; Lalchandani, 2012) have measured the ground level concentration of atmospheric pollutants from brick kilns. The concentrations were, in most of the cases, high, and resulted in exceedance of local and international guidelines or permissible limits. The concentration declines as the distance from the kiln increases.

The negative effects of pollution from brick kilns include health challenges to humans and animals, degeneration of land cover, loss of soil and soil contamination, damage to agriculture, reduced visibility, depletion of soil nutrients and the ozone layer, increased soil erosion, damage to buildings, contamination or acidification of surface and ground water systems, as well as consequential social and economic effects (WHO, 2000; Pariyar *et al,* 2013; BIA, 2006; RERIC, 2003; Lalchandani, 2012; DEA, 2010; Bisht & Neupane, 2015; Skinder *et al,* 2014a; Rafiq & Khan, 2014; USEPA, 2012; Skinder *et al,* 2015; Shrestha & Raut, 2002; Singh & Asgher, 2005; Schmidt, 2013; Hossain & Abdullah, 2012).

Health effects and symptoms associated with atmospheric emissions from brick production are mostly respiratory, pulmonary and cardio vascular infections. These include contraction or spasm of the airways and bronchi (commonly referred to as asthma attacks), inflammation of the mucous membranes (bronchitis), increased secretions in lung and heart tissues, impairment of the lung function, increase in blood and throat pressure, headache, fatigue, dizziness and chest pain, as well as irritation of the eyes and nose (Skinder *et al,* 2014b; Pariyar *et al,* 2013; Rafiq & Khan, 2014; WHO, 2000; USEPA, 2012; Casarett *et al*, 1996; Heyder & Takenaka, 1996; World Bank, 1998; WHO, 1979; Amdur, 1978; Guttikunda & Khaliquzzaman, 2014; Darain *et al,* 2016).

It has also been reported that adults and children engaging in brick making activities are at a higher risk of being exposed to smoke, dust and organic pollutants, especially when wood or coal are utilized as fuel. These fuels also release dust-bound polycyclic aromatic hydrocarbons (PAHs) which have been identified as high risk carcinogens. Brick workers may be exposed to PAHs via dermal contact, inhalation, as well as ingestion (Kamal *et al,* 2014).

The effects of brick kiln emissions on soil characteristics and vegetation have also been investigated. Studies show increase in soil acidity, as well as increase in concentration of heavy metals, nitrate and sulfate near brick kilns (100 to 150 metres downwind of the kiln), which consequently results in reduced soil quality (Bisht & Neupane, 2015; Schmidt, 2013).

According to the Organization for Economic Co-operation and Development, OECD (1981) and National Acid Precipitation Assessment Program, NAPAP (1990), visible damage to sensitive plant species may become noticeable when they are exposed to heavy metals concentrations of 1 850 µg/m^3 for 1 hour or concentrations of 500 µg/m^3 for 8 hours or concentrations of 40 µg/m^3 for the entire maturing season. Visible foliar injury to mango, apricot and plum trees have been investigated and associated with increased hydrogen fluoride concentrations in ambient air near brick kilns in Southeast Asia (Ahmad *et al,* 2011).

Soil contamination around brick making facilities may also lead to distortion of plant biomass, alteration of plant structure as well as change in species diversity (Gupta & Narayan, 2010; Skinder *et al,* 2015; Rafiq & Khan, 2014; Schmidt, 2013).

Finally, contamination of water resources as a result of pollutant dispersion around brick clusters in India has also been investigated, indicating an increase in total solids, calcium and total hardness, as well as a reduction in dissolved oxygen in all water resources assessed (Khan & Vyas, 2008).

All studies and investigations mentioned above have either identified a direct association of emissions with brick kilns, or were conducted in a region with high brick kiln activities relative to other industrial activities. For instance, the charts in Figure 4 show brick kilns as the highest and second highest source of PM_{10} and TSP respectively, in the Kathmandu valley, Nepal.

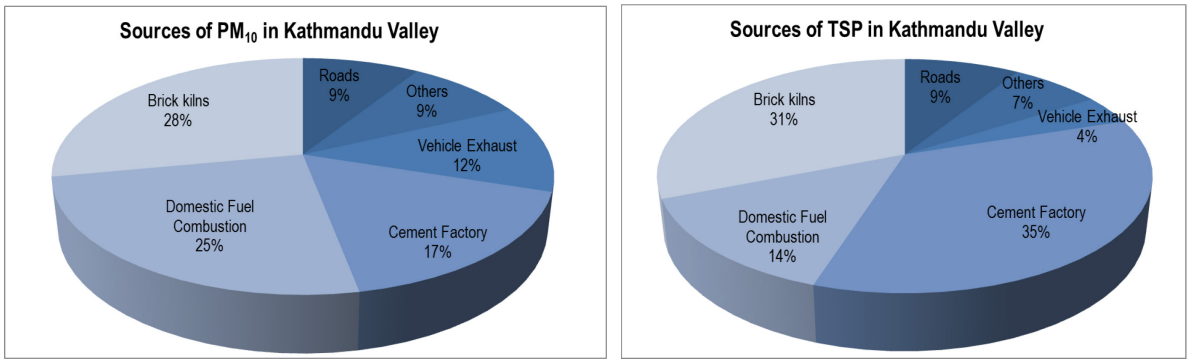


Figure 4: Sources of PM_{10} and TSP in Kathmandu valley, Nepal (World Bank, 1997; Haack & Khatiwada, 2007)

2.4 POLLUTANTS ASSOCIATED WITH BRICK KILNS

Skinder *et al* (2014b), USEPA (1997a), Maithel *et al* (2012), Akinshipe (2013), EIP (1995), Skinder *et al* (2014a), Imran *et al* (2014) and Bellprat (2009) identify pollutant emissions from clay brick firing to include the following:

- Particulate matter (PM) or total suspended particulates (TSP);
- All PM passing into a sampler whose inlet has a median cut-off of 10 micrometres (PM_{10});
- All PM passing into a sampler whose inlet has a median cut-off of 2.5 micrometres ($PM_{2.5}$);
- All PM passing into a sampler whose inlet has a median cut-off of 1 micrometres (PM_{1});
- Sulfur dioxide (SO_2);
- Sulfur trioxide (SO_3);
- Nitrogen oxides (NO_x), (including nitrogen dioxide (NO_2) and nitrogen monoxide (NO));
- Carbon monoxide (CO);
- Carbon dioxide (CO_2),
- Metals (including Cooper (Cu), Chromium (Cr), Lead (Pb), Nickel (Ni), Zinc (Zn), Cadmium (Cd), Iron (Fe), Manganese (Mn);
- Fluorides; and
- Organic compounds (including methane, ethane, volatile organic compounds (VOCs), persistent organic compounds (POPs) and some hazardous air pollutants (HCl and HCN).

Brickmaking activities include mining, crushing and blending, grinding and screening, souring, ageing, drying, packing, firing, unpacking and packaging. Extensive literature on these activities has been published by Akinshipe (2013), USEPA 1999b, NPI (1998), Merschmeyer (1999), (2000b) and Kornmann *et al* (2007). Typical pollutants associated with these activities are summarized in Table 4.

Table 4: Summary of emissions from brickmaking processes (Cardenas *et al,* 2009; CBA, 2002; Imran *et al,* 2014; Bellprat, 2009, Akinshipe, 2013)

Pollutants	Mining	Crushing	Milling	Drying[1]	Hauling[2]	Firing
Total PM	✓[3]	✓	✓	–	✓	✓
PM_{10}	✓	✓	✓	–	✓	✓
$PM_{2.5}$	✓	✓	✓	–	✓	✓
SO_2	–	–	–	–	✓	✓
SO_3	–	–	–	–	–	✓
NO_x (NO_2 and NO)	–	–	–	–	✓	✓
CO	–	–	–	–	–	✓
CO_2	–	–	–	–	–	✓
Metals	–	–	–	–	–	✓
Fluorides	–	–	–	–	–	✓
TOCs[4]	–	–	–	–	✓	✓

NOTE: [1] Drying is assumed to be sun-drying, which is typical of South African brick making processes (CBA, 2002; 2005)

[2] Hauling emissions include vehicle entrained emissions from roads, as well as vehicle exhaust emissions

[3] Size of the tick indicates the anticipated extent of the emissions

[4] TOCs include methane, ethane, volatile organic compounds (VOCs), persistent organic compounds (POPs) and some hazardous air pollutants (HAPs)

2.5 BRICK FIRING TECHNOLOGIES

Brick firing has evolved beyond ancient, traditional, basic and common techniques, to more sophisticated, energy efficient technologies (Wingfield *et al,* 1997; Pokhre & Lee, 2014; Pool & Maithel, 2012). According to the Central Pollution Control Board, CPCB (2007), there are over 300 000 continuous and intermittent, formal and informal kilns operating worldwide.

The succeeding sections describe some of the most common firing technologies around the world, which include:

- Tunnel kiln;
- Hoffman kiln;
- Vertical shaft brick kiln (VSBK);
- Down-draught kiln (DDK);
- Fixed chimney Bull's trench kiln (FCBTK);
- Zig-zag kiln; and
- Clamp kiln

Less popular types of kiln for brick firing include the Habla kiln, an energy efficient variant to the Zig-zag kiln invented in Germany (Maithel *et al,* 2014e; Habla, 2016); the igloo or beehive kiln, which is commonly used in Zimbabwe for

firing bricks and other kinds of materials (Tawodzera, 1997; Heeney, 2003); kondagaon kiln (Ravi *et al,* 2007); and Bhadrawati kiln (Ravi *et al,* 2007).

Other less common kilns include the scove kiln, which is essentially a typical clamp kiln plastered with mud on the outer walls to reduce heat loss (ILO, 1984); the scotch kiln; also an improvement on the clamp kiln, in which the base of the kiln, the outer walls and the fire channels are permanently built structures (ILO, 1984; Heeney, 2003); the marquez kiln, a new type of kiln in Mexico, which consists of two arch-roofed chambers that are connected by a clay channel (Bellprat, 2009); shuttle kiln (Hibberd, 1996; Koroneos & Dompros, 2007); the barrel arch kiln; the Suffolk kiln; the stack kiln; the Ideal Kiln; the Belgian kiln (Rowden, 1964); and the dome kiln (Heeney, 2003).

2.5.1 TUNNEL KILN

CBA, (2005), Daraina *et al* (2013) and Kornmann *et al* (2007) describe a tunnel kiln as a long horizontal tunnel in which green bricks are set on "kiln cars" and are driven continuously through a long stationary firing zone where the bricks and combustion gas move in opposite direction and the temperature is regulated at 900 – 1200 ^{o}C (Figure 5). The kiln cars can be moved along the tunnel continuously or at fixed intervals, with air supply and extraction systems provided at several points along the kiln structure (Daraina *et al,* 2013; RSPCB, 2011; Maithel *et al,* 2012).

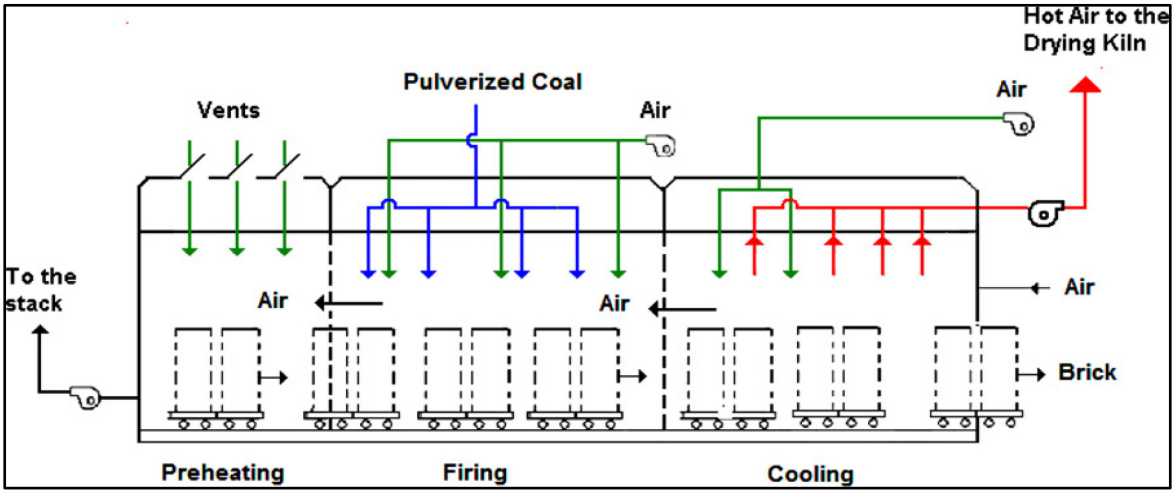


Figure 5: Tunnel kiln schematic design (Kaya *et al,* 2008)

According to Maithel *et al (*2014h), the length of a tunnel kiln varies from 60 to 150 metres, with three distinct zone identified in the operating kiln, namely: the preheating zone (where preheating and final drying occur); the firing zone (where the fuel, usually pulverized or granulated coal, is fed and combustion occurs); and the cooling zone (where inflow of cold air is used to cool the bricks at the exit end of the kiln). The inside chamber of a typical tunnel kiln is shown in Figure 6.

Tunnel kilns are low in labour demand but require high electricity and capital costs. They are capable of receiving 60 000 – 200 000 bricks per day; and the bricks require 3 – 5 days for drying and firing to be completed (Habla, 2016; Maithel *et al,* 2012). According to CBA (2005) and Maithel *et al* (2012), tunnel kilns are capable of firing a variety of

bricks; producing bricks that meet specific demands in terms of size, shapes and colour. Its advantage lies in its ability to establish control over the firing process; its ease of mechanization (thereby reducing the labour requirement); and large production volume. A modification to the tunnel kiln is the roller kiln, described by Kornmann *et al (*2007), which can fire bricks at a short duration of 3 – 8 hours.

USEPA (1997a) and Maithel *et al (*2012) describe tunnel kilns as the most common kiln firing technology in the developed nations, putting its invention at around 1877 in Germany.

Figure 6: Inner chamber of a tunnel kiln (Maithel *et al,* 2014h)

2.5.2 HOFFMAN KILN

The Hoffman kiln, a semi-mechanized kiln, was invented by Friedrich Hoffman in Germany in 1858 (Neaverson, 1994; RSPCB, 2011). It is similar to the transverse arch kiln (TVA) and was initially used for firing roofing tiles (Maithel *et al,* 2014f; Daraina *et al,* 2013). The Hoffmann or barrel arch kiln has a number of open-wall circular ring chambers through which bricks and fuel are stacked for firing in a continuous process (Ubaque *et al,* 2010; Thring, 1962).

The fire in a Hoffmann kiln passes through stacked bricks inside a rectangular or elliptical shaped annular circuit as shown in Figure 7. The movement of the fire in the firing zone – where fuel is fed to the kiln – is induced by draught from a chimney that is connected to the central flue duct (Maithel *et al,* 2014f; Maithel *et al,* 2012).

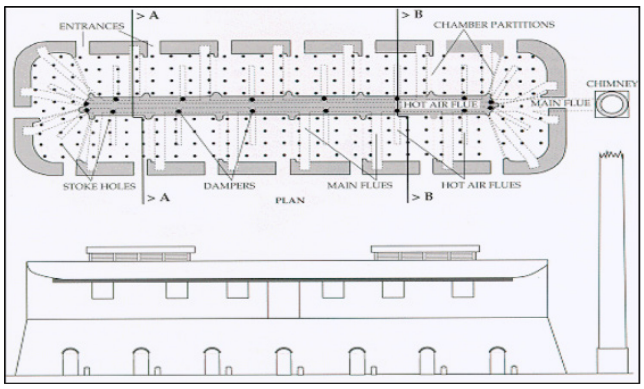


Figure 7: Schematic of a modern Hoffmann kiln (Baum, 2010)

The fired bricks are removed from the cooling zone or chamber when the firing and cooling process is complete. Simultaneously, another load of bricks is fed to the fire chamber at the pre-heating zone to ensure a continuous firing process (Neaverson, 1994; Ubaque *et al,* 2010; Thring, 1962; CBA, 2002).

According to Habla (2016) and Neaverson (1994), Hoffmann kilns are seldom operated in India since the early 20th century and have been replaced by the large, wall chambered TVAs and the tunnel kilns. Another variation of the Hoffmann kiln is the hybrid Hoffmann kiln, which was developed in China and is still extensively used in China and South Asia, including India, Bangladesh etc. (Maithel *et al,* 2014g; Chen *et al,* 2017). According to Lopez *et al (*2012) and Baum (2010), an estimated 90% of the total bricks produced in China are fired using modifications of Hoffman Kilns (Figure 8).

Figure 8: Hoffman kiln structures in Asia (Sarraf *et al,* 2011; Pradhan, 2015)

2.5.3 VERTICAL SHAFT BRICK KILN

The vertical shaft brick kiln (VSBK) was invented in China in 1958 as a modification to the traditional updraft intermittent kiln, operating on the principles of effective consumption of the heat produced by the combustion of the fuel (Habla, 2016; Maithel *et al,* 2012). A VSBK consists of a long, rectangular, vertical shaft through which green bricks and pulverized coal or fuel are lowered from top to bottom in batches (Habla, 2016; Maithel *et al,* 2012; CDM, 2006). According to Maithel *et al (*2012) and De Giovanetti & Volsteedt (2013), the kiln works in the form of a "counter-current heat exchanger", since heat exchange occurs between the continuous flowing updraft air and the intermittently downwards moving bricks.

There are 3 distinct sections in an operating VSBK, as shown in Figure 9:

- **The preheating zone** – this is the top section of the shaft where the incoming green bricks are preheated by the upward moving flue gases;
- **The firing zone** – this is located in the mid-section of the shaft where fuel combustion occurs; and
- **The cooling zone –** located in the lower section of the shaft where the fired bricks are cooled down by the cold ambient in-coming air entering the shaft.

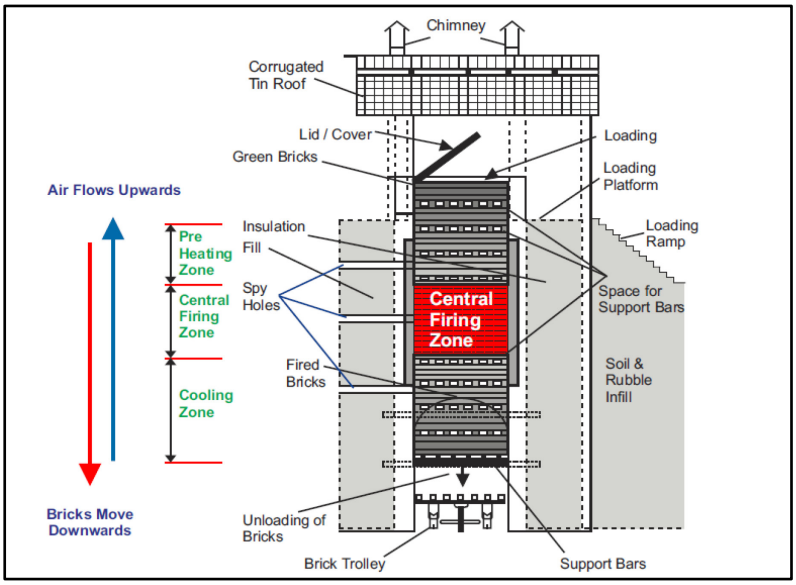


Figure 9: Schematic of a single shaft VSBK with a chain pulley block unloading system (TARA, 2014e)

The bricks pass through pre-heating, firing and cooling zones before reaching the bottom of the shaft where they are de-hacked (Subroto, 2012; Maithel *et al,* 2012; Daraina *et al,* 2013). Thermal efficiency in the kiln is enhanced with the aid of insulating materials such as fly ash, clay, rice husk and even glass wool (Maithel *et al,* 2014i). In the modern VSBKs, typical in South Africa, Vietnam and Malawi, the use of internal or body fuel is supplemented by a small quantity of external fuel (De Giovanetti & Volsteedt, 2013; EECB, 2014; Maithel *et al,* 2014; TARA, 2014a).

Chimneys are also fitted into the kiln and the lid is shut tight during operation in order to minimize fugitive emissions. As a result, VSBKs are relatively high in energy efficiency, low in operating costs, and they are suitable for firing bricks of high quality and specifications (Subroto, 2012; Maithel *et al,* 2012; De Giovanetti & Volsteedt, 2013; Maithel *et al,* 2014i). Typical VSBK structures in Asia and South Africa are shown in Figure 10.

Figure 10: VSBK structures in Asia (left) and South Africa (right) (Maithel *et al,* 2014i; De Giovanetti & Volsteedt, 2013)

2.5.4 DOWN-DRAUGHT KILN

The down draught kiln (DDK) is an intermittent kiln with a permanently built structure which includes a rectangular firing chamber and a barrel-vaulted roof that is connected to a chimney through an underground flue duct (CBA, 2002; Maithel *et al,* 2014b; Punmia *et al,* 2003; Daraina *et al,* 2013). Fireboxes are used to supply hot gases from the

bottom of the chamber (Figure 11) to the roof of the kiln where they are drawn downwards by the chimney draft through the green bricks and out through the chimney stack (CBA, 2002; Maithel *et al,* 2014b). Continuous feeding of fuel (e.g. by coal, gas or oil, firewood, twigs and branches) helps ensure there is a uniform heat distribution in the kiln until the target temperature is attained. This target temperature is maintained for a specific period until the fire subsides, thereby ensuring better thermal performance and lesser heat loss (CBA, 2002; Maithel *et al,* 2014b; Punmia *et al,* 2003). The kiln cools down in 2 – 3 days and the fired bricks are de-hacked in readiness for the next batch (CBA, 2002; Maithel *et al,* 2014b; Punmia *et al,* 2003).

Figure 11: Schematic (left) and structure (right) of a typical DDK (Maithel *et al,* 2014b; Pradhan, 2015)

Other kilns with similar configuration to the down-draught kiln are the up-draught and cross-draught kilns, differing in the direction of the heat flow as shown in Figure 12. The down draught kiln is one of four kiln types used extensively in South Africa (CBA, 2002).

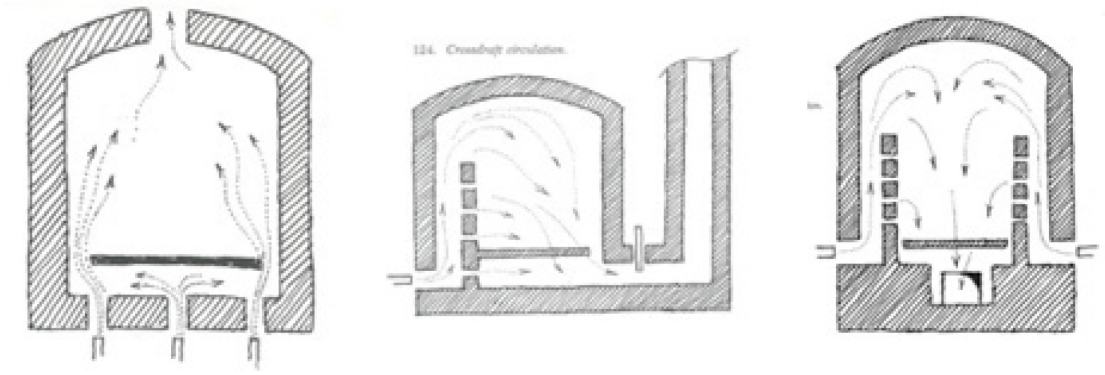


Figure 12: Schematics of the up-draught, cross-draught and down-draught kilns (Fairbank, 2010)

2.5.5 FIXED CHIMNEY BULL'S TRENCH KILN

Maithel *et al* (2012) and Maithel *et al* (2014c) describe the fixed chimney Bull's trench kiln (FCBTK) as a continuous, cross-draught, ring-shaped or annular, moving-fire kiln that is fixed with a permanent chimney structure that provides natural draught to the kiln. In the FCBTK (Figure 13), the bricks are stacked in the firing zone, a ring space formed between the inner and outer walls of the kiln, while the moving fire passes through the green bricks (Maithel *et al,* 2014c; Maithel *et al,* 2012).

The FCBTK utilizes an immovable chimney, an improvement over the Bull's trench kiln (BTK) and the movable chimney Bull's trench kiln (MCBTK), which employs a moving metallic chimney. The sidewalls in the FCBTK are permanent, constructed above the ground, while the roof is temporary, formed from a covering of ash or brick dust, which serves as a seal over the green bricks (ILO, 1984; Maithel *et al,* 2014c).

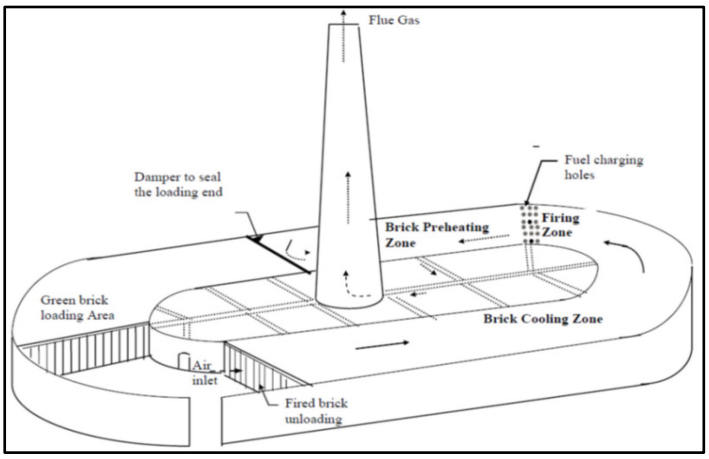


Figure 13: Cross section of a typical FCBTK (Maithel, 2003)

According to Maithel *et al (*2012), the bricks are stacked in a column and blade arrangement, with the unloading end of the kiln kept open for inflow of cold air, while the brick-loading end of the kiln is sealed with various kinds of materials, including plastic, paper, cloth or iron.

Typical MCBTK and FCBTK schematics are shown in Figure 14. Three distinct zones are identified in the FCBTK, namely, the cooling, combustion and pre-heating zone. In the **cooling zone**, air enters the kiln from the unloading end of the kiln, exchanges heat with fired bricks, resulting in the heating of air and the cooling of the fired bricks. In the **combustion zone** (the fuel feeding and firing zone), hot gases are released from combustion of coal, firewood, or agriculture residue (which is fed from the kiln feedholes on the roof). Finally, the **brick pre-heating zone** utilizes heat from fugitive flue gases to dry green bricks (Maithel *et al,* 2014c; Maithel *et al,* 2012; CDM, 2006).

According to CDM (2006), FCBTK has the capacity to produce consistent colour and high quality fired bricks. Clusters of FCBTK operating in Dhaka and Pakistan are shown in Figure 15.

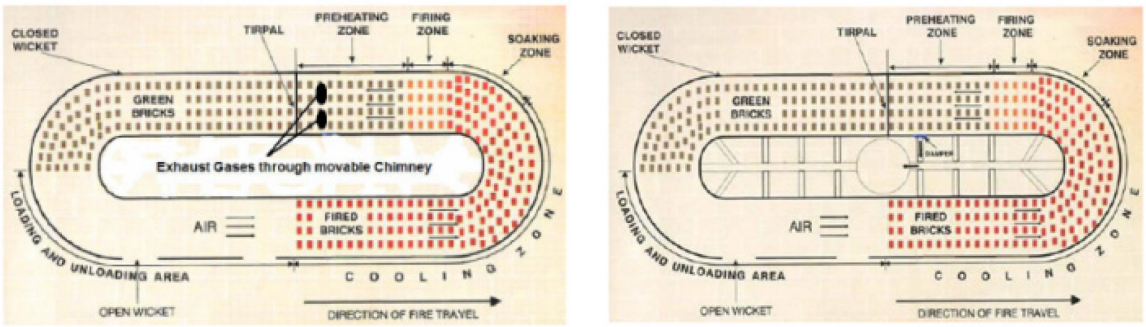


Figure 14: Comparing the MCBTK (left) and FCBTK (right) cross section (Manandhar & Dangol, 2013)

Figure 15: Clusters of fixed chimney BTK operating in Dhaka (left) and Pakistan (right) (Guttikunda & Khaliquzzaman, 2014; Schmidt, 2013)

2.5.6 ZIG-ZAG KILN

The zig-zag kiln is a modification and improvement over the FCBTK. The heat in a zig-zig kiln follows a zig-zag pattern, rather than the straight path in the FCBTK (Maithel *et al,* 2012; ILO, 1984). The zig-zag kiln design results in higher heat transfer rates between the bricks and air due to increased turbulence and velocity achieved through frequent change in direction of flue gases (Maithel *et al,* 2012; Lalchandani, 2012). Consequently, improved combustion is archived due to increased mixing of air and fuel in the combustion zone (Figure 16). Also, a smaller footprint can be designed for the kiln due to increased combustion and longer volatilization time in the combustion zone (Maithel *et al,* 2012; Lalchandani, 2012; Maithel *et al,* 2014d). A high or induced draught zig-zag kiln is an improved zig-zag kiln fitted with a fan in order to stimulate the draught required for the air flow (Maithel *et al,* 2014d; Maithel *et al,* 2012).

Three distinct zones are identified in the Zig-zag kiln, which are similar to the FCBTK: **the cooling zone**, where the cold air exchanges heat with the fired bricks, resulting in the heating of air and the cooling of the fired bricks; **the combustion,** where hot gases are released from the combustion of the fuel (coal), usually fed from the feedholes; and **the brick pre-heating zone**, where pre-heating of the green bricks is made possible by flue gases (Maithel *et al,* 2014d; Maithel *et al,* 2012).

The kiln does not have a permanent roof structure; hence stacked bricks are covered with a layer of ash brick dust. This acts as a temporary roof and also seals the kiln from leakages, thereby minimizing heat loss (Maithel *et al,* 2014d; Maithel *et al,* 2012).

The Zig-zag kiln is also known as the high draught kiln (HDK) developed by the Central Building Research Institute (CBRI) in India (RSPCB, 2011; CDM, 2006; Maithel *et al,* 2012).

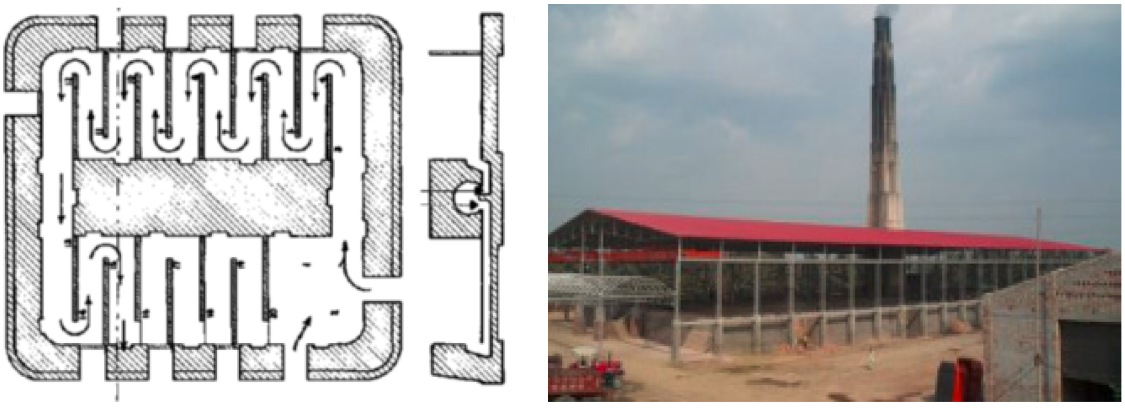


Figure 16: Schematics (left) and structure of a typical zig-zag kiln (Baum, 2010; Baum, 2015)

2.5.7 CLAMP KILN

Clamps are primitive or traditional kilns, lacking a permanent structure and invented by the Egyptians around 4000 BC (RSPCB, 2011; Baum, 2010). According to Lordan (2011), Wienerberger (2015), Smith (2013), Maithel *et al* (2012), Guttikunda *et al* (2013), RSPCB (2011), Baum (2010) and CCAC (2015), the clamp kiln is one of the most commonly used brick firing technique in developing countries, including India (25 – 40 %) and South Africa (68 – 85 %).

The bricks in a clamp kiln are packed in a pyramid-shaped configuration with layers of combustible material such as wood, cinder, coal or coke at the floor or bottom of the kiln (common practice in South Africa), and after each layer of bricks (common practice in Asia). A few layers of previously fired bricks – 'scintle' – are arranged to serve as a funnel or conduit to accommodate the base combustible matter. A layer or two of previously fired bricks are also packed on top of the 'green' bricks to serve as insulation (RSPCB, 2011; CBA, 2002; 2005).

According to Obeng *et al (*2001) and RSPCB (2011), clamp kilns are labour intensive and are often operated in "clusters". They burn fuel inefficiently and are highly polluting. On the positive side, they are simple to build, thereby affording operators the ease of locating close to a clay source, in order to minimize cost of transportation and production logistics.

When the bottom layer of the kiln packed with fuel is ignited, it sets the bricks on fire one layer at a time until the whole kiln is ablaze. The temperature inside the kiln rises gradually, kindling the fuel packed on top of each layer (for informal clamps) or fuel mixed into the clay (for South African industrial scale clamps) at about 800 ^{o}C and peaking at a maximum of 1200 – 1400 ^{o}C (CBA, 2002; 2005; Akinshipe, 2013; RSPCB, 2011; Cermalab, 2014; Maithel *et al,* 2014a).

2.5.7.1 FORMAL AND INFORMAL USE OF CLAMP KILN TECHNOLOGY

Clamp kilns have been gradually phased out in developed countries due to mechanization and the advent of continuous kilns, but they are still predominant in developing countries, including South Africa, South Asia, Central America and East Africa (Maithel *et al,* 2014a; Jefremovas, 2002; Erbe, 2011; Akinshipe, 2013; CBA, 2002; 2005).

Cermalab (2014) has this to say about informal clamp kiln operation in Eastern Cape Province, South Africa:

> *"The informal clay brick makers lack formality in terms of the licensing laws, tax laws, labour laws and environment health regulations. These operations are small scale, mostly family or household-based enterprises that are unregulated by government institutions". (Cermalab, 2014: 16)*

However, clamp kiln technology, in the formal brick production sector in South Africa, has evolved beyond the basic, energy inefficient, atmospheric polluting technology that is prevalent in most developing nations of the world (Akinshipe & Kornelius, 2015; Maithel *et al,* 2014a; ILO, 1984; CBA 2012; CBA, 2015a; Weyant *et al,* 2014a). This evolution has been facilitated by the Clay Brick Association (CBA) of South Africa, an association made up of brick producers, offering technical support to its members and upholding quality standards in brick manufacturing (Hibberd, 1996; CBA, 2015b).

It is therefore essential that the differences between the South African "formal" or "commercial" clamp kiln operation and the "informal" or "small-scaled" clamp kiln operation (found mostly in South Asia, Central America, Africa and other developing nations) be identified. A large-capacity South African clamp kiln in its latter period of firing is depicted in Figure 17, while a typical informal clamp kiln in Asia is depicted in Figure 18.

Figure 17: Industrial scale clamp kiln at Nova Bricks, South Africa

Figure 18: Typical informal clamp kiln (Cermalab, 2014)

The following has been identified as areas in which the South African “commercial” clamp kiln operation have been developed beyond the global “informal” or “small-scale” clamp kiln operation:

1. Mechanization
2. Energy Efficiency
3. Internal or "Body" Fuels
4. Size or Capacity of Kiln

2.5.7.1.1 MECHANIZATION

The South African formal clamp kiln operation utilizes various kinds of machinery in clay processing and kiln packing operations. These machineries include fork lifts, front-end loaders, bulldozers, scrapers, mechanical shovels, hoppers, conveyors, crushers, mills, mechanical screens, feeders, conveyors, robotic arms etc. (Figure 19) (CBA, 2015b; CBA 2002; 2005). Mechanization, as well as souring – storage of processed clay over a period of time – helps to produce smooth, uniform and consistent clay material (since the molecular structure of the clay is allowed to develop optimally). This ensures that the bricks are evenly dried and that less energy is required for firing, thereby providing a more consistent quality of fired bricks (Cermalab, 2014; Gibberd, 2014).

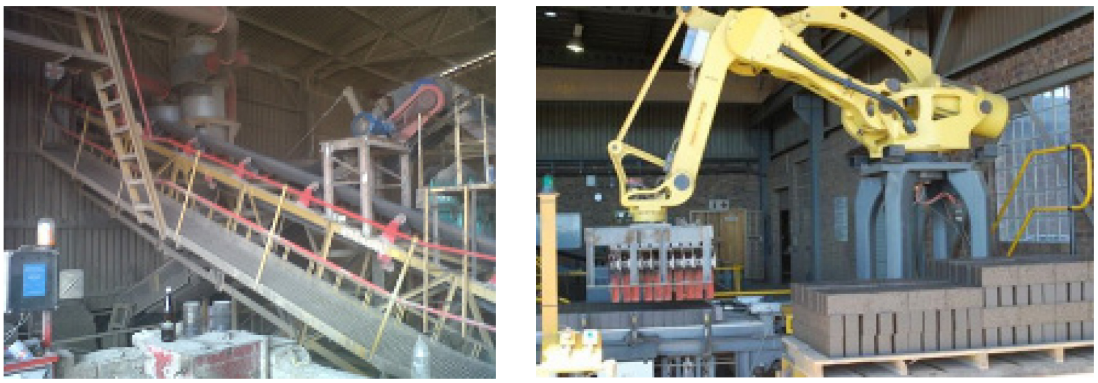


Figure 19: Crusher conveyor at Bert’s Bricks (left) and robotic arm at Nova Bricks (right) South Africa

Informal clamp kiln operations do not employ machines for size reduction and processing of clay material after mining. According to Pool & Maithel (2012), an estimated 95 % of bricks are moulded by hand in South Asia. The clay material is mixed with water and milled to form paste manually (Figure 20). Adequate souring of the clay material is not achieved and packing of the kiln is also done manually (Erbe, 2011; Cermalab, 2014; Maithel *et al,* 2014a; Scott, 2013).

Figure 20: Typical brick making activities in informal sectors in Asia and Central America (Cermalab, 2014; Goyer, 2006)

2.5.7.1.2 ENERGY EFFICIENCY

A survey of formal brick producers in South Africa, conducted by Karin (2015), revealed that 88% of brick producers are actively pursuing measures for improving energy efficiency. The survey further records that 65% of brick producers currently fall within the industry bench mark of 3.4 MJ/kg energy consumption; and 53% of brick producers have implemented an optimization of their current systems and technology, as well as implementation of energy monitoring across their operations. This survey included clamp kiln operators (which accounts for 68 – 85 % of the industry) as well as other kiln types (Mienie *et al,* 2015; Scott, 2013). In addition, improved management and quality control of raw materials and fuels will result in lower heat losses and higher energy efficiencies.

In the informal clamp kiln operation, firing is reputed to be energy inefficient, resulting in air pollution issues and health challenges (DMC-Nepal, 2003; ILO, 1984; Habla, 2016).

2.5.7.1.3 INTERNAL OR "BODY" FUELS

According to CBA (2002), CBA (2005), Akinshipe (2013), Akinshipe & Kornelius (2015), it is common practice for SA clamp kiln operators to mix fuel (mostly “duff” coal or carbon-containing fly ash) into clay during processing. A typical coal to clay mixture ratio is about 1:9 (Lordan, 2011; Burger & Breitenbach, 2008). This ensures that the temperature in the kiln is evenly distributed and the bricks are fired to a consistent quality (CBA, 2002; 2005). “Small nuts” coal is stacked in the base layer to serve as external fuel for igniting the kiln (CBA, 2005; Lordan, 2011).

In informal clamp kiln operation, fuel is not normally mixed with the clay. Fuel is either fed constantly into the kiln during firing, or is packed on top of the bricks in layers, as shown in Figure 21 (Cermalab, 2014; Erbe, 2011).

Figure 21: Brick and fuel packing methodology in informal (left, Cermalab (2014)) and formal clamp kiln (right, Nova Bricks, South Africa)

2.5.7.1.4 Size or Capacity of Kiln

Table 67 (Appendix A) provides the range of capacities of various types of firing techniques. The informal clamp kilns are mostly fired in clusters and their operation is based on immediate local need, averaging about 5 000 to 500 000 bricks per clamp kiln (Cermalab, 2014). According to Subrahmanya (2006b), brick kilns can be classified into three classes: small kilns (firing less than 1 000 000 bricks per year); medium kilns (firing 1 000 000 – 2 500 000 bricks per year); and large kilns (firing more than 2 500 000 bricks per year). In Asia and elsewhere, clamp kilns are generally classified in the small kilns category while BTKs, MCBTKs and FCBTKs are generally classified in the medium and large kilns classes.

The South African formal clamp kilns are operated at an industrial scale, averaging about 1 000 000 to 14 000 000 bricks per batch (Akinshipe, 2013; Akinshipe & Kornelius, 2015; Cermalab, 2014). Hence, heat losses through the walls of the kiln are much lower in the bigger clamps due to a higher volume to external surface area ratio of the kiln (Daraina *et al,* 2013; Cermalab, 2014). The larger clamp kilns are therefore, more efficient than smaller kilns (Figure 17 and Figure 18).

2.5.7.2 Previous Studies on Clamp Kiln Emission Quantification

Akinshipe (2013), Potgieter & Jansen (2010) and Burger & Breitenbach (2008) carried out on-site investigations into emissions quantification from brick making clamp kiln sites in South Africa. Guttikunda *et al (*2013), Lalchandani (2012) and Maithel *et al (*2012) also investigated the quantification of emissions caused by particulates from brick kilns in Southeast Asia.

Burger & Breitenbach, 2008 reviewed the operations and emission generating activities from one functional clamp kiln at Apollo Bricks, Atlantis; quantifying on-site emissions using ambient measurement as well as simulation of potential air quality impacts at ambient level.

The study conducted short-term ambient measurements which were utilized in atmospheric dispersion modelling for quantification of emissions from a clamp kiln firing 880,000 bricks. The dispersion model was set up to simulate pollutants concentrations at the measurement points using an assumed emission rate. The actual emission rate from the clamp kiln was then calculated backwards from the assumed emission rate to give 0.47 g/s for SO_2, 0.15 g/s for NO_2, and 3.21 g/s for PM_{10}**.** The emission rates were recalculated in Akinshipe (2013) to produce emission factor of **0.97 g/brick** for SO_2, **0.31 g/brick** for NO_2, and **6.59 g/brick** for PM_{10}.

Akinshipe (2013) investigated the use of ambient monitoring and atmospheric dispersion simulation of monitoring results to simulate emission rates and emission factors for clamp kilns. The study involved the use of passive diffusive samplers to determine ambient SO_2 and NO_2 concentrations downwind of 3 clamp kiln sites (small, medium and large) representative of the brick firing clamp kiln industry in South Africa.

The SO_2 emission rate for this study was estimated from a technique that has been termed "reverse-modelling" or "reverse dispersion modelling", which integrates ambient monitoring results into a dispersion model (the Atmospheric Dispersion Modelling System software – ADMS) and thereby calculates the actual emission rate from the assumed rate (in this case, 1 g/s).

The study also adopted the use of "bi-point" source configurations to allow typical clamp kiln dimension to be simulated with the standard source configurations available in dispersion models. This proved to improve the simulation of the buoyancy-induced plume rise. The "reverse-modelling" technique and "bi-point" source configuration produced SO_2 emission rates ranging from -9 % to +22 % when compared with mass balance results, with an average of **2.06 g/brick,** indicating that the "reverse dispersion modelling" technique provides sufficient or reliable emission rate estimates for SO_2.

It was also discovered that on-site NO_x emissions from internal combustion engines (stationary and moving) are significant enough to impact on the efficacy of the "reverse dispersion modelling" technique for NO_x emission estimation. Quantified NO_x emissions from these internal combustion engines were almost as much as emissions from the kiln at the three different operators. Hence, a NO_x emission rate for clamp kiln could not be calculated from the "reverse-modelling" technique in the study. It is surmised that the data obtained by Burger and Breitenbach (2008) suffered from the same shortcoming.

Furthermore, monitoring and "reverse-modelling" of PM_{10} emissions from clamp kiln could not be conducted by Akinshipe (2013) due to unavailability of adequate monitoring technique and equipment for measuring emissions from a volume source that has the configuration of a clamp kiln. The contribution of external sources of fugitive dust on a clamp kiln site such as crushing and screening, vehicle entrainment, materials handling and wind erosion could not be adequately eliminated to estimate PM_{10} emissions released from the kiln only.

The study conducted by Potgieter & Jansen (2010) involved the review of operations and emission generating activities from three operational sites in South Africa; the estimation of emissions from on-site clamp kiln firing; and general estimation of potential impacts on the ambient air quality. The study utilized on-site ambient measurements,

applying estimations and assumptions in quantifying emissions from the clamp kilns operating on the sites. It was also concluded from the study that approximately 13.4% of the ash content inherent in the fuel is emitted from the clamp kiln firing process.

The study undertaken by Lalchandani (2012), Maithel *et al (*2012) and Guttikunda *et al (*2013) quantified emissions from various types of brick kilns in Southeast Asia. The major technologies utilized in brick firing in this region include the FCBTK, BTK, clamp kiln, and VSBK**.** The percentage of clamp kilns included in these studies could not be confirmed.

2.5.7.3 LIMITATIONS ON PREVIOUS CLAMP KILN EMISSION QUANTIFICATION STUDIES

Akinshipe (2013) identified the following limitations in the quantification of clamp kiln emissions from the studies conducted by Burger & Breitenbach (2008) and Potgieter & Jansen (2010):

- The studies did not account for the effect of plume rise due to buoyancy of emissions from clamp kilns. In simulation of impacts due to emissions from clamp kilns, a significant difference between ambient and flue gas temperature released from the kiln will generate substantial plume rise due to buoyancy, dispersing the ground level impact of the pollutants further downwind from the kiln;
- Short-term particulates measurements were utilized in these studies. Since there is a significant variation in emission rates during different stages of the clamp kiln firing cycle, the measured data may not be a true representation of the average emissions over the entire firing duration of the kiln; and
- The equipment utilized in measuring emissions from the clamp kiln in these studies requires that the kiln be completely isolated, such that only the emissions from the kiln is captured, while eliminating emissions from other sources or activities such as vehicle traffic, wind erosion and other closely located clamp kilns. This is to prevent interference by unwanted emissions from external sources. These studies could not utilize proper isolation of the kiln being monitored;

In addition, the following limitations have been identified from the studies conducted by Akinshipe (2013):

- Information on source-specific parameters (e.g. moisture and silt content) was not available for the study. Generic source data published by the USEPA emission estimation documents was utilized in the study.
- Uncertainties cannot be absolutely eliminated in dispersion models, or in any geophysical model. A dispersion model represents the most probable result of a collection of experimental outcomes.

  Uncertainties may be due to inaccuracies in the input data-set; inaccuracies in the model dynamics; and inaccuracies due to stochastic processes or mechanical turbulence in the atmosphere (Burger & Breitenbach, 2008; Akinshipe 2013). Therefore, dispersion modelling and the “reverse-modelling” technique, though adequate for simulating emission rates from non-conventional sources, may not be the most appropriate scientific method for estimating emission rates and quantifying emission parameters from a complex configuration such as the clamp kiln.

- Finally, the study assumed that all the energy in the coal is used up in firing the bricks in the kiln. Since clamp kiln firing is not a fully controlled combustion process, this assumption may be quite different from the actual combustion process in the kiln.

In summary, the studies conducted by Akinshipe (2013), Burger & Breitenbach (2008) and Potgieter & Jansen (2010) provided suitable estimation techniques for quantifying emissions from clamp kilns and clamp kiln sites. These studies motivate the need for an appropriate scientific technique for adequate direct capture and measurement of pollutant emissions from clamp kilns and other complex configuration sources of atmospheric pollution.

2.6 Summary of Brick Kiln Emissions and Process Metrics

Several literature sources have published results on emissions and process metrics from various types of brick kilns. Table 5, Table 6 and Table 7 summarize the result of measured suspended PM, CO_2 and PM_{10} emissions, while, Table 8, Table 9, Table 10 and Table 11 summarize the result of SO_2, NO_x, $PM_{2.5}$ and CO emissions from literature. Temperature ranges in various kilns are also provided in Table 12. Additional literature summary tables are provided in Section 10.1 (Appendix A), catering for metrics such as specific energy consumption of brick kilns, geographical distribution of various brick kilns from around the world, brick production by countries, firing capacities of various brick kilns and duration of firing for different types of kiln.

Table 5: Measured suspended PM emissions (as obtained from literature)

Reference	Clamp (Informal/ Traditional)	VSBK	Tunnel	Hoffmann /TVA	BTK / MCBTK	FCBTK	Zigzag /HDK	DDK
RSPCB (2011)					602 - 1721	219 - 558	354 - 853	
Maithel *et al* (2012)		0.11	0.31			0.86	0.26	1.56
Maithel *et al* (2014h)			41 (21 - 53)					
Maithel *et al* (2014f)				260 (200 - 315)				
Maithel *et al* (2014i)		107 (101 - 114)						
Maithel *et al* (2014b)								531 (240 - 1088)
Maithel *et al* (2014c)						570 (150 - 1250)		
Maithel *et al* (2014d)							96 (34 - 183)	
Russel & Vogel (1999)				60 - 70				
Baum (2010)		70			1021	380		
Sarraf *et al* (2011)				< 100		1000+	500 - 1000+	
Maithel *et al* (2003)		170 (77 - 250)				350 (220 - 550)	550 (350 - 850)	
Manandhar & Dangol (2013)		101			840	125 - 238	116	
Manandhar & Dangol (2013)						0.86		
Klimont (2012)		0.18	0.3			0.85	0.195	1.55
Baum (2010), re-calculated in Lopez *et al* (2012)	1.91				8.06	1.71		
Colour Legend	***g/kg***		***g/brick***			***mg/Nm³***		

Table 6: Measured CO_2 emissions (as obtained from literature)

Reference	Clamp (Informal/ Traditional)	VSBK	Tunnel	BTK / MCBTK	FCBTK	Zigzag/HDK	DDK
RSPCB (2011)				3.3	2.7	3.0	
Maithel *et al* (2014h)			166.3		131		
Maithel *et al* (2014i)		70.5 (63 - 79)					
Müller (2015)		41			186		
Maithel *et al* (2014b)							282.4
Maithel *et al* (2012), Hoque *et al* (2012)		70	166		115	103	282
Maithel *et al* (2014c)					131 (95 - 164)		
Manandhar & Dangol (2013)					115		
Maithel *et al* (2014d)						105 (100 - 117)	
Baum (2010), calculated in Lopez *et al* (2012)	77 - 171	26 - 38	42 - 96	46 - 67	42 - 58		
Manandhar & Dangol (2013)	471	166		249	182 - 232	182	
Colour Legend	***g/kg***		***g/brick***		***%***	***tons/100,000 bricks***	

Table 7: Measured PM_{10} emissions (as obtained from literature)

Reference	Clamp (Formal/ Industrial)	VSBK	Tunnel	Hoffmann /TVA	FCBTK	Zigzag /HDK	DDK
Maithel *et al* (2014h)			0.24		1.18		
Maithel *et al* (2014g)				0.29			
Maithel *et al* (2014i)		0.15 (0.12 - 0.19)					
Müller (2015)		0.15			1.14		
Maithel *et al* (2014b)							1.56
Maithel *et al* (2014c)					1.18 (0.26 - 2.63)		
Maithel *et al* (2014d)						0.24 (0.09 - 0.47)	
Burger *et al,* (2008), calculated in Akinshipe, (2013)	6.59						
Burger *et al,* (2008), calculated in Akinshipe, (2013)	2.32						
Baum (2015)		0.1	0.26		1.18	0.21	1.55
Colour Legend	***g/kg***			***g/brick***			

Table 8: Measured SO_2 emissions (as obtained from literature)

Reference	Clamp (Formal/ Industrial)	VSBK	Tunnel	BTK / MCBTK	FCBTK	Zigzag/HDK
RSPCB (2011)				0.26	0.29	1.12
Akinshipe (2013) (using reverse dispersion modelling)	0.73					
Akinshipe (2013) (using sulfur mass balance)	0.84					
Müller (2015)		0.02			0.38	
Maithel *et al* (2012)		0.54	0.72		0.66	0.32
Burger *et al,* (2008), calculated in Akinshipe, (2013)	0.34					
USEPA 1995			0.6			
Manandhar & Dangol (2013)					0.66	
Manandhar & Dangol (2013)		36			170 - 228	145
Colour Legend	***g/kg***		***g/brick***		***mg/Nm³***	

Table 9: Measured NO_x and Hydrocarbons emissions (as obtained from literature)

Reference	NO_x			
	Clamp (Formal/ Industrial)	BTK / MCBTK	FCBTK	Zigzag/HDK
RSPCB (2011)		0.08	0.11	0.2
Burger *et al,* 2008 (calculated in Akinshipe, 2013)	0.31			
Burger *et al,* 2008 (calculated in Akinshipe, 2013)	0.11			
	Hydrocarbons			
RSPCB (2011)		275	216	227
Colour Legend	***g/kg***	***g/brick***		***mg/Nm³***

Table 10: Measured $PM_{2.5}$ emissions (as obtained from literature)

Reference	VSBK	Tunnel	FCBTK	Zigzag/HDK	DDK
Maithel *et al* (2012)	0.09	0.18	0.18	0.13	0.97
Maithel *et al* (2012)					331 (227 - 516)
Baum (2015)	0.09	0.18	0.18	0.09	0.95
Manandhar & Dangol (2013)			0.18		
Colour Legend	***g/kg***			***mg/Nm³***	

Table 11: Measured CO emissions (as obtained from literature)

Reference	VSBK	Tunnel	BTK / MCBTK	FCBTK	Zigzag /HDK	DDK
RSPCB (2011)			0.33	0.3	0.3	
Maithel *et al* (2012)	1.84	2.45		2.25	1.47	5.78
Maithel *et al* (2014h)		3.31		2.0		
Maithel *et al* (2014i)	1.8 (0.9 - 2.8)					
Maithel *et al* (2014b)						5.78
Maithel *et al* (2014c)				2 (1.1 - 3.4)		
Maithel *et al* (2014d)					1.6 (0.9 - 2.4)	
Manandhar & Dangol (2013)				2.25		
Le & Oanh (2010)				2.3		
Colour Legend	***g/kg***		***mg/m³***		***%***	

Table 12: Maximum firing temperature within brick kilns (as obtained from literature)

Reference	Clamp (Informal/ Traditional)	Clamp (Formal/ Industrial)	VSBK	Tunnel	Hoffmann /TVA	BTK/ MCBTK	FCBTK	Zigzag /HDK	DDK
	Degree Celsius (^oC)								
RSPCB (2011)	750 - 800				850 - 1050	950 - 1000	950 - 1000	950 - 1000	850 - 950
Maithel *et al* (2014h)				900 - 1050					
CBA 2002		1400							
CDM (2006)			1000						
Rowden (1964)					1040				1120 – 1200

Table 13: Flue gas metrics (RSPCB, 2011)

Flue gas metrics	Unit	Kiln Type		
		BTK / MCBTK	FCBTK	Zigzag/HDK
Exit temperature	^0C	100 – 200	80 – 120	75 – 100
Exit velocity	m/s	5 – 7	8 –10	12 – 15
Exit flow rate	m^3/hour	5500 – 7000	7000 – 9000	10000 – 12000
Percentage CO	%	0.33	0.3	0.3
Percentage CO_2	%	3.3	2.7	3.0

2.7 REGULATIONS REGARDING EMISSIONS FROM BRICK KILNS

Regulations regarding brick kilns have been promulgated by several countries. Table 14 provides a summary of emission standards for various kiln types by countries.

In South Africa, all kilns for ceramic production (including production of tiles, bricks, refractory bricks, stone ware or porcelain ware), as well as clamp kilns for brick production, have been declared as part of the listed activities that "*result in atmospheric emissions which have or may have a significant detrimental effect on the environment, including health, social conditions, economic conditions, ecological conditions or cultural heritage*" (DEA, 2010; DEA, 2013).

The South African National Environmental Management: Air Quality Act (NEM:AQA) stipulates emission limits for each listed activity as well as requirements for measurement of emissions (DEA 2013). Operators of Listed Activities are required to submit an application for Atmospheric Emissions License (AEL).

Emission standards for kilns utilized in ceramic production in South Africa (Listed Activity number 5.7) are given in Table 15. This is applicable to all facilities producing 100 tons per annum or more.

Emissions standards for clamp kilns in South African (Listed Activity number 5.3) have however, not been set due to the uniqueness of the configuration of emission release and inability to capture the emission into a single or confined stream.

Table 14: Emissions standards for brick kilns by various countries

PM (mg/Nm^3)						
References	**Clamp (Formal/ Industrial)**	**VSBK**	**BTK / MCBTK**	**FCBTK**	**Down-Draught**	**Tunnel**
India (Maithel *et al,* 2014i; Lalchandani & Maithel, 2013)		250				
India (Maithel *et al,* 2014b)					1200	
India - Small kilns < 15 000 bricks per Day (Maithel *et al,* 2014c; Maithel *et al,* 2014d; Lalchandani & Maithel, 2013; Maithel & Uma, 2000)				1000		
India Large kilns > 15 000 bricks per Day (Maithel *et al,* 2014c; Maithel *et al,* 2014d; Lalchandani & Maithel, 2013; Maithel & Uma, 2000)				750		
Bangladesh (Maithel *et al,* 2014c)				1000		
Nepal (Maithel *et al,* 2014c; MOE, 2010; Maithel *et al,*2014i)		400/600		600 - 700		
India (Baum, 2010)			750			
South Africa	Refer to Table 16	Refer to Table 15	–	–	Refer to Table 15	Refer to Table 15

DEA (2012) describes the challenges regarding clamp kiln configuration succinctly as follows:

> *"Brickworks using clamp kiln technology emit SO_2 and particulates near ground level, and compared with industrial emissions, the plume is relatively cool. The pollutants are therefore released into the stable surface layer where dispersion is inhibited, particularly at night and in the winter. As a result of poor dispersion, the ambient concentrations are high at the source and the effect is generally limited to the surrounding area".*

As a result, ambient measurement requirements, rather than emission standards, are set for clamp kiln facilities in South Africa (Table 16), since the emissions are mostly localized and limited dispersion to the atmosphere is achieved (Irm, 2012; Akinshipe, 2013).

Table 15: Emission standards for ceramic production (DEA, 2013)

Description	**The production of tiles, bricks, refractory bricks, stoneware or porcelain ware by firing, excluding clamp kilns**		
Application	**All installations producing 100 tons per annum or more**		
Substance or mixture of substance		Plant status	Mg/Nm3 under normal conditions of 273 Kelvin and 101.3 kPa.
Common name	Chemical symbol		
Dust fall	N/A	New	50
		Existing	150
Sulfur dioxide	SO_2	New	400
		Existing	1000
Total fluorides measured as hydrogen fluoride	HF	New	50
		Existing	50

Table 16: Ambient measurement requirements for brick production using clamp kilns (DEA, 2013)

Description	**The production of bricks using clamp kilns**		
Application	**All installations producing more than 10 000 bricks per month.**		
Substance or mixture of substance		Plant status	mg/Nm^3 under normal conditions of 273 Kelvin and 101,3 kPa
Common name	Chemical symbol		
Dust fall	N/A	New	[a]
		Existing	[a]
Sulfur dioxide	SO_2	New	[b]
		Existing	[b]
[a] three months running average not to exceed limit value for adjacent land use according to dust control regulations promulgated in terms of section 32 of the NEM: AQA, 2004 (Act No. 39 of 2004), in eight principal wind directions			
[b] Twelve months running average not to exceed limit value as per GN 1210 of 24 December 2009. Passive diffusive measurement approved by the licensing authority carried out monthly			
(a) The following special arrangement shall apply - Where co-feeding with waste materials with calorific value allowed in terms of the Waste Disposal Standards published in terms of the Waste Act, 2008 (Act No.59 of 2008) occurs, additional requirements under subcategory 1.6 shall apply			

2.8 Energy Use in the Clay Brick Industry

According to Hibberd (1996), approximately 38 PJ of energy was consumed by the South African clay brick industry in 1995. The types of energy utilized in this industry are generally a combination of the following:

- Coal (various types of coal e.g. duff, filter cake, coal fly ash, peas and nuts);
- Diesel;
- Heavy fuel oil;
- Gas; and
- Electricity

A comparison of the specific energy consumption (SEC) of brick industries in various countries was published by Hibberd (1996), and is represented in Table 17. In addition, the break-down of the SEC into various brick kilns from various literature sources is presented in Table 64 (Appendix A, Section 10.1).

The South African clay brick industry, as at 1995, consumed the third highest energy in the industry (3.42 MJ/kg). There has been little or no improvement in energy consumption since then, as Karin (2015) puts the South African clay brick industry SEC benchmark at 3.4 MJ/kg.

Table 17: A comparison of SEC by countries (adapted from Hibberd, 1996)

Country	Production (Millions of Tons)	Fuel Consumption (PJ)	SEC (MJ/kg)
Morocco	1.5	3	1.78
Germany	10	19	1.94
Greece	2.16	5	1.96
Ireland	0.95	2	1.97
Italy	17.6	42	2.37
Spain	12.6	30	2.40
France	5.41	14	2.57
U.K.	5	13	2.66
Denmark	0.86	2	2.69
Netherlands	3.1	9	2.76
India	55	120	2.80
Portugal	4.15	12	2.86
Algeria	3	9	3.14
South Africa	11.1	38	3.42
Canada	0.84	3	3.59
Australia	5.73	20	3.88

According to De Villiers & Mearns (1994) and Hibberd (1996), the specific energy required to fire a brick can be estimated as a summation of the energy required to dry the bricks and evaporate the mechanical water (estimated to be 0.54 MJ/kg), plus the energy required for chemical reactions in the brick (estimated to be 0.2 MJ/kg). In addition, Heimsoth (1984) concluded that a large proportion of the total energy requirement for firing bricks in a tunnel kiln is actually in the form of losses, including wall losses (25%), exhaust losses (30%) and recoverable cooling air (30%).

Improved energy efficiency may therefore imply a significant reduction in energy consumption without compromise on the quality or quantity of production; and often, it may result in improved quality and quantity of production. A reduction in energy consumption is therefore a significant mechanism for reducing atmospheric emissions and combating global warming, since large proportion of these emissions are released from fuel sources (Hibberd, 1996).

CHAPTER THREE

3 MODEL KILN DESIGN AND MONITORING METHODOLOGY

The need for a practicable technique for capturing and channelling flue gases emanating from a clamp kiln is predicated on the unavailability of emission metrics, as well as inadequate scientific technique for estimating these metrics. This section reports on the technique and the equipment employed in achieving model kiln design, emission capture, channelling, monitoring and analyses.

3.1 MODEL KILN SITE

3.1.1 LOCATION

The model kiln is located in a functional and easily accessible clamp kiln factory – Nova Bricks. Nova Bricks is located along Delmas road in Wingate Park, a suburb of Pretoria, South Africa. The site is located 25 km southeast of central Pretoria and 40 km northeast of central Johannesburg (Figure 22). The model kiln is built in a secluded location on the Nova Bricks site in order to restrict or minimize the influence of external air pollution sources (Figure 23).

Figure 22: Locality map showing location of the model kiln site

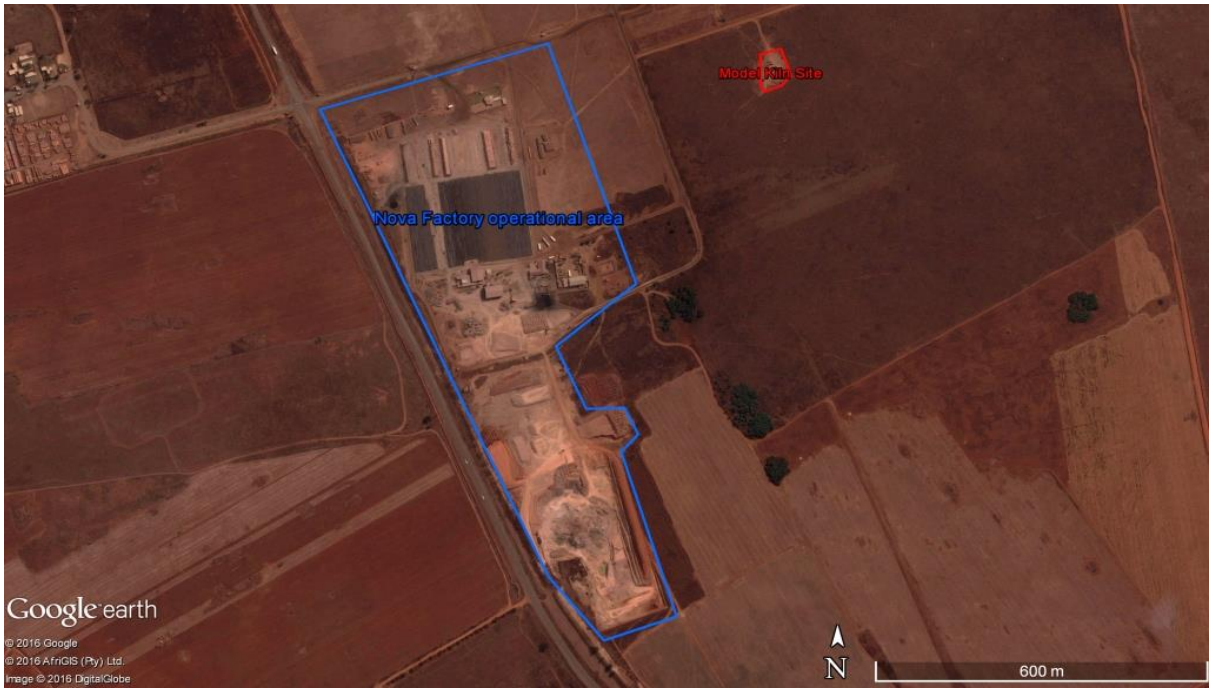


Figure 23: Nova Bricks site (blue marking) showing operational areas and location of model kiln site (red marking)

3.1.2 REGIONAL LAND USE

Land use activities in the surroundings of the model kiln site include clay mining, coal mining, clamp kiln firing, tunnel kiln firing, farming, grassland and cultivated land etc.

3.1.3 METEOROLOGICAL CONDITIONS

The study of the meteorological conditions of an area helps predict the dispersion potential of pollutants in the atmosphere (Cooper *et al,* 2002). Pollutants released into the atmosphere are transported, diffused and eventually removed from the atmosphere by physical and meteorological mechanisms. These mechanisms are as a result of thermal and mechanical turbulence within the boundary layer of the earth (Peavy *et al,* 1985; Tiwary *et al,* 2010; Burger & Breitenbach, 2008).

According to Tiwary *et al (*2010) and Peavy *et al* (1985), four basic elements of the atmosphere – wind, moisture, pressure and energy content – influence the weather conditions of the atmosphere, causing variations in diurnal and nocturnal, as well as seasonal observations. The study of these elements, in the form of recorded hourly average weather data, helps to understand the mechanisms of pollutant dispersion within the region (Tiwary *et al,* 2010; Peavy *et al,* 1985; Cooper *et al,* 2002).

Hourly average weather data that was analysed for the model kiln site include wind speed, wind direction, temperature, air pressure, relative humidity and precipitation. The data was obtained from the OR Tambo International Airport Weather Station operated by the South African Weather Services (SAWS) for the period January 2013 to December 2015. The station is located about 26 km southwest of the model kiln site (Figure 22).

The area surrounding the model kiln site and the OR Tambo International Airport is characterized by a flat surface with slight sparse vegetation. Hence, the OR Tambo International Airport weather data is considered to be representative of the weather conditions at the model kiln site.

The study of these meteorological conditions helps to understand the ambient condition of the model kiln site and how the conditions will influence the design of the model kiln and the firing and monitoring of emissions.

3.1.3.1 Wind Rose

A wind rose provides graphic representation of prevailing winds by indicating the proportion or percentage of time the wind blows from various directions and at various speeds. Wind speed and wind direction determines how quickly pollutants are dispersed from their sources (Lutgens *et al,* 2013; Tiwary *et al,* 2010).

The periodic and seasonal wind roses for 2013 to 2015 are presented in Figure 24 and Figure 25. Data availability recorded for this period is ~99.8 % with an average wind speed of 4.2 m/s. The wind field for the entire period was dominated by winds from the north and northwest. The night-time wind rose recorded high wind speeds dominated by winds from the north and northwest, while the day-time wind rose recorded dominant winds from the north.

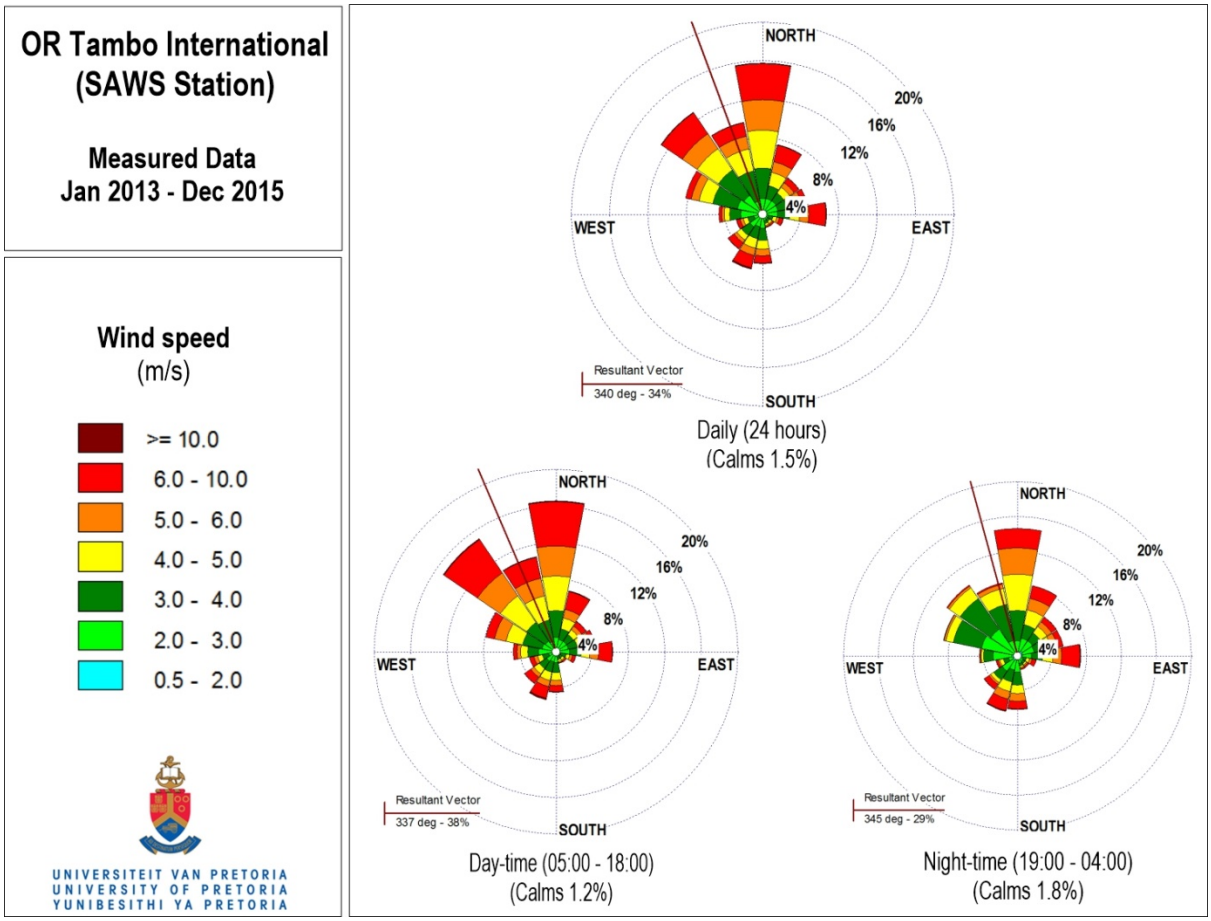


Figure 24: 24-hours, day-time and night-time wind roses – OR Tambo International Airport weather station

Seasonal wind roses produced slight variations from the periodic wind roses. The autumn wind rose recorded moderate wind speeds from the northwest and west northwest. The summer and winter wind roses recorded higher wind speeds from the north and northwest, with moderate components from the east and southwest respectively. The spring wind rose recorded significantly higher wind speeds from the north, with less dominant winds from the northwest and north-northwest.

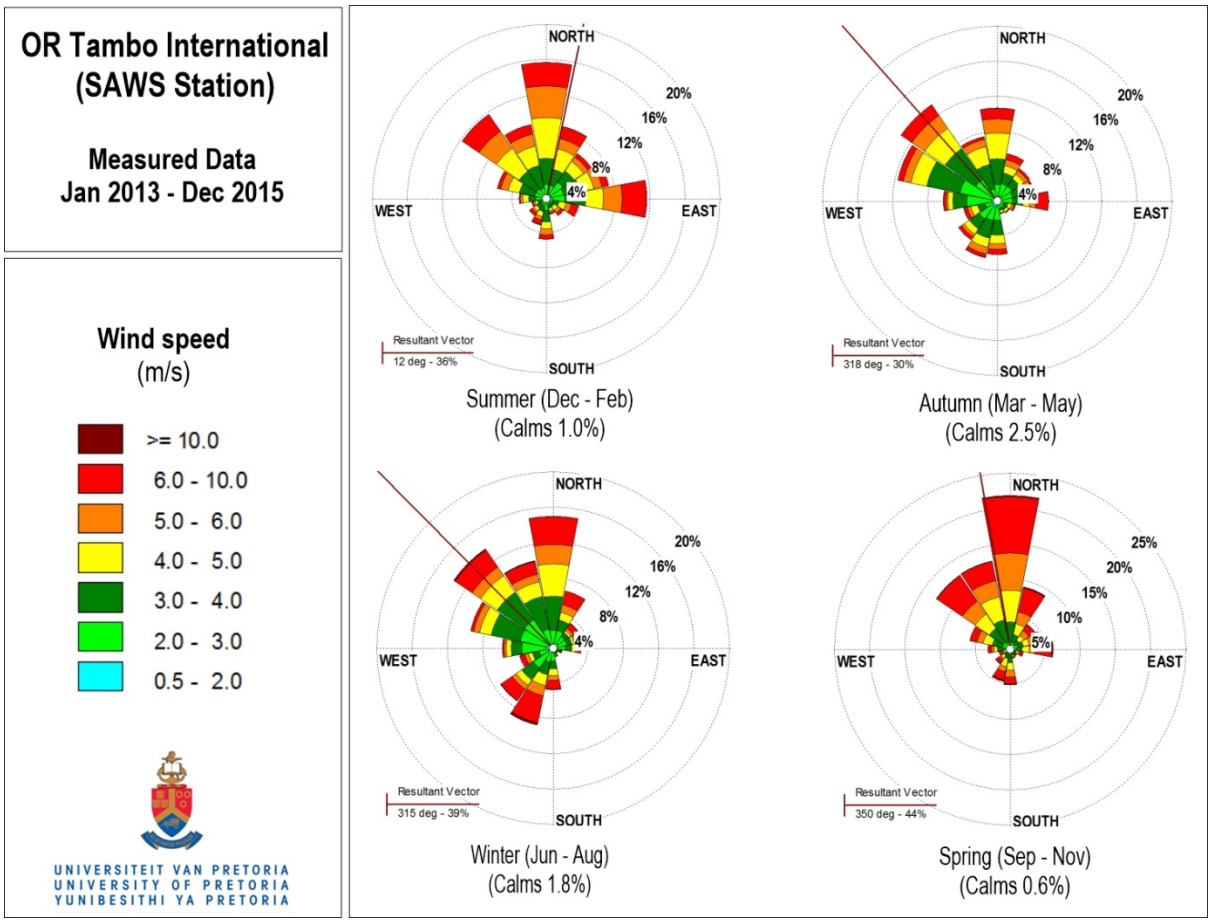


Figure 25: Seasonal wind roses – OR Tambo International Airport weather station

3.1.3.2 TEMPERATURE

Temperature is one of the essential elements of weather and climate. It is significant in determining seasonal and diurnal variation in surface heating, which is essential for determining surface circulation patterns. Ambient temperature also influences the impact of plume buoyancy, determining the extent to which emissions are projected and dispersed from their sources (Lutgens *et al,* 2013; Tiwary *et al,* 2010; Cooper *et al,* 2002).

The diurnal monthly temperature profile is presented in Figure 26, while the monthly minimum, average and maximum temperatures are presented in Figure 27. Monthly temperatures ranged between -3.3 °C and 33.0 °C. During the day, temperatures increase to reach maximum at around 15:00 – 16:00 in the afternoon during summer. Ambient air temperature decreases to reach a minimum at around 07:00 – 08:00 (before sunrise) during winter.

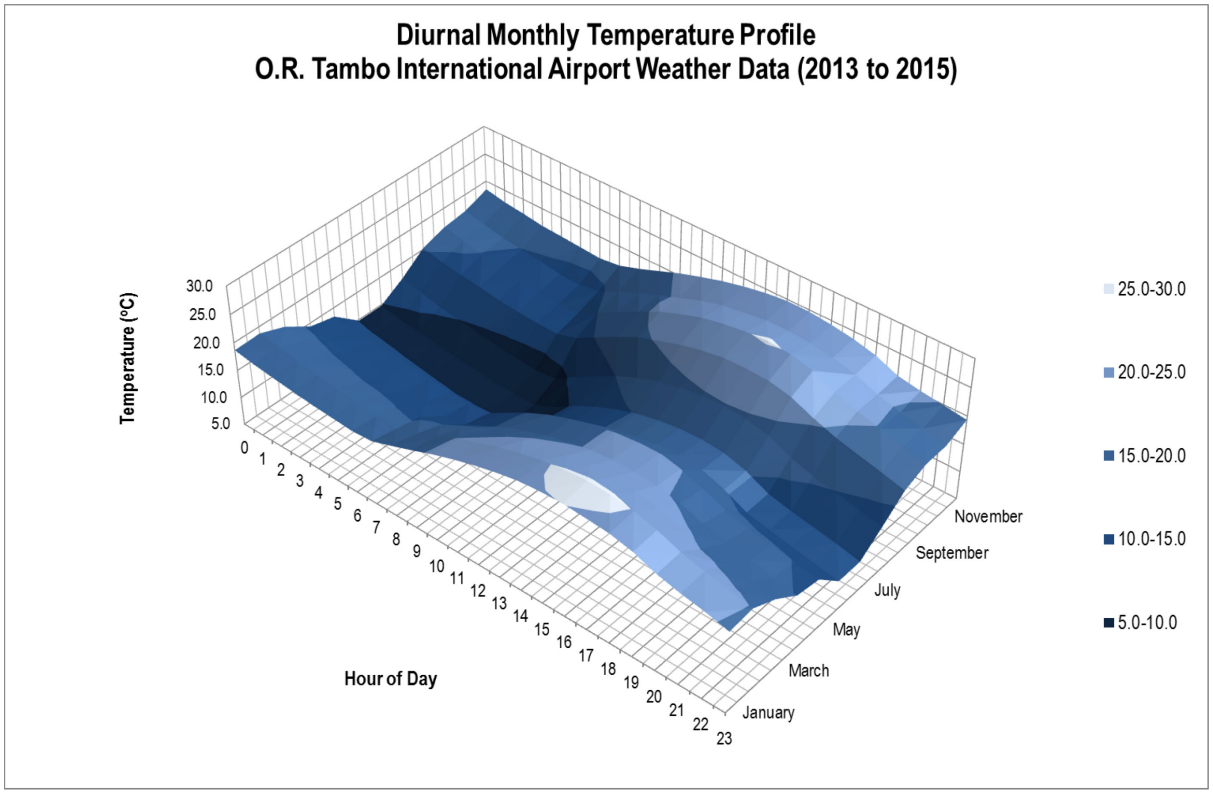
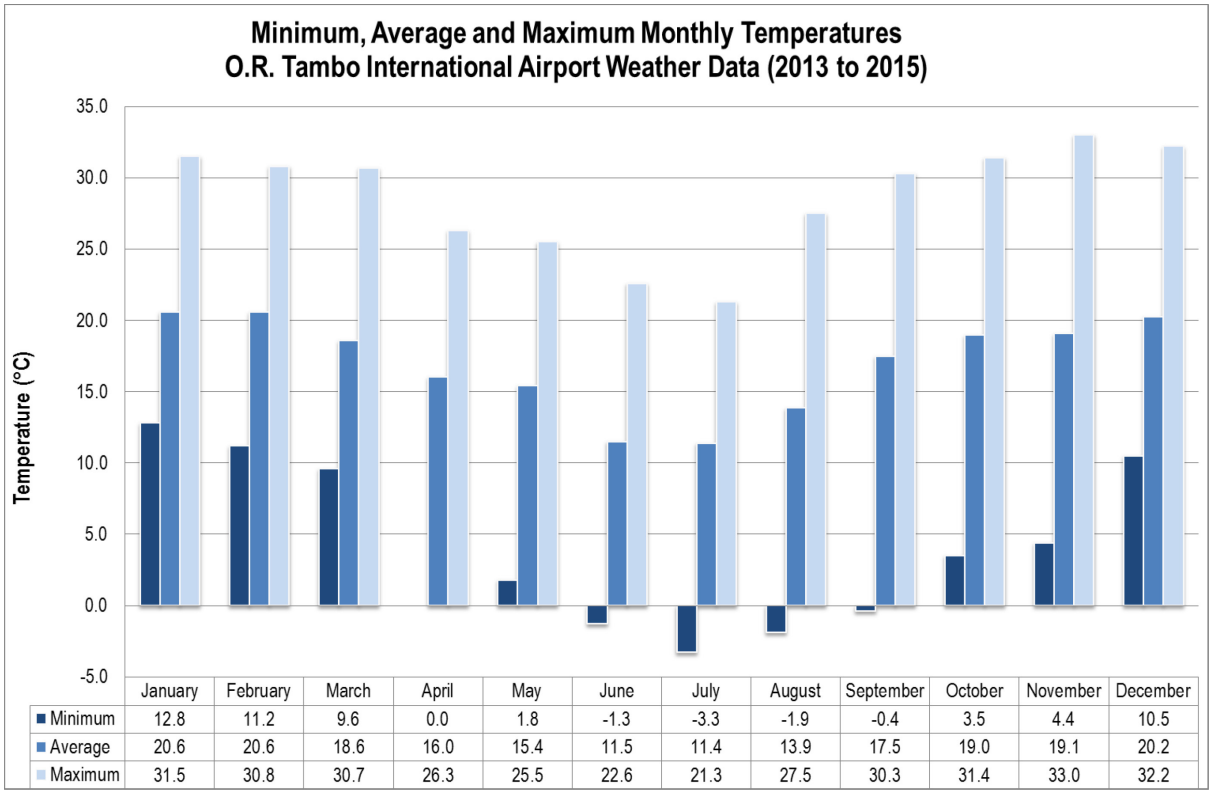


Figure 26: Diurnal monthly temperature profile



	January	February	March	April	May	June	July	August	September	October	November	December
Minimum	12.8	11.2	9.6	0.0	1.8	-1.3	-3.3	-1.9	-0.4	3.5	4.4	10.5
Average	20.6	20.6	18.6	16.0	15.4	11.5	11.4	13.9	17.5	19.0	19.1	20.2
Maximum	31.5	30.8	30.7	26.3	25.5	22.6	21.3	27.5	30.3	31.4	33.0	32.2

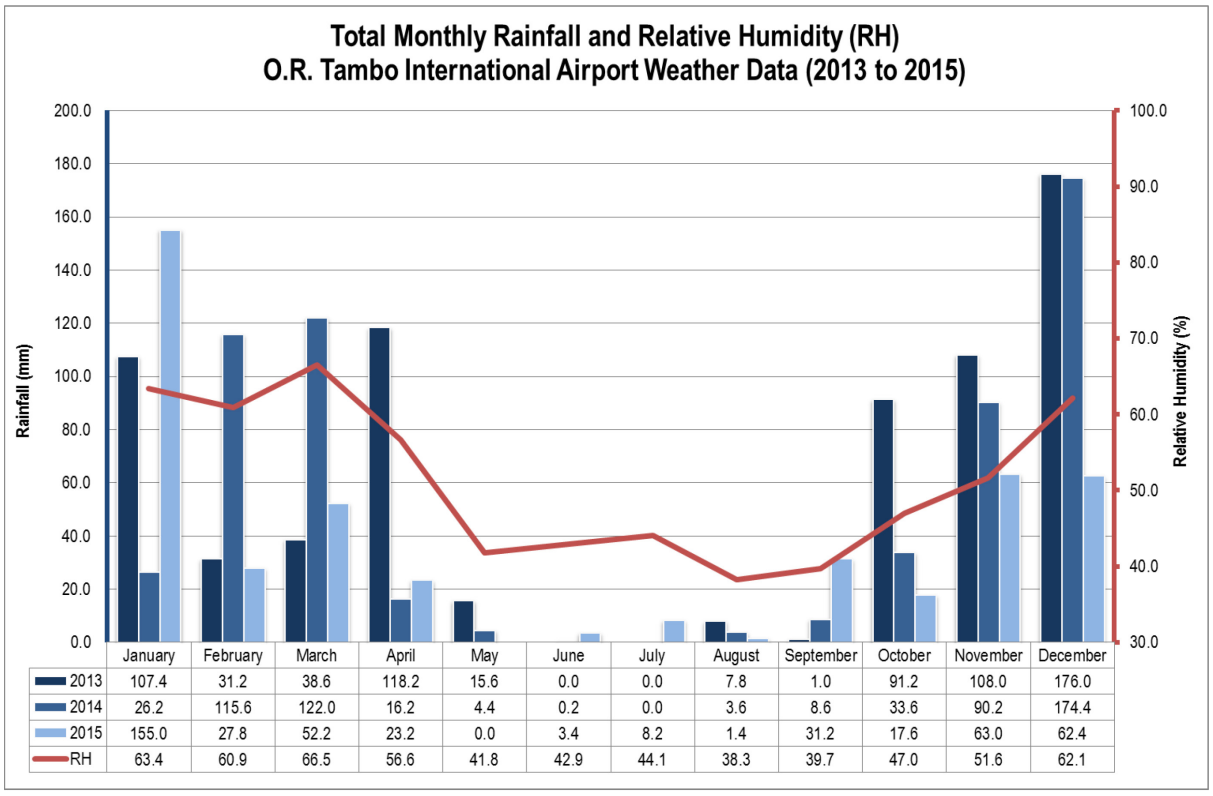
Figure 27: Monthly temperature summary

3.1.3.3 RAINFALL AND RELATIVE HUMIDITY

Rainfall is the most common and easiest to measure form of precipitation. It is measured in inches or millimetres using a rain gauge. Rainfall is one of the effective mechanisms for the removal of pollutants from the atmosphere; hence it is an essential weather component in air pollution studies. A "trace of precipitation" is reported when the amount of rainfall is less than 0.254 mm (Lutgens *et al,* 2013).

The weather data at OR Tambo International Airport recorded annual rainfall of 696 mm, 595 mm and 445 mm for the 2013, 2014 and 2015 period respectively. The amount of rainfall begins to increase during the spring months, reaching its peak by the summer months; and begins to dip by late autumn, hitting its lowest during the winter months (Figure 28). The number of days per year in which the rainfall amount exceeded the "trace of precipitation" amount of 0.254 mm is 79, 73 and 65, respectively for the years 2013, 2014 and 2015.

Relative humidity is the ratio of the actual water vapour content (moisture in the air) compared to the amount of water vapour required for saturation (maximum moisture the air can "hold") at a particular temperature and pressure. Humidity can influence the amount of precipitation recorded in a region and can also influence the impact of air pollution on visibility. For instance, a high relative humidity will significantly increase the adverse effects of pollution on visibility (Lutgens *et al,* 2013; Tiwary *et al,* 2010). The annual mean relative humidity recorded over the 2013, 2014 and 2015 period was ~ 52.4 %, 53.9 % and 47.5 % respectively (Figure 28).



	January	February	March	April	May	June	July	August	September	October	November	December
2013	107.4	31.2	38.6	118.2	15.6	0.0	0.0	7.8	1.0	91.2	108.0	176.0
2014	26.2	115.6	122.0	16.2	4.4	0.2	0.0	3.6	8.6	33.6	90.2	174.4
2015	155.0	27.8	52.2	23.2	0.0	3.4	8.2	1.4	31.2	17.6	63.0	62.4
RH	63.4	60.9	66.5	56.6	41.8	42.9	44.1	38.3	39.7	47.0	51.6	62.1

Figure 28: Monthly rainfall and relative humidity

3.2 MODEL KILN DESIGN

The model kiln configuration was designed to simulate a transverse slice of a full-scale South African clamp kiln, but with lesser firing capacity of 20 000 – 35 000 bricks per firing cycle. The design is premised on the hypothesis that the length dimension in a full-scale kiln is much larger than the width; therefore, the lateral gas flow and hence, the energy flow, from the shorter side, will be much lower than the flow from the longer sides. In addition, the base layers of the bricks are packed in a way to allow lateral air flow from the shorter sides of the kiln. Consequently, it is anticipated that, if a transverse slice of the full-scale kiln is isolated by constructing two side walls to provide adequate insulation, conditions similar to those in the full-scale kiln can be replicated in the model kiln (Figure 29).

As a result of the simulation, gas flow pattern and energy profile in the model kiln are expected to simulate gas flow pattern and energy profile in the original kiln. Consequently, the rate of combustion, as well as other physical and chemical processes in the model kiln (such as exchange of cold air, release of flue gases, and ignition of the fuel mixed into the bricks etc.), are expected to occur and progress in similar fashion to the original kiln. Thus, the firing process in the model kiln is expected to simulate the firing process in the full-scale clamp kiln. The configuration for the model kiln slice is illustrated in Figure 30.

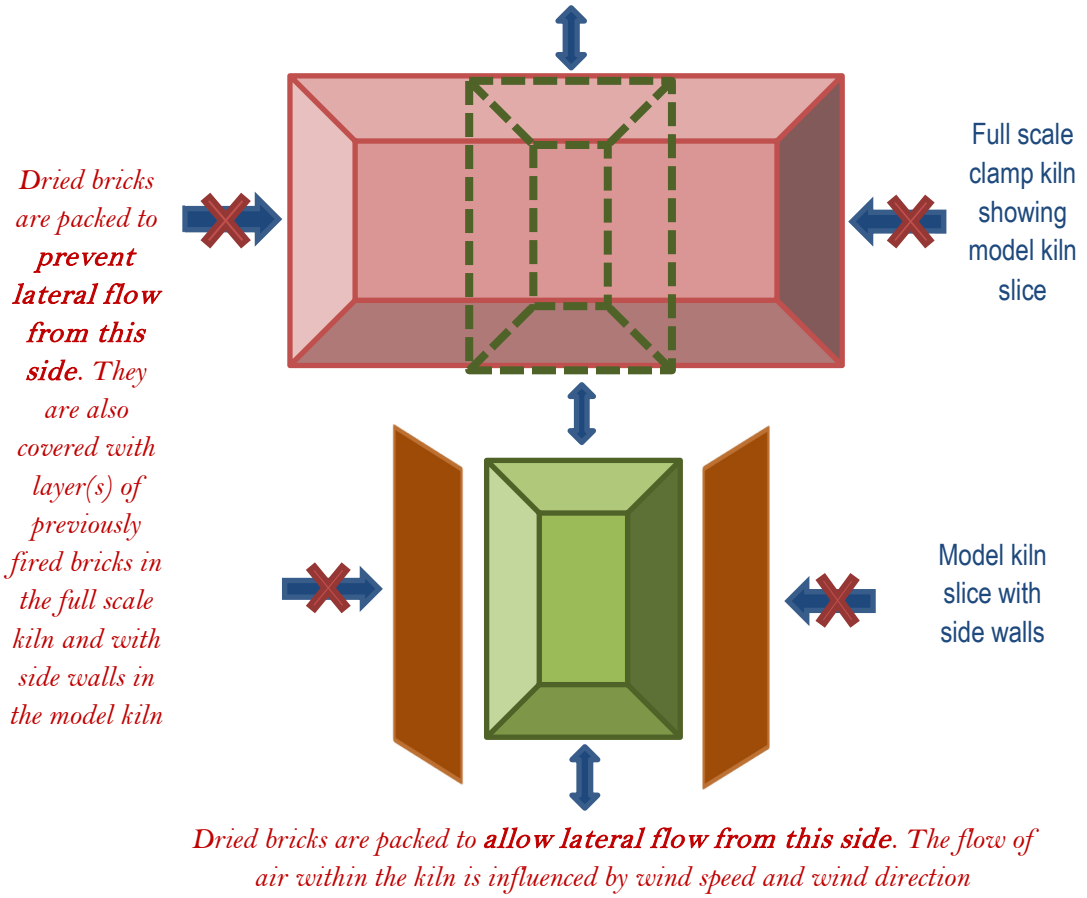


Figure 29: Illustration of air flow in a traditional South African clamp and the model kiln

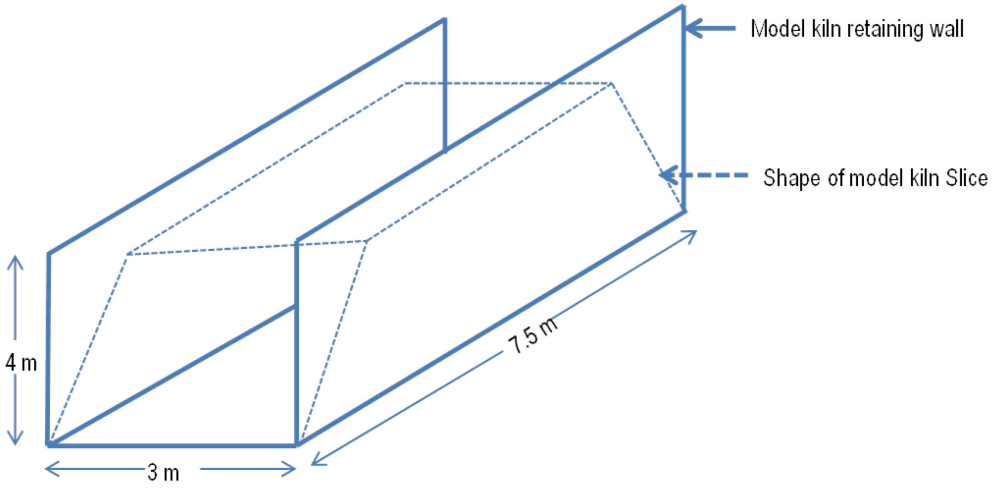


Figure 30: Model kiln configuration

Model Kiln Brick Quantity Calculation

Volume between retaining walls = (4 x 3 x 7.5) m^3 = 90 m^3

Assume 30 % reduction in volume due to slope of pyramid shape (trapezium-like shape at an angle of about 60°) and the air spaces between the bricks and in the bottom layers.

Volume of pyramid = 90 m^3 x (100 – 30) % = 63.0 m^3

Average size of bricks (CBA 2002; CBA, 2015b) = (0.222 x 0.106 x 0.073) m^3

Volume of pyramid = 1.7178 x10^{-3} m^3

Quantity of bricks = 63.0 m^3 / 1.7178 x10^{-3} m^3 per brick

*Quantity = 36 675 bricks **

(* Actual firing capacity of 20 000 – 35 000 utilized bricks per batch since bricks are not packed right to the top of the kiln)

The model kiln is constructed with its semi-enclosed sides to the direction of the prevalent airflow from the north and northwest of the region, in order to allow adequate supply of air during brick firing. A green-coloured plastic wire mesh wind screen (shade netting) is installed 5 metres away, to the north and northwest of the model kiln in order to minimize excessive airflow during extreme wind conditions (Figure 31).

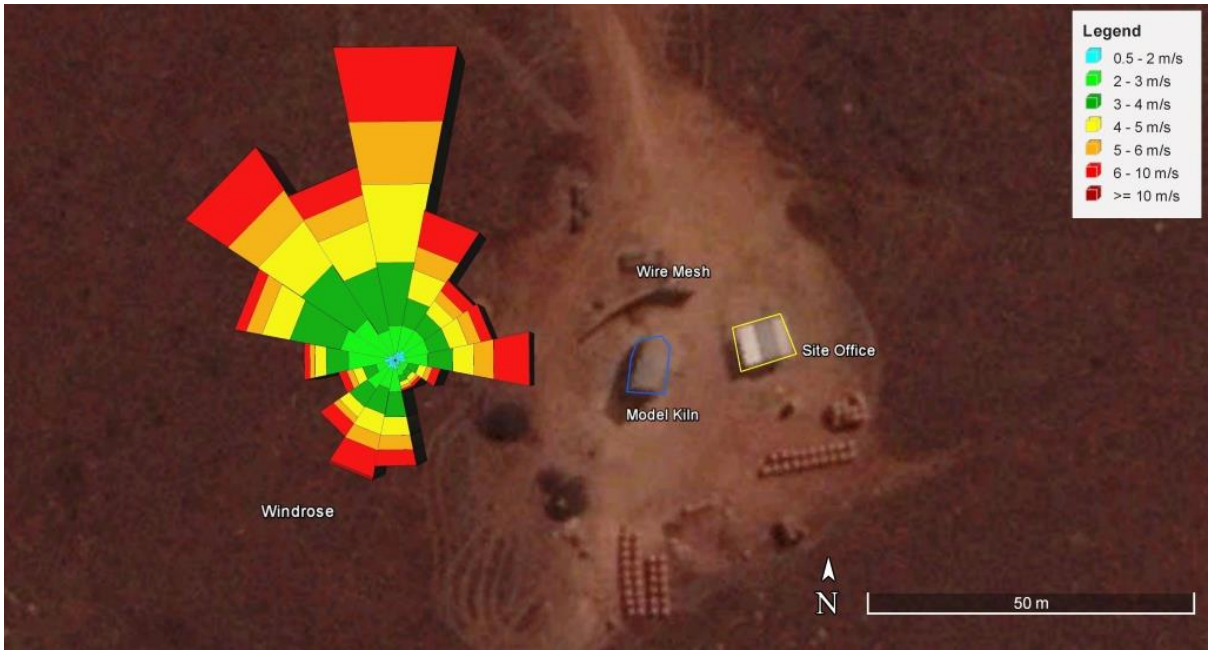


Figure 31: Model kiln site layout showing wind rose

The top of the kiln is hooded with an insulated galvanised steel cover bearing a horizontal stack outlet, with a cross sectional area of 0.13 m^2. A horizontal stack was considered more feasible for the purpose of this study. A horizontal stack minimises the vertical climbing height required for the person taking the measurement to reach the monitoring point and thus contributes to safe operation.

The stack is equipped with a "bifurcated case axial" fan which extracts and channels the flue gas through the stack to the monitoring point. The design ensures adequate capture and channelling of the flue gas through the stack, with minimum losses experienced via the semi-enclosed sides. Galvanized steel sliding side boards are fitted to the open sides of the model kiln wall. These boards are kept opened during packing and unpacking of bricks in the kiln; but are closed for the firing duration and while hourly measurements are taken (Figure 32).

Figure 32: On-going model kiln packing process (left); packed model kiln with sliding doors closed (right); – note position of extraction duct and sampling platform and green mesh windscreen

3.3 KILN AND MONITORING EQUIPMENT

3.3.1 BIFURCATED CASE AXIAL FAN

The bifurcated case axial fan is a specially designed fan that has a split airway with a direct driven electric motor operating in ambient air within the motor compartment. The air stream is diverted on either side of the motor compartment, and converges downstream after by-passing the electric motor, as shown in Figure 33 (Vent-Axia, 2010a; 2010b; 2015). The fan is utilized in industrial processes that emit hot or cold flue gases, and is deemed suitable for effective extraction and channelling of flue gas through the model kiln stack (Vent-Axia, 2010a; 2010b; 2015). Its operating temperature range is from -20 to + 200^{o}C, an improvement over the standard drive fans operating at a temperature range of - 20 to + 50 ^{o}C (Envirotec, 2006).

The inlet velocity through the openings (with the "draught" doors closed) is expected to be in the order of 0.5 m/s, as obtained from the outlet fan curve (Vent-Axia, 2010a; 2010b; 2015). This velocity is less than the normal wind velocities experienced by full-size kilns. The forced draught in the model kiln is therefore not expected to cause a material difference in air supply or flow conditions over the outside wall of the packed kiln when compared to a full-size kiln. Hence, it is not anticipated that there would be significant difference between combustion conditions in the model kiln and a full-scale kiln. Even if differences occur in the flow conditions between the model kiln and the full-size kiln, measurements between the different test firings will be run under comparable conditions.

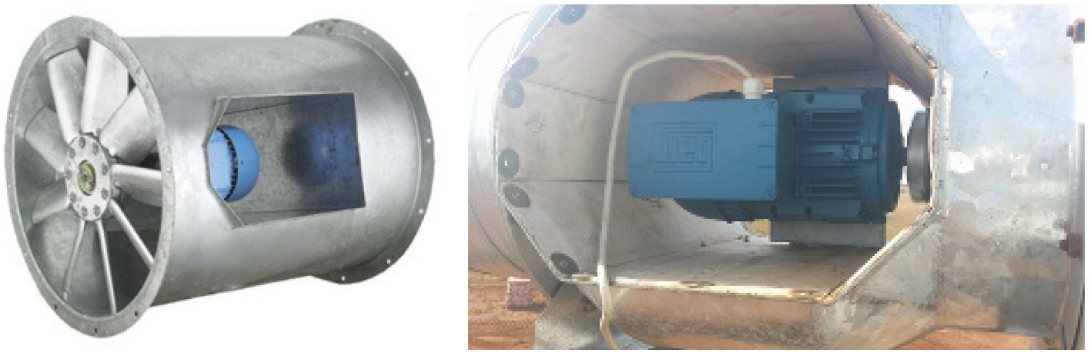


Figure 33: A typical Bifurcated Axial fan; and the 1.5 KW 2P 220V B3T WEG ALLY motored axial fan installed at the model kiln stack

3.3.2 PM MONITORS

PM measurement was undertaken using the Sidepak™ Personal Aerosol Monitor Model AM510 and the DustTrak™ DRX Handheld Aerosol Monitor Model 8534 (Figure 34).

The Sidepak™ Personal Aerosol Monitor Model AM510 is a laser photometer that measures airborne particle (PM_{10}) mass concentration with the aid of a built in sampling pump that is equipped with adjustable flow rate (TSI Incorporated, 2012; 2013). The Sidepak™ Personal Aerosol Monitor was considered adequate to measure particulate matter less than 10 micron in size. It has been shown (Lodge, 1988; Harrison & Perry, 1986), that the

concentration error for particles less than 10 micron in size rarely exceeds 10% only when the sampling velocity is a factor of 3 or more higher or lower than the velocity in the duct. In order to allow extended continuous sampling, as well as the comparison of a large number of firing variables to be considered (which is not practicable with isokinetic sampling), it was decided to accept this magnitude of error.

The DustTrak™ DRX Handheld Aerosol Monitor model 8534 is a new laser photometer that can measure up to five size-segregated particulate mass fraction concentrations simultaneously (TSI Incorporated, 2011; 2014b). The monitor is a continuous 90° light-scattering laser photometer that measures and displays real-time size-segregated particulate mass fraction concentrations corresponding to PM_1, $PM_{2.5}$, Respirable or PM_4, PM_{10}, and Total PM (PM_{15}). The monitor utilizes simultaneous single particle detection and particle cloud (total area of scattered light) to achieve particulate mass fraction measurements (TSI Incorporated, 2011; 2014a).

According to TSI Incorporated (2011) and (2014b), DustTrak monitors measure aerosol contaminants such as smoke, dust, mists and fumes, utilizing a sheath air system that captures or isolates the aerosol in an optics chamber, ensuring that the optics are kept clean for improved consistency and minimal maintenance requirements.

The SidePak Monitor's sampling range of 0.001 – 20 mg/m^3 proved to be insufficient in capturing concentrations higher than 20 mg/m^3 during peak firing sessions, since various literature references quantified similar brick kiln PM emissions to be between 30 – 300 mg/m^3 (refer to Table 5). Consequently, during Batch 13 measurement, a DustTrak™ DRX Handheld Aerosol Monitor model 8534, (with a sampling range of 0.001 – 150 mg/m^3) was made available to measure PM size-segregated mass fractions and offer an adjustment factor to the limited sampling range of the SidePak Monitor. It has also been shown by TSI Incorporated (2014c) and McInnes (2009) that the DustTrak Monitor shows excellent correlation with the Tapered Element Oscillating Microbalance (TEOM) Monitor, when the proper inlet conditioner is used (Figure 35).

In addition, the size-segregated aerosol mass fraction measurement technique offers a superior measurement technique to either a basic photometer or an optical particle counter (OPC), in that it provides the size resolution of an OPC, while still delivering the mass concentration of a photometer (photometers are used at high mass concentration, but they do not provide size information and they have been known to underestimate large particle mass concentrations; while OPC's provide particle count and size information, without provision for mass concentration information).

The DustTrak Monitor also possess gravimetric sampling capability, made possible with the use of a 37-mm filter cassette inserted in-line with the aerosol stream, which enables users to perform integral gravimetric analysis for custom reference calibrations (TSI Incorporated, 2011; 2014b).

Figure 34: The Sidepak™ Personal Aerosol Monitor model AM510 (left) and the DustTrak™ DRX Handheld Aerosol Monitor model 8534 (right)

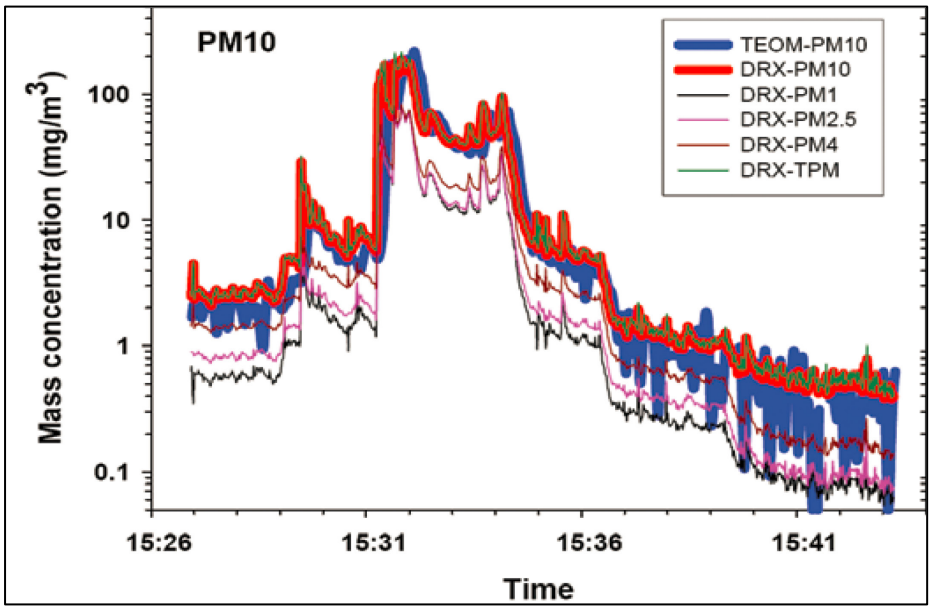


Figure 35: Comparison of Arizona Test Dust (A1 test dust) mass concentration measured by the DustTrak DRX and the TEOM with a PM_{10} impactor (TSI Incorporated, 2014c)

3.3.2.1 DustTrak and SidePak Calibration to Gravimetric Measurement

The gravimetric method has been established as the standard reference method for measuring PM mass concentration. It provides accurate and reliable measurements, though not in real-time, and it is not suitable for determining variations in PM concentrations when sampling is conducted for short periods (Charron, 2004; Rupprecht *et al,* 1992). Real time monitors, such as the SidePak, DustTrak and TEOM, can detect variations in PM concentrations within seconds. In addition, for real time monitors, especially photometers, the relationship between the extent of scattered light and the corresponding mass concentration is dependent on the type of aerosol being measured (Jiang, 2011a; 2011b).

The SidePak and DustTrak monitors utilized in this study were calibrated annually at the factory against the Arizona test Dust (A1 test dust). When the default calibration factor of 1.00 is used, the monitors assume that the measured aerosol possess similar properties (such as refractive index, size distribution and density) with the A1

test dust. For instance, the A1 test dust has a refractive index equal to 1.54, a particle density equal to 2.65 µg/m^3, a lognormal size distribution with a geometric mass mean diameter (GMD) equal to 2.12 µm, and a geometric standard deviation (GSD) of 1.572. Second hand smoke particles, however, have particle density ranging from 1.00 – 1.12 µg/m^3, a GMD ranging from 0.2 – 0.5 µm, and a refractive index ranging from 1.45 – 1.62 (Jiang, 2011a; 2011b). Since these metrics typically vary with aerosols, an aerosol calibration factor is required to standardize the measured concentrations to actual gravimetric values.

Calibration factors need to take to account the type of aerosol being measured. While several literature references provide SidePak and DustTrak calibration factors for common aerosols such as ambient air, indoor air, wood smoke, indoor smoke, forest fires emissions and laboratory wood stove smoke; SidePak and DustTrak calibration factors for coal combustion or flue gas from coal combustion processes are not available. Table 18 provides SidePak and DustTrak calibration factors for various aerosols obtained from literature.

Also, it is worthwhile to note that the properties of the aerosol (refractive index, size distribution and density) are not solely responsible for the variation in calibration factor. Other factors, such as atmospheric condition, combustion conditions, difference in properties of combustion materials, location, seasonal and daily weather conditions may influence variation in calibration factor (Jiang, 2011a; 2011b).

Table 18: PM Calibration factors obtained from literature

Source	PM fraction	Environment or Aerosol measured	Calibration Factor (SidePak)	Calibration factor (DustTrak)
Zhu *et al* (2007)	$PM_{2.5}$	Outdoor air in a controlled facility	0.3	–
Jiang *et al* (2011)	$PM_{2.5}$	Outdoor air (in winter)	0.66 – 0.93	–
	$PM_{2.5}$	Rural outdoor aerosol	0.49	–
	$PM_{2.5}$	Burning wood chips	0.77	–
	$PM_{2.5}$	Indoor air in a smoking casino	0.33	–
Braniš & Hovorka (2005)	$PM_{2.5}$	Ambient air	–	0.25 – 0.47
	PM_{10}	Ambient air	–	0.31 – 0.79
Chung *et al* (2001)	$PM_{2.5}$	Ambient air	–	0.33
Yanosky *et al* (2002)	PM_{10}	Ambient air with wood smoke	–	0.38
Wallace *et al* (2011)	$PM_{2.5}$	Ambient air	–	0.38 – 0.45
McNamara *et al* (2011)	$PM_{2.5}$	Indoor air with wood stove burning	–	0.63
		Controlled laboratory wood stove emission	–	0.61
		Indoor air during forest fires	–	0.59
Kingham *et al* (2006)	PM_{10}	Wood smoke	–	0.37
	$PM_{2.5}$	Indoor air during forest fires	–	0.63
		Laboratory wood stove	–	0.46
Heal *et al* (2000)	PM_{10}	Ambient air	–	0.45
Language *et al* (2016)	PM_4	Indoor solid fuel combustion	0.24	0.14

An attempt was made to obtain calibration factors for the model kiln combustion aerosols. During Batch 13 firing run, monitoring of emissions using the SidePak and DustTrak monitors, as well as gravimetric sampling (reference measurement) were taken. The Gillian™ pump was used to sample PM_{10} aerosols at a flow rate of 1.2 litres per minute on to two gravimetric filter cassettes. Both photometric and gravimetric sampling was taken concurrently to ensure accuracy over the monitoring duration (one gravimetric filter cassettes was used for the first half of model kiln firing and the second over the second half of firing run).

However, a calibration factor could not be obtained due to error encountered with the laboratory analysis conducted to post-weigh the gravimetric filter cassettes. The cause of this error could not be determined. Therefore, a calibration factor of **0.61** was obtained from literature (Table 18). This calibration factor was obtained by McNamara et al (2011) from controlled laboratory wood stove for $PM_{2.5}$ emissions and is considered the most similar aerosol to combustion-related particulates found in literature. The calibration factor for $PM_{2.5}$ emissions is considered similar to PM_{10} emissions since combustion-related particulates are composed of extremely fine PM (since it is made up of nucleotides and particles that are yet to coagulate in the atmosphere).

3.3.3 GAS SAMPLERS

In this study, the E INSTRUMENTS Model 5500 and the ENERAC Model 700 Integrated Emissions System gas analysers or samplers (Figure 36) were utilized in measuring gaseous pollutants. E Instruments (2012) and ENERAC Inc. (2005) describes both gas analysers as versatile or adaptable emissions measurement system that utilize similar processes in measuring gaseous pollutants (including CO, NO, NO_x, NO_2 and SO_2) and emission parameters (including exit velocity, flue gas temperature, combustion efficiency, excess air, percentage oxygen, percentage carbon dioxide etc.).

According to E Instruments (2012) and ENERAC Inc. (2005), both gas analysers are designed to measure, record and transmit combustion metrics in an emission stream using the following processes, techniques or methods:

- In measuring NO_x emissions from stationary combustion sources, a high quality proprietary electrochemical sensors in accordance with the USEPA Provisional Reference Methods i.e. EMTIC CTM-022 (EMTIC, 1995), CTM-030 (EMTIC, 1997) and CTM-034 (EMTIC, 1999) for portable NO_x analysers is utilized;
- In measuring CO, SO_2, and O_2 emissions from mobile and stationary combustion sources, trademarked electrochemical sensors are utilized;
- In measuring gaseous hydrocarbons as propane, CO and CO_2 simultaneously, the Nondispersive Infrared (NDIR) technology is utilized, which complies with the USEPA's Reference Method 25B Appendix A 40CFR60 'Determination of Total Gaseous Organic Concentration Using a Nondispersive Infrared Analyser' (EMTIC, 1991);
- In computing emission rates for gaseous pollutants (NO_x, SO_2, CO, etc.), the USEPA's 40CFR75 regulations for continuous emissions monitoring is complied with; and

- Measurement of stack exit velocity, volumetric flow rate, combustion efficiency and other combustion parameters also complies with the EPA Method 2 or 2C, Appendix A of 40CFR60 (EMTIC, 1991).

Figure 36: The E INSTRUMENTS Model 5500 (left) and the ENERAC Model 700 Integrated Emissions System (right)

An S-type Pitot tube (Figure 37), connected to a pressure sensor with hoses, utilizes a differential pressure measurement when inserted into the stack with the high pressure side tipped to face the direction of the stack flue gas flow (E Instruments, 2012; Biarnes *et al,* 2013). The velocity calculation is given as:

$$\boldsymbol{V = K * C * \sqrt{\Delta P} * \frac{\sqrt{Tstack+273}}{\sqrt{M * P}}} \qquad \text{Equation 8}$$

Where:

V = stack gas velocity (m/s)

K = pitot tube velocity constant (34.97)

C = velocity pressure coefficient (for S-type pitot = 0.84) (dimensionless)

$\sqrt{\Delta P}$ = square root of differential pressure of stack gas (mmH_2O)

T_{stack} = stack temperature (^oC)

M = molecular weight of stack gas, wet basis (g/g mole)

P = absolute stack gas pressure (mmHg)

M is the molecular weight of the stack gas on a wet basis in g/g mole. Typically, the main components of the stack gas are CO_2, O_2, N_2 and water. The dry weight is calculated by:

$$\boldsymbol{Mdry = 44\frac{\%CO_2}{100} + 32\frac{\%O_2}{100} + 28\frac{\%CO}{100} + 28\frac{\%N_2}{100}} \qquad \text{Equation 9}$$

Where:

M_{dry} = dry molecular weight of stack gas (g/g mole)

$\%CO_2$ = percentage CO_2 in gas stream

$\%O_2$ = percentage O_2 in gas stream

$\%N_2$ = percentage N_2 in gas stream

44 = molecular weight of carbon dioxide (g/g mole)

32 = molecular weight of oxygen (g/g mole)

28 = molecular weight of carbon monoxide and nitrogen (g/g mole)

M_{dry} can then be converted to a wet basis by:

$$\boldsymbol{Mwet = Mdry(1 - B_{wo}) + 18(B_{wo})} \qquad \text{Equation 10}$$

Where:

M_{wet} = wet molecular weight of stack gas (g/g mole)

M_{dry} = dry molecular weight of stack gas (g/g mole)

B_{wo} = proportional of water vapour in the gas stream by volume

18 = molecular weight of water in (g/g mole)

Figure 37: S-type Pitot tube

3.4 Model Kiln Packing and Firing Methodology

The model kiln packing and firing methodology for each batch assumed similar methodology utilized at the source factory that provided the bricks. These factories utilize similar techniques (with slight differences observed) in packing and firing their bricks. The common brick packing methodology utilized for the model kiln is described in this section.

A base layer or 'table' is constructed in a manner to allow free flow of air underneath the kiln using 1 – 2 layers of stacked bricks (see Figure 38 and Figure 39 below). 2 – 3 courses of bricks, packed on top of the 'table', (called 'scintle' layer), are built and packed with coal – 'peas' or 'small nuts'. According to CBA (2015b), the number of layers and quantity of fuel used in the 'scintle' is dependent on the type of clay and fuel utilized, as well as the

target temperature to be achieved. It is suggested by clamp kiln operators that dark coloured clay bricks require higher heat energy for firing than light coloured ones (CBA, 2015b).

Figure 38: Construction of 'table' (left) and 'scintle' (right) inside the model kiln

Beyond the 'scintle layer', 25 – 36 layers of green bricks are stacked on top of one another in a pyramid shape, with opening to allow for air flow from the semi-opened sides of the model kiln. A cover or 'blanket' of previously fired bricks is packed on top and exposed sides to limit heat loss from within the kiln.

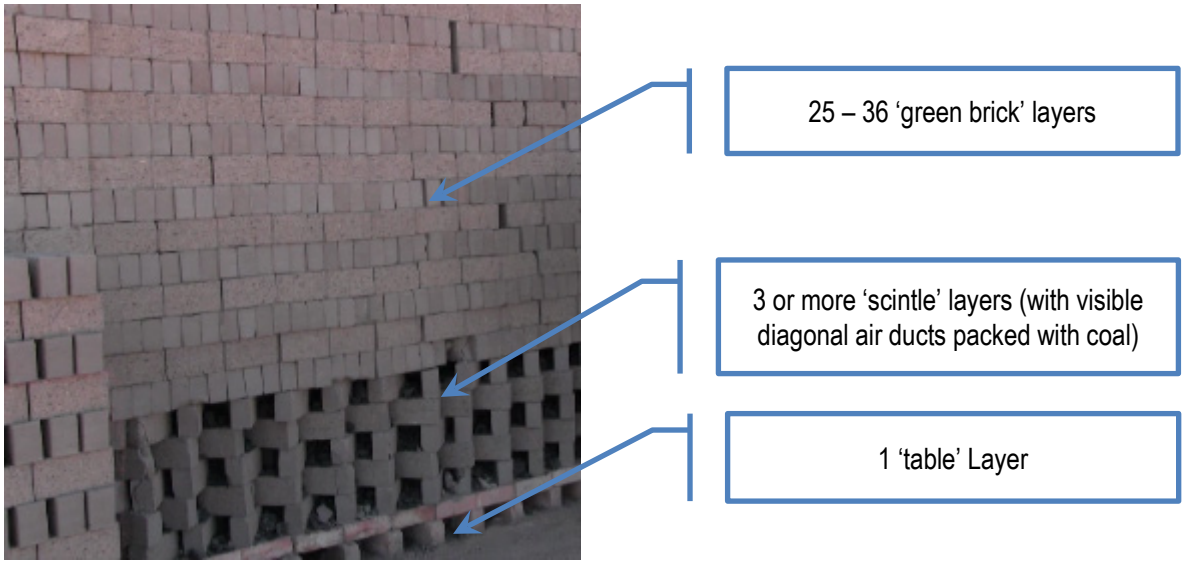


Figure 39: Illustration of packing layers in a typical clamp kiln

Packing of bricks into the kiln was done manually by 6 – 10 men (for each batch of firing), with the aid of equipment such as forklifts and front end loaders. Personal protective equipment that was used include helmets, green or red coveralls, hand gloves, dust masks etc.

Start-up of the firing process was done for most batches with the use of a 'fire-box', which is basically a stack of bricks housing sufficient amount of coal to start the firing process (Figure 40). Batches 3 and 12 operator utilized diesel (20 litres) and natural gas respectively, to start-up their firing process.

Figure 40: Typical 'fire-box' used for starting the brick firing process

3.5 Model Kiln Firing and Stack Monitoring

A series of thirteen model kiln firing and concurrent stack monitoring campaign was conducted in order to collect emissions data. Measurement and data recording was carried out for the entire duration of each firing campaign; which included hourly measurements for gaseous pollutants, particulates and process parameters. For each hourly measurement, readings were taken every second for all the parameters and then averaged over 5 – 6 minutes. Thus measurement was considered representative for the entire hour since continuous monitoring was not feasible for the entire hour. Hourly ambient measurements were also taken to record potential background input.

Input and firing conditions, techniques and parameters were varied over each firing and monitoring campaign. The objective is to simulate the source factory's method of processing, packing and firing, as well as the intrinsic properties of the clay and coal materials from each factory. These variables include the following:

- Source of 'green' bricks to be fired were obtained from different brick factories across South Africa, with only one brick source utilized per firing campaign (the location of each source factory is shown in Figure 41);
- Method of bricks processing, packing and firing were in similar manner to the technique employed at the source factory;
- Intrinsic properties of clay material (such as clay type, chemical composition of clay, moisture content etc.) varied according to source of clay utilized;
- Sulfur content of fuel varied according to the source of coal supply. Coal supply varies from one factory to another; and
- Calorific value or energy content, ash content and total carbon content of coal varied from one factory to another. The major source of fuel for South African clamp kiln is coal – 'peas', 'small nuts', carbon fly ash (CFA) and 'duff' coal (Lordan, 2011; CBA, 2002, 2005). Duff coal or CFA are used as 'body fuel' (that is, mixed into the clay during processing), while the 'small nuts' or 'peas' are used as 'external fuel' in the 'scintle' or the bottom ignition layer of the kiln (Akinshipe, 2013; 2015; CBA, 2015b).

- For each firing cycle, fuel parameters were obtained from the respective factories or determined by laboratory analysis.

Figure 41: Map showing source of green bricks in South Africa (Google Earth Image, 2016)

The chemical composition of clay material from Soweto, South Africa, (location of Batch 12 clay brick factory) is presented in Table 19. Chemical compositions of clay from other source factories were not available for inclusion in this report.

Table 19: Chemical composition of clay material from Soweto, South Africa (Source: Laboratory result from source factory)

Chemical Constituent	%
Silica, SiO_2	55.8
Alumina, Al_2O_3	22.2
Ferric oxide, Fe_2O_3	2.00
Iron oxide, FeO	0.47
Lime, CaO	0.95
Magnesia, MgO	0.44
Potash, K_2O	0.63
Soda, Na_2O	0.11
Phosphorus(V) oxide, P_2O_5	0.19
Loss on Ignition (1000 ^oC)	13.8

3.5.1 TEST FIRING – BATCH ONE

Batch one test firing and concurrent monitoring campaign was conducted from the 28th of August 2014 at 08:30 to the 31st of August 2014 at 17:15. This was conducted as a test run for the model kiln installation and monitoring equipment. The monitoring exercise was disrupted on Day 3 due to fan malfunction. The initial fan installed for this test run was a standard drive fan with an operating temperature -20 to + 50°C (Environtec, 2006), which could not withstand the high temperature of the flue gas from the kiln.

3.5.2 KILN FIRING – BATCH TWO TO BATCH THIRTEEN

Kiln firing and concurrent stack monitoring was conducted for Batch 2 to Batch 13 from November 2014 to May 2016. The bifurcated axial fan (described in Section 3.3.1) was installed for these runs. Input and firing conditions, observations and parameters recorded during these monitoring campaigns are presented in Table 20. These variables are comparable to those obtained at a full scale clamp kiln operation at the factory from where the bricks are sourced.

The model kiln is shown at various stages of firing in Figure 42, Figure 43 and Figure 44.

Figure 42: Visible smoke exiting the semi-enclosed sideboards during kiln start-up

Figure 43: Model kiln scintle ablaze during night-time (left); inner chamber of model kiln at advanced stage of firing during day-time with side boards opened to take photograph (right)

Figure 44: On-going stack monitoring at model kiln (left); visible smoke emitted from the bricks towards the roof duct while side boards are opened to take photograph (right)

Table 20: Input and observations during clamp kiln firing and monitoring

Input and Observation	Firing and Monitoring Batch												
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Date and time of firing and monitoring (start)	28th Aug. 08:00	26th Nov. 12:00	14th Jan. 03:00	5th Feb 10:00	6th Mar. 12:00	24th Mar. 10:00	26th May 10:00	22nd Jun. 10:00	28th July 15:00	24th Aug. 08:00	17th Sep. 08:00	8th Feb. 20:00	10th May 15:00
Date and time of firing and monitoring (end)	31st Aug. 17:00	5th Dec. 17:00	25th Jan. 23:15	16th Feb. 23:00	16th Mar. 07:00	4th Apr. 11:00	5th Jun. 06:00	29th Jun. 23:00	7th Aug. 14:00	1st Sep. 08:00	26th Sep 12:00	16th Feb. 10:00	20th May 14:00
Year of firing	2014	2014	2015	2015	2015	2015	2015	2015	2015	2015	2015	2016	2016
Stack cross-sectional area (m^2)	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13
Frequency of data logging (second)	1	1	1	1	1	1	1	1	1	1	1	1	1
Duration of data logging per hour (minutes)	5 – 6	5 – 6	5 – 6	5 – 6	5 – 6	5 – 6	5 – 6	5 – 6	5 – 6	5 – 6	5 – 6	5 – 6	5 – 6
Monitoring equipment used (PM)	A	A	A	A	A	A	A	A	A	A	A	A	A & D
Monitoring equipment used (Gases)	B	B	B	B	B	B	C	B	B	B	B	B	B
Total hours of firing	ND	211	273	273	236	266	237	182	240	193	221	183	240
Total hours of monitoring	ND	191	258	253	140	137	236	181	238	191	218	162	206
Total hours of missing data	ND	20	15	20	96	129	1	1	2	2	3	21	34
Percentage data availability (%)	ND	90.5%	94.5%	92.7%	59.3%	51.5%	99.6%	99.5%	99.2%	99.0%	98.6%	88.5%	85.8%
Number of hours of precipitation	ND	8	8	9	5	10	0	0	0	0	2	2	0
Number of green bricks fired	32000	26000	28500	30000	32356	20700	24000	24000	29000	29500	30000	26500	20000
Quantity of coal in bricks (kg)	ND	5933	7886	19800	10720	7632	6000	6000	5800	14504	3000	8529	5000
Quantity of external fuel (kg)	ND	2543	1980	3000	1650	1663	1800	1800	2100	2500	6230	3600	1300
Quantity of coal in fire box (kg)	ND	50	70	ND	60	200	200	200	500	ND	ND	ND	200

NOTE:

"ND" implies "no data"
"NA" implies "not applicable"
"D" implies "diesel"
"P" implies "paraffin"
"G" implies "gas"
A = Sidepak™ Personal Aerosol Monitor Model AM510
B = E INSTRUMENTS Model 5500
C = ENERAC Model 700
D = DustTrak™ DRX Handheld Aerosol Monitor Model 8534
"With scintle'" implies the quantity has been combined with the quantity of coal in the "scintle" layer

3.6 KILN PROCESS ANALYSIS METHODOLOGY

3.6.1 COMBUSTION EFFICIENCY ANALYSIS

Combustion occurs when fuel reacts with the oxygen in air to produce heat energy. In this study, the energy produced when fuel is combusted in an exothermic reaction is used to burn bricks as shown in the following chemical equations:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O + \text{Heat Energy} \quad \text{Equation 11}$$

$$C + O_2 \rightarrow CO_2 + \text{Heat Energy} \quad \text{Equation 12}$$

$$2H_2 + O_2 \rightarrow 2H_2O + \text{Heat Energy} \quad \text{Equation 13}$$

Complete combustion occurs when adequate quantities of fuel and oxygen in air (i.e. fuel to air ratio) react for an adequate period of time and under suitable conditions of turbulence and temperature (Biarnes *et al,* 2013; E Instruments, 2012). Optimum combustion can be achieved in a combustion chamber if the volume of excess air and consequently, oxygen is high enough to use up the carbon and/or CO available in the fuel completely; and at the same time, the volume of excess air is limited enough to minimize energy loss through flue gas release to the atmosphere via exhaust streams as well as openings in the firing chamber.

Hence, combustion efficiency is maximized when heat loss is kept to a minimum and more energy is conserved in the kiln. This can be achieved by regulating air supply adequately for the combustion process while limiting availability of excess air which generates greater amount of heat losses. The stack combustion efficiency measurement is a measure of the CO_2/CO ratio and the net temperature between the stack gas and ambient air (Biarnes *et al,* 2013); based on an assumption of the calorific value of the fuel utilised in the combustion process.

3.6.2 PERCENTAGE EXCESS AIR AND CARBON DIOXIDE ANALYSIS

Excess air is often required in a combustion chamber to maximize combustion efficiency. The amount of oxygen in the air available to react with the fuel is maximized, while turbulence is also increased in the chamber for adequate mixing (Biarnes *et al,* 2013; Weyant, 2014).

The percentage of excess air in a firing chamber is necessary to ascertain the combustion efficiency of firing. As more air enters the kiln, more of the fuel is combusted until complete combustion is achieved, giving off larger amounts of CO_2 and lesser quantities of CO (Figure 45). Beyond complete combustion, any additional air will lead to greater amount of heat losses through the semi-enclosed side walls of the model kiln (Biarnes *et al,* 2013). Excess air is calculated as follows:

$$\%\ \text{Excess Air} = \left(\frac{\%\ O_2\ measured}{20.9 - \%\ O_2\ measured}\right) * 100 \quad \text{Equation 14}$$

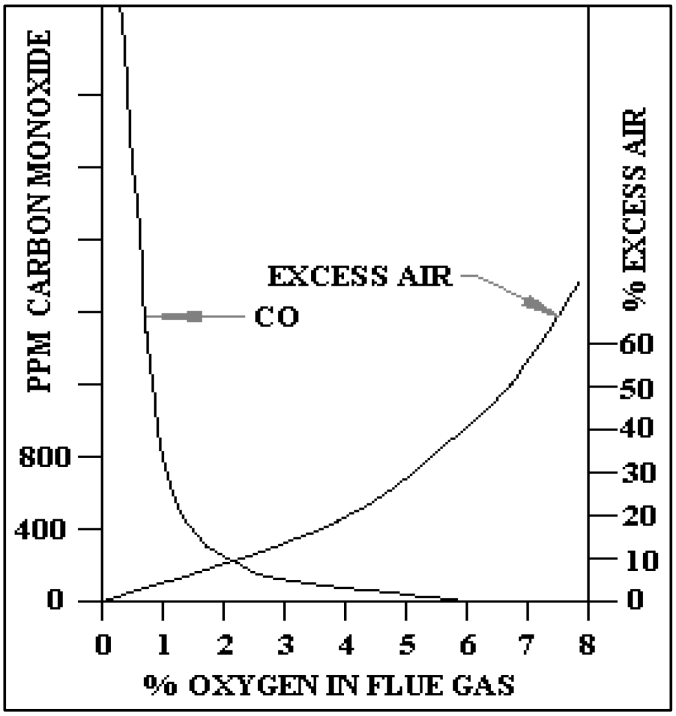


Figure 45: Relationship between excess air and CO levels in a combustion chamber (Biarnes *et al,* 2013)

Percentage carbon dioxide is calculated as a function of the maximum possible stoichiometric amount of CO_2 that can be released by a given fuel and the O_2 concentration, as shown in the equation provided by Biarnes *et al* (2013):

$$\%\ \mathbf{CO_2(Volume)} = \mathbf{CO_2\ (maximum)} * \left(\frac{\mathbf{20.9} - \%\ \mathbf{O_2}\ \boldsymbol{measured}}{\mathbf{20.9}}\right) \qquad \text{Equation 15}$$

CHAPTER FOUR

4 EMISSION RESULTS, DISCUSSION AND EMISSION FACTORS CALIBRATION

4.1 EVALUATION OF MODEL KILN FIRING

It is essential to evaluate the performance of the model kiln in firing clay bricks and to compare the quality of bricks fired in the model kiln to those fired in traditional clamp kilns. Physical and laboratory evaluation of bricks fired in the model kiln were conducted.

4.1.1 PHYSICAL EVALUATION OF FIRED BRICKS

Physical examination is a proven method for detecting defects in clay brick production, including clay brick firing (Schilderman, 1999a). Physical examinations suggested by Schilderman (1999a) include:

- **Softness/Hardness:** Testing how easily the edges and surfaces break off when scratched with finger nails. Softness indicates under-firing of clay bricks.
- **Strength:** Testing how easily bricks crack or break when two bricks are hit together; easy breakage indicates under-firing of the bricks.
- **Sound:** The sound given off by a properly fired brick is quite different from an under-fired one. While a sharp tingling sound is given off by a properly fired brick, a dull thumping sound is given off by an underfired bricks.
- **Core colour:** Breaking a brick in half and observing the colour of the core; a high range of colour variation in the core suggests uneven firing or under-firing of the bricks, while an even colour suggest adequate and even firing.

Physical observations recorded for Batch 2 to Batch 13 are presented in Table 21, indicating that the bricks were, in most cases, adequately fired in the model kiln. In addition, physical appearance of the bricks fired in the model kiln (depicted in Figure 46) show similar appearance to bricks fired in a full-scale kiln. Also, it should be noted that the differences apparent in appearance of the bricks may be due to difference in raw material and firing method utilized for each batch. An estimated 70 – 90 % of the total brick fired in the model kiln across Batch 2 to Batch 13 were considered adequately fired.

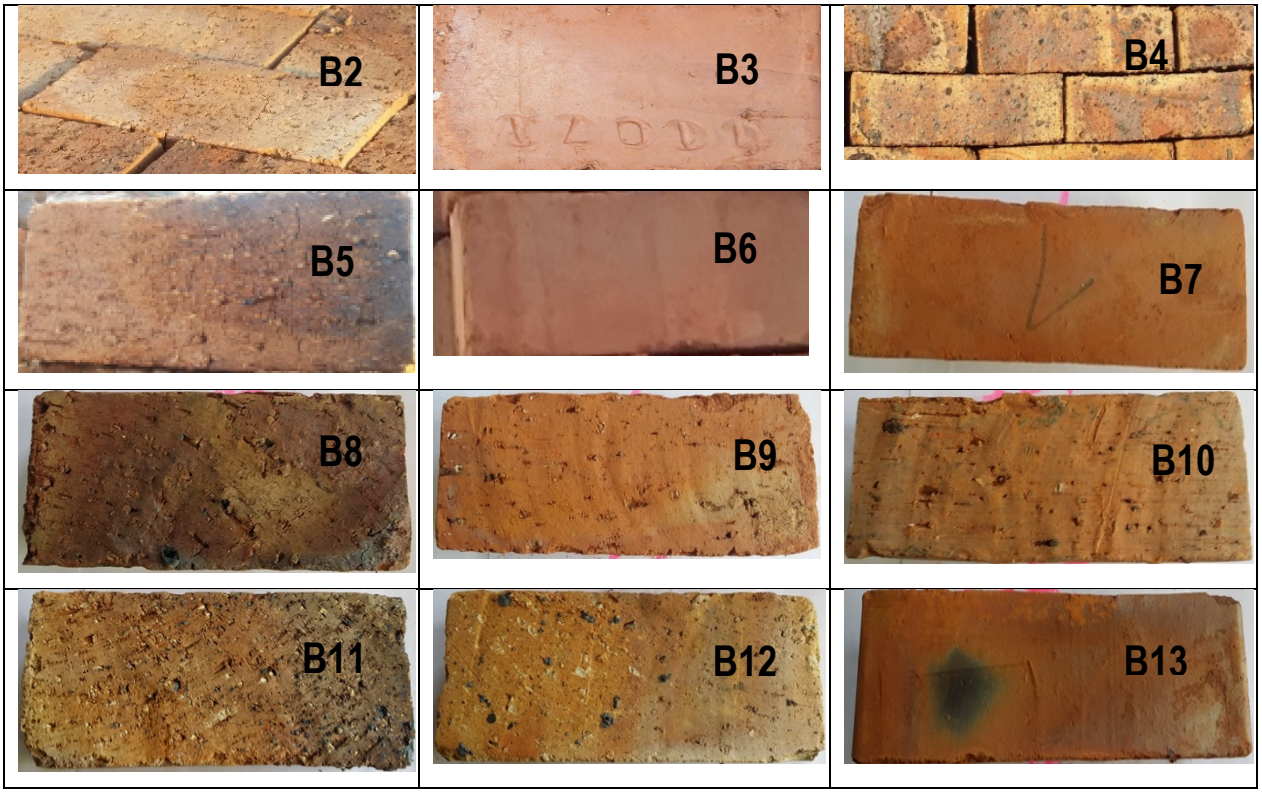


Figure 46: Physical appearance of model kiln fired bricks (Batch 2 to Batch 13 – differences apparent in appearance of the bricks may be due to difference in raw material and firing method utilized for each batch)

Table 21: Physical evaluation of Batch 2 to Batch 13 fired bricks – hardness, strength, tingling sound and even core colour suggest adequately firing of bricks

Batch	Hardness/Softness	Strength	Sound	Core colour
Batch 2	Hard	Strong	Sharp	Even
Batch 3	Hard	Strong	Sharp	Even
Batch 4	Hard	Strong	Sharp	Even
Batch 5	Hard	Strong	Sharp	Even
Batch 6	Hard	Strong	Sharp	Uneven
Batch 7	Hard	Strong	Sharp	Uneven
Batch 8	Hard	Strong	Sharp	Even
Batch 9	Hard	Strong	Sharp	Even
Batch 10	Hard	Strong	Sharp	Even
Batch 11	Hard	Strong	Sharp	Even
Batch 12	Hard	Strong	Sharp	Even
Batch 13	Hard	Strong	Sharp	Even

4.1.2 LABORATORY ANALYSIS OF FIRED BRICKS

Compressive strength and water absorption tests are commonly used to determine the structural integrity of clay bricks (CBA, 2015b). The compressive strength test, measured in megapascal (MPa), is the ratio of failure load to the cross-sectional area resisting that load, and is conducted by breaking brick samples in compression-testing machines (National Ready Mixed Concrete Association, NRMCA, 2003). The water absorption test, commonly given in percent by mass, is a measure of the influence of a 24-hour immersion in cold water on the bond between brick particles (Venkatesan *et al,* 2015).

Selected brick samples fired in the model kiln were sent to the laboratory for analysis (one sample each from Batch 7 to Batch 13). The methodologies stipulated by the South African Bureau of Standards (SABS) as it relates to the South African National Standard (SANS) for the manufacturing of burnt clay masonry units – SANS 227:2007 (SABS, 2007) were used in the laboratory analysis. Results of laboratory analysis are presented in Table 22. The result of the compressive strength and water absorption test show that the bricks fired in the model kiln achieved compressive strength and water absorption test values that are well within typical industry ranges. The analysed bricks also meet the SABS requirement in terms of compressive strength as well as masonry brick dimensions.

Table 22: Compressive strength and water absorption tests for Batch 7 to Batch13

Batch [1]	Quantity	Clay Brick Dimensions			Compressive Strength Test		Water Absorption Test (24-hour)		
		Length (mm)	Breadth (mm)	Height (mm)	Force (kN)	MPa	Dry mass (g)	Wet mass (g)	Absorption (%)
7	1	220.6	104.9	73.7	340.7	14.7	3050.7	3395.3	11.3
8	1	217.4	105.6	71.2	458.2	20.0	2918.2	3287.0	12.6
9	1	221.3	103.8	73.7	257.3	11.2	2640.0	3274.3	24.0
10	1	218.9	102.5	72.4	574.0	25.6	2681.9	3125.5	16.5
11	1	224.6	107.5	71.7	349.7	14.5	2899.8	3424.3	18.1
12	1	224.7	100.6	71.1	718.8	31.8	2632.3	2991.1	13.6
13	1	220.2	107.2	69.5	532.1	22.5	2963.6	3435.0	15.9
Average	1	221.1	104.6	71.9	461.5	20.0	2826.6	3276.1	16.0
Typical range in SA [1, 2]	–	222 ±3.5	106 ± 2	73 ± 2	Not available	7 – 30	2420 – 3070	3071 – 4059	14.1
SABS requirement [1, 3]	–	<300	<130	<120	Not applicable	>10.5	Not applicable	Not applicable	Not applicable
Conclusion (pass/fail)	–	Pass	Pass	Pass	Not applicable	Pass	Not applicable	Not applicable	Not applicable

NOTE:

[1] Samples from Batch 2 to Batch 7 were not tested

[2] CBA (2015b)

[3] Data collected from field study

[4] SABS (2007)

4.2 EMISSIONS RESULTS AND DISCUSSION

Atmospheric emission results obtained from stack monitoring for each firing cycle are presented in this section along with discussions on the implication of each result. Pollutant concentrations are presented in mg/m^3 or ppm (refer to Section 1.3). Batch 1 results could not be obtained due to equipment breakdown at the early stage of firing. In addition, significant periods during Batches 5, 6, 7 and 13 firing campaigns were also characterized by equipment malfunction (gas samplers) as well as power failure, but measured data were considered adequate for further analyses. Data availability is above 85% for all batches, except for Batches 5 and 6 with less than 60% data availability (refer to Table 20).

For each of the variables, the mean of the distribution was taken as the most appropriate measure of central tendency, since various emission releasing reactions and processes occur in the kiln at different periods during the firing cycle (refer to Section 2.2). These reactions and processes include the following:

- release of 'mechanical water' and 'combined water';
- combustion of external fuel in the base layer and the internal fuel mixed into the bricks;
- dissociation of carbonates in the clay material;
- oxidation conditions leading to dissociation of $CaSO_4$ and release of CO_2 (and eventually SO_2); or retention of $CaSO_4$ and FeS_2 in a reducing environment to give off CO and H_2; and
- Destruction or development of lattice structure and change in crystal phase of the clay material.

It should be noted that the emission concentrations and process metrics (output metrics) presented in this section have not been corrected to account for occasional losses of flue gas from underneath the sliding boards, especially during extremely windy conditions. In addition, polynomial curves are utilized in this section to better illustrate time trends over the firing period.

4.2.1 CO EMISSIONS

CO concentration time series plots are presented in Figure 47, Figure 48 and Figure 49 excluding Batches 1 and 7; which could not be obtained due to equipment breakdown and power failure. Histograms of CO emissions are also shown in Figure 50 for each firing batch. Measured CO concentration shows similar trends across various batches, with concentration initiating at low levels; gradually rising and reaching peak concentrations within 30 – 100 hours (i.e. first and second quarter of firing duration across various batches), and gradually falling again to low levels towards the end of the firing cycle. In most cases, the concentrations show a positively skewed histogram (leaning towards lower emissions), typical of kiln combustion process which gradually ignites fuel and carbonaceous compounds in the bricks; and burning out over time. Since physical examination (by touch) of the external fuel in the 'scintle' layer of the kiln indicated that this burns off within 1 – 2 days of firing, implying that a

large proportion of CO emissions during peak periods are from combustion of the external fuel in the 'scintle' layer. This suggests incomplete combustion and inefficient use of fuel for firing.

CO maximum, mean, median and minimum emission concentrations, as well as standard deviation (SD) from the mean, are presented in Table 23. The highest average emissions are recorded during Batches 2 and 12; while Batches 3 and 6 recorded the lowest average emission rates. The minimum concentration recorded was zero for all batches.

Table 23: CO emission summary

	CO Concentration (mg/m^3)											
Batch	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Max.	5886	690.0	1936	1424	764.0	ND	2736	868.0	1808	877.8	3979	ND
Mean	1809	189.6	458.0	113.3	195.7	ND	684.6	156.9	414.2	555.6	785.6	ND
SD	1733	190.6	540.5	214.1	160.8	ND	766.9	209.6	553.6	908.0	1070	ND
Median	1242	121	209	6	0	0	346	40	81	84	230	ND
Min.	0.0	0.0	0.0	0.0	0.0	ND	0.0	0.0	0.0	0.0	0.0	ND

NOTE: "ND" implies "no data"; "SD" implies "standard deviation"; "Max." implies "maximum"; while "Min." implies "minimum"

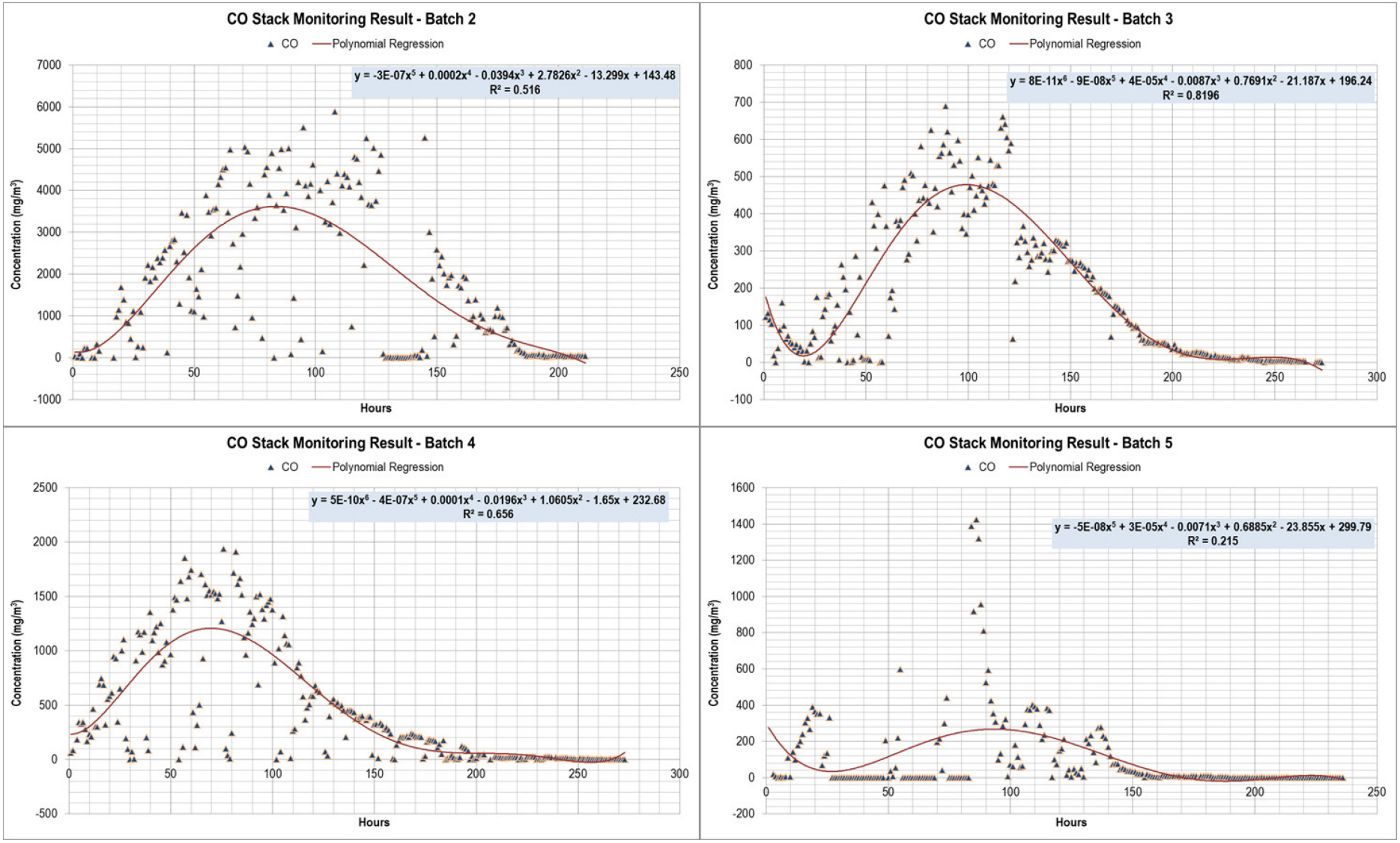


Figure 47: CO emission concentration in mg/m³ (Batches 2, 3, 4 and 5)

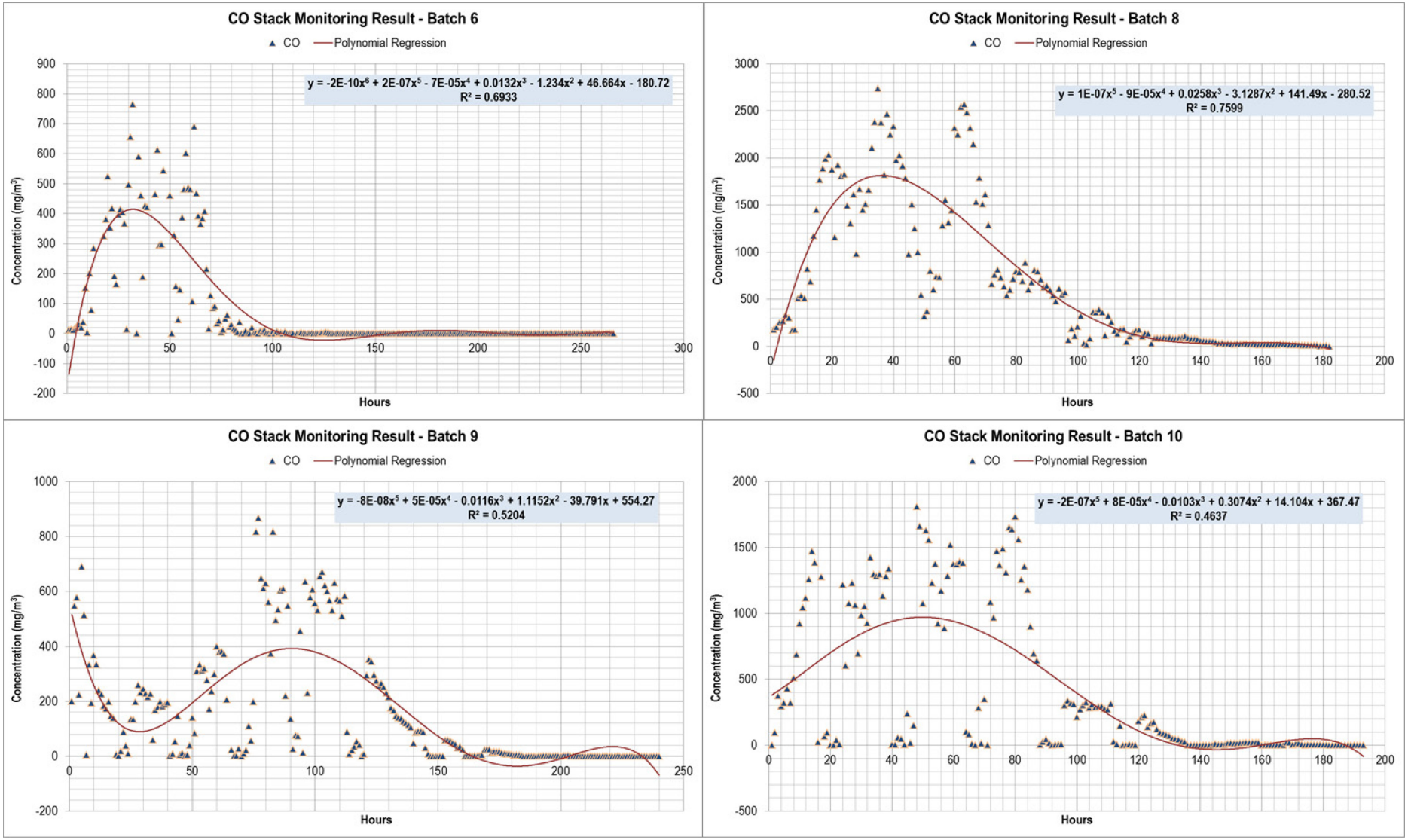


Figure 48: CO emission concentration in mg/m³ (Batches 6, 8, 9 and 10)

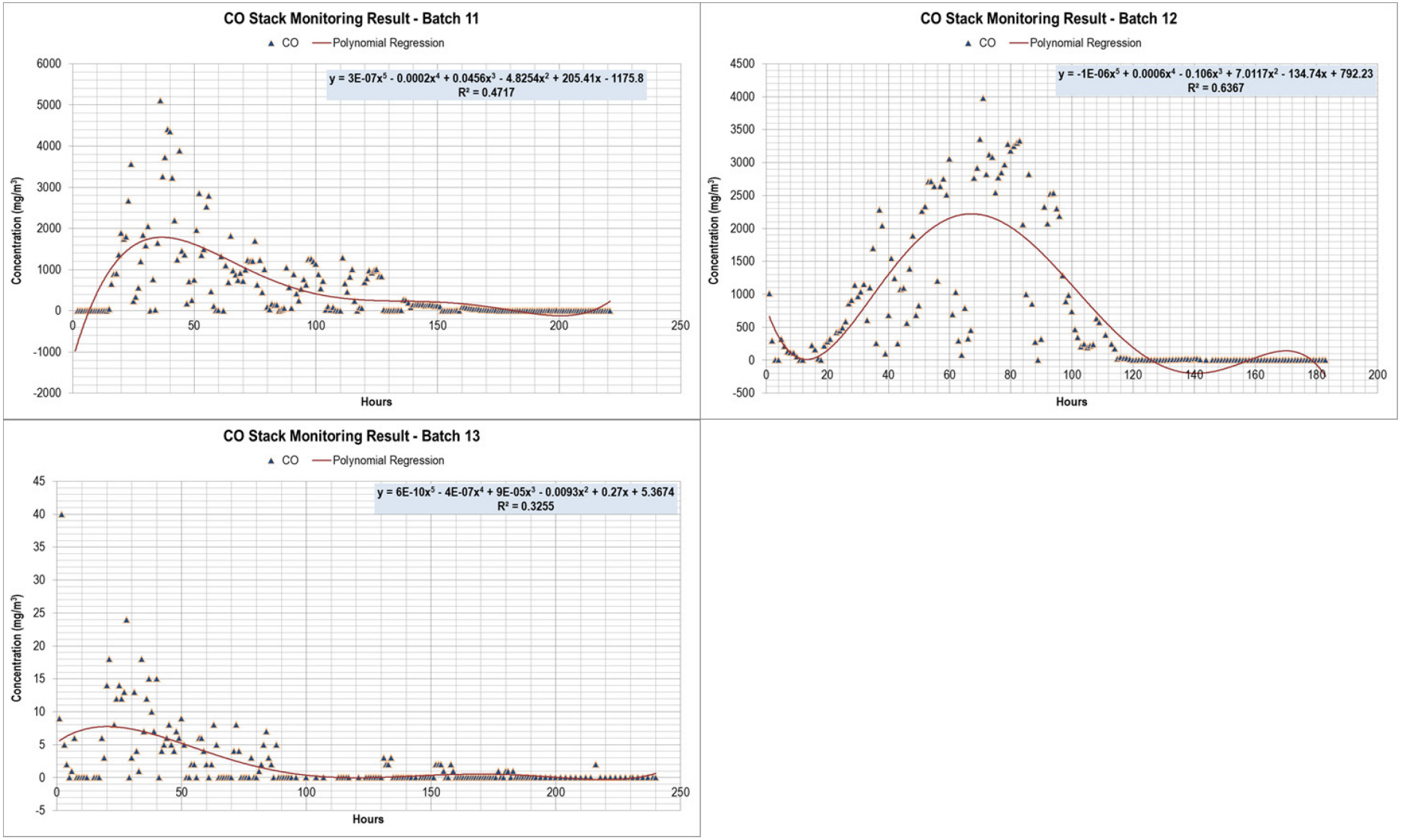


Figure 49: CO emission concentration in mg/m³ (Batches 11, 12 and 13)

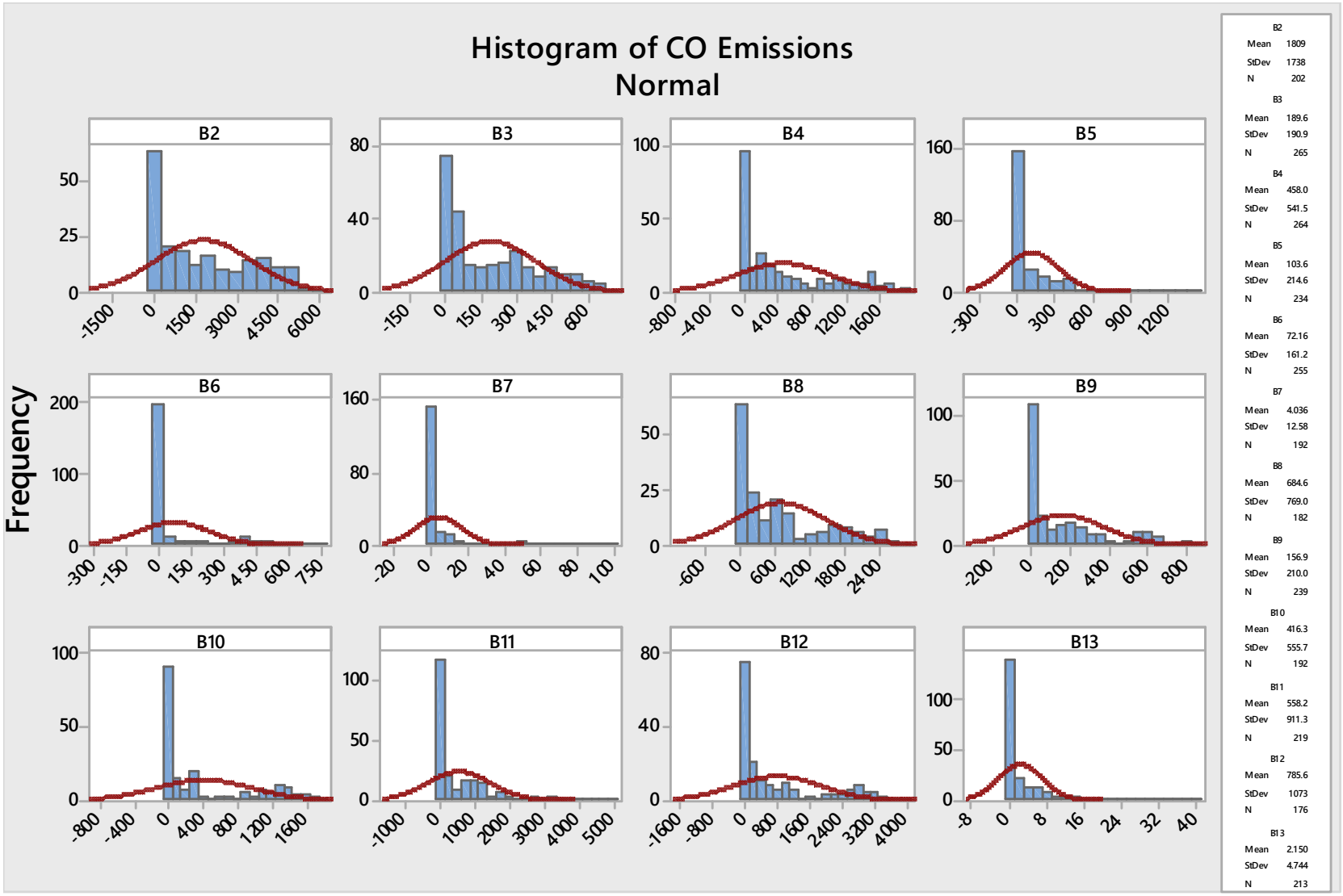


Figure 50: Histogram of CO emission concentrations across Batch 2 to Batch 13

A CO emission variability plot for all batches is shown in Figure 51, which indicates positively skewed CO emissions (leaning towards lower CO concentrations). Batch 3 displays the best indication of consistent emissions over the firing period (since shorter bars and a centred median in the variability plot is an indication of lower variability and consistent emissions). Batches 2, 11 and 12 show extreme levels of data variability, which suggest that these batches were inefficiently fired due to uneven combustion as a result of unevenly mixed fuel or inhomogeneous clay in raw bricks. These extreme variability could not be linked to the energy input, since the SEC of these batches (2.30 MJ/kg, 2.29 MJ/kg and 2.59 MJ/kg for Batches 2, 11 and 12 respectively) are comparable to the average SEC over Batch 2 to Batch 13 (2.57 MJ/kg).

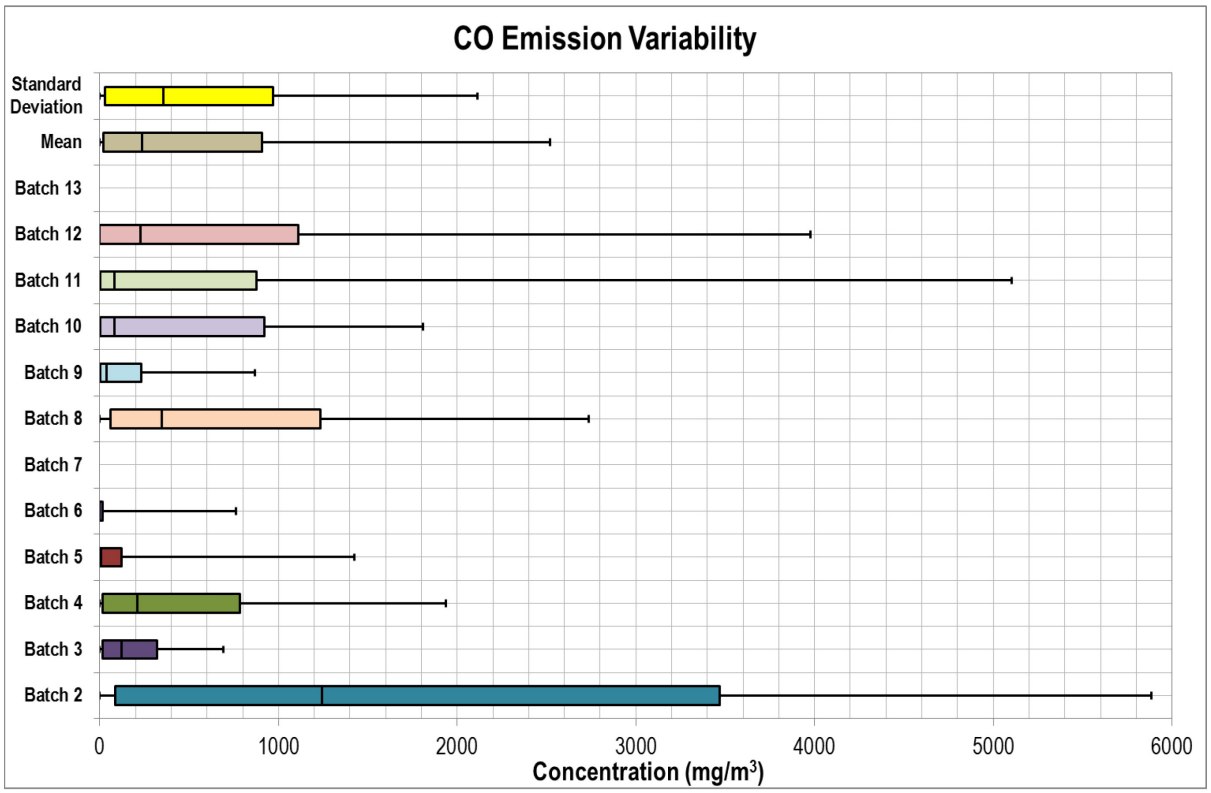


Figure 51: CO emission variability plot – Batch 3 displays the best indication of consistent emissions over the firing period, while Batch 2, Batch 11 and Batch 12 shows extreme levels of data variability

4.2.2 NO_2 Emissions

NO_2 emission was not detected throughout the entire firing duration for Batch 2 to Batch 13. All NO_2 measurements recorded zero values. This may be attributed to the high temperature occurring within the kiln, since it has been established that NO is preferentially formed from combustion of fossil fuels at high temperatures. In a typical combustion chamber, thermodynamic equilibrium is formed between nitrogen, oxygen, NO and NO_2 at temperatures in the combustion ranges. Thermodynamically, the higher the temperature, the more the equilibrium shifts to the production of NO rather than NO_2.

Atmospheric NO_2 formation, on the other hand, is driven by photochemical oxidation of NO in the atmosphere at much lower temperatures, among other means (Bartok & Sarofim, 1991; Heywood, 1988; USEPA, 1999).

4.2.3 NO AND NO_X EMISSIONS

NO_x or NO concentration time series plots are presented in Figure 52, Figure 53 and Figure 54, with the exception of Batches 1, 7 and 13; which could not be obtained due to equipment breakdown and power failure. Histograms of NO_x/NO emissions are also shown in Figure 55 for each firing batch. All NO_x measurements for all batches recorded the same values as the NO, and since NO_2 is not released from the kiln (Section 4.2.2), it can be concluded that all NO_x emitted from the kiln is actually in NO form.

During Batches 3, 5, 8 and 11 firing cycle, measured NO concentration shows slight trends across batches, with concentration initiating at low levels, with a gradual rise in levels during the first and second quarter of the firing cycle; and reaching peak concentrations within 80 – 120 hours (i.e. second and third quarter of firing), and gradually falling again to low levels towards the end of the firing cycle. Batches 2, 4, 6, 9, 10 and 12 do not show any regularity across the firing duration. The measured NO concentrations for these batches do not exhibit any consistent trends; with concentrations initiating at mid-levels, rising and falling over the firing period. The initial mid-level concentrations observed during these batches may be attributed to combustion of the external fuel in the 'scintle' layer. A sudden and irregular spike in concentration level was also observed during Batch 2 firing. The cause of this could not be determined. In most cases, the concentrations show a positively skewed histogram (leaning towards lower emissions), typical of kiln combustion process which gradually ignites fuel in the bricks; and burning out over time.

Maximum, mean and minimum NO concentrations, as well as standard deviation from the mean, are presented in Table 24. The highest average emissions are recorded during Batches 2 and 12; while Batches 3 and 6 recorded the lowest average emissions across the firing period. The minimum concentration recorded was zero for all batches.

Table 24: NO emission summary

	NO Concentration (mg/m³)											
Batch	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Max.	68.0	10.0	10.0	11.0	19.0	ND	16.0	17.0	17.0	13.0	25.0	ND
Mean	6.0	2.8	1.5	1.2	3.8	ND	5.6	1.2	3.8	1.1	3.5	ND
SD	11.5	2.9	2.1	2.1	1.2	ND	5.0	2.4	4.4	2.1	4.6	ND
Median	2.5	2	0	0	0	0	4	0	1	0	1.5	ND
Min.	0.0	0.0	0.0	0.0	0.0	ND	0.0	0.0	0.0	0.0	0.0	ND

NOTE: "ND" implies "no data"; "SD" implies "standard deviation"; "Max." implies "maximum"; while "Min." implies "minimum"

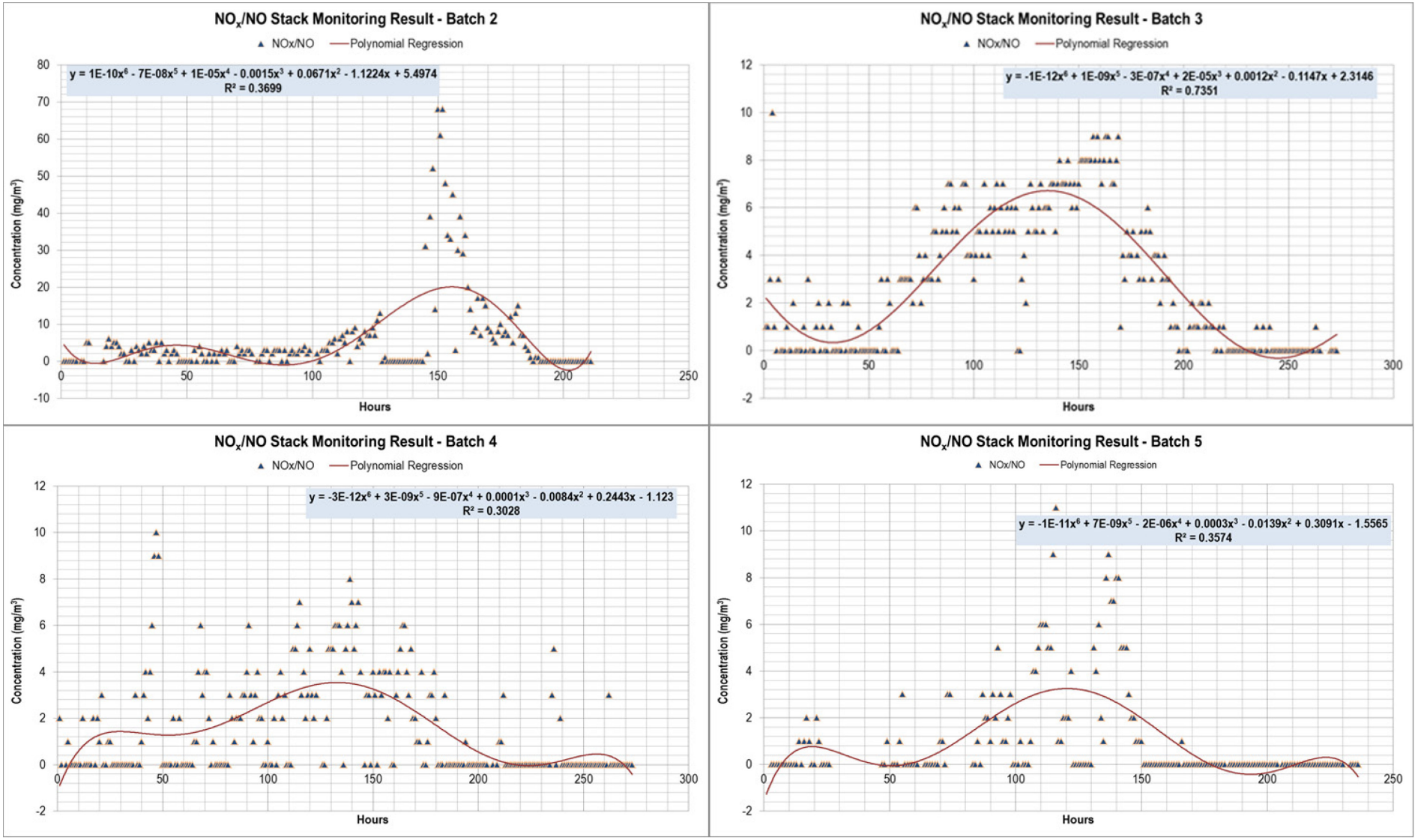


Figure 52: NO_x/NO emission concentration in mg/m^3 (Batches 2, 3, 4 and 5)

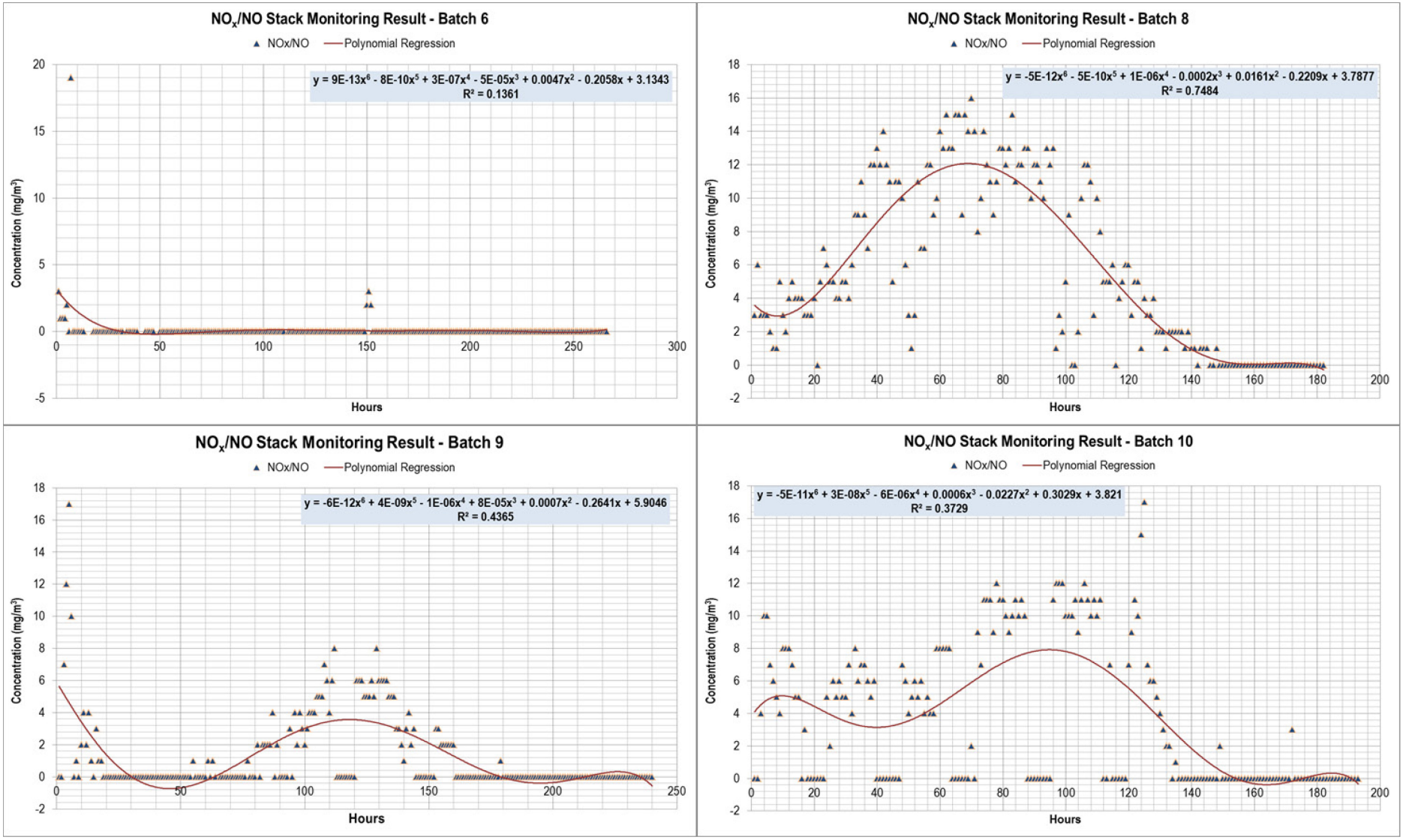


Figure 53: NO_x/NO emission concentration in mg/m^3 (Batches 6, 8, 9 and 10)

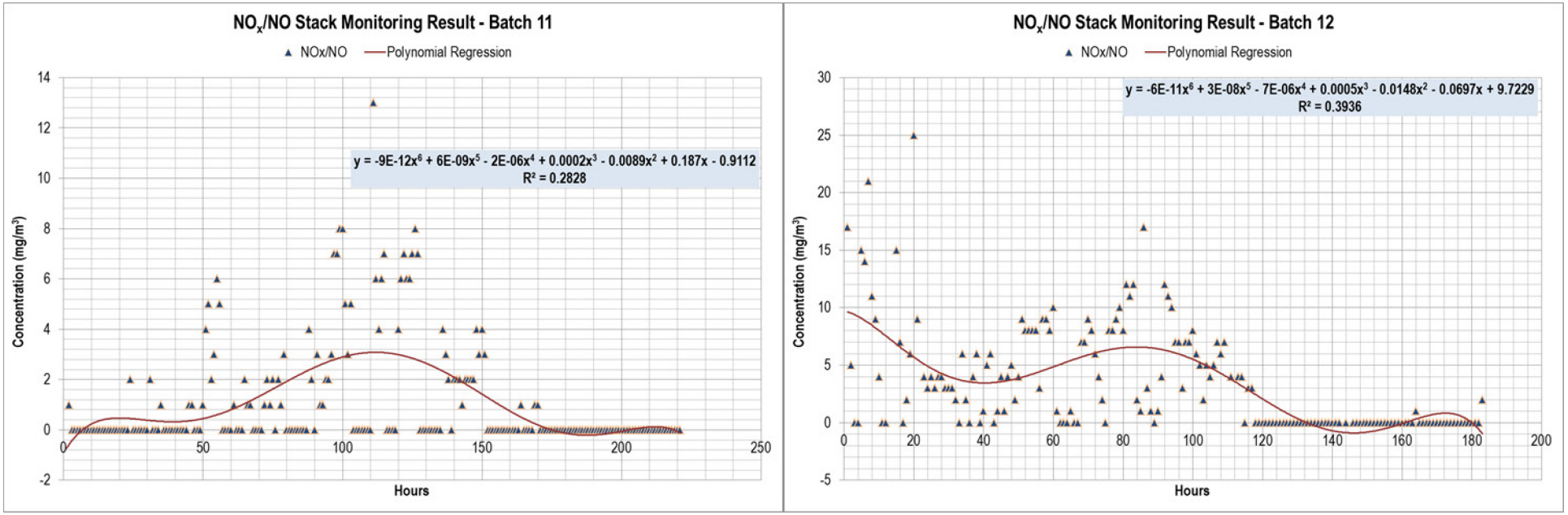


Figure 54: NO_x/NO emission concentration in mg/m^3 (Batches 11 and 12)

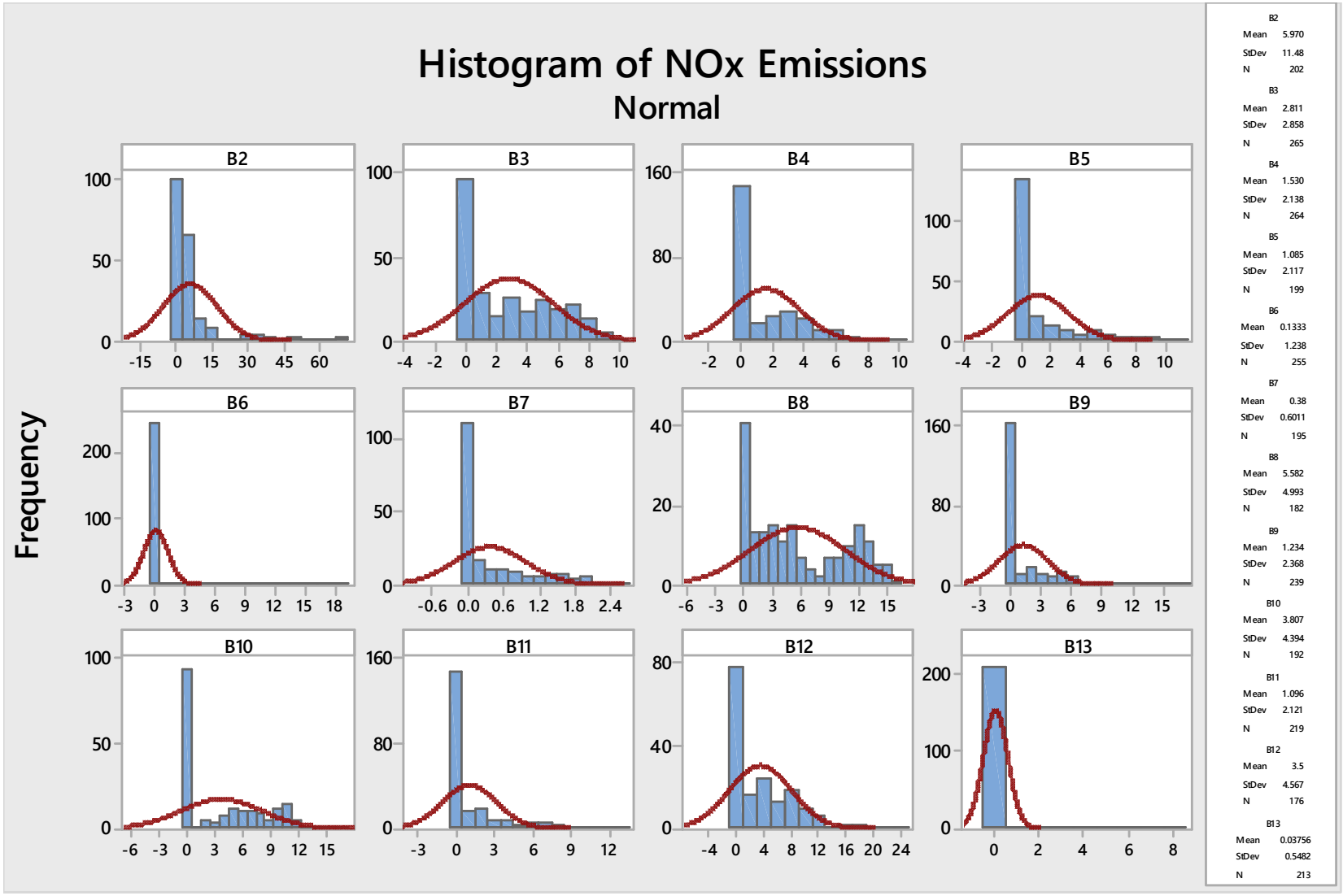


Figure 55: Histogram of NOx emission concentrations across Batch 2 to Batch 13

An NO/NO_x emission variability plot is shown in Figure 56 which indicates positively skewed NO/NO_x emissions (leaning towards lower NO/NO_x concentrations). Batches 3 and 8 displayed the best indication of consistent and steadier emissions over the firing period (shorter bars and a centred median is an indication of lower variability and steadier emissions). Batches 2, 6 and 12 show high levels of data variability, which suggest that these batches were inefficiently fired due to unevenly mixed fuel or inhomogeneous clay in raw bricks.

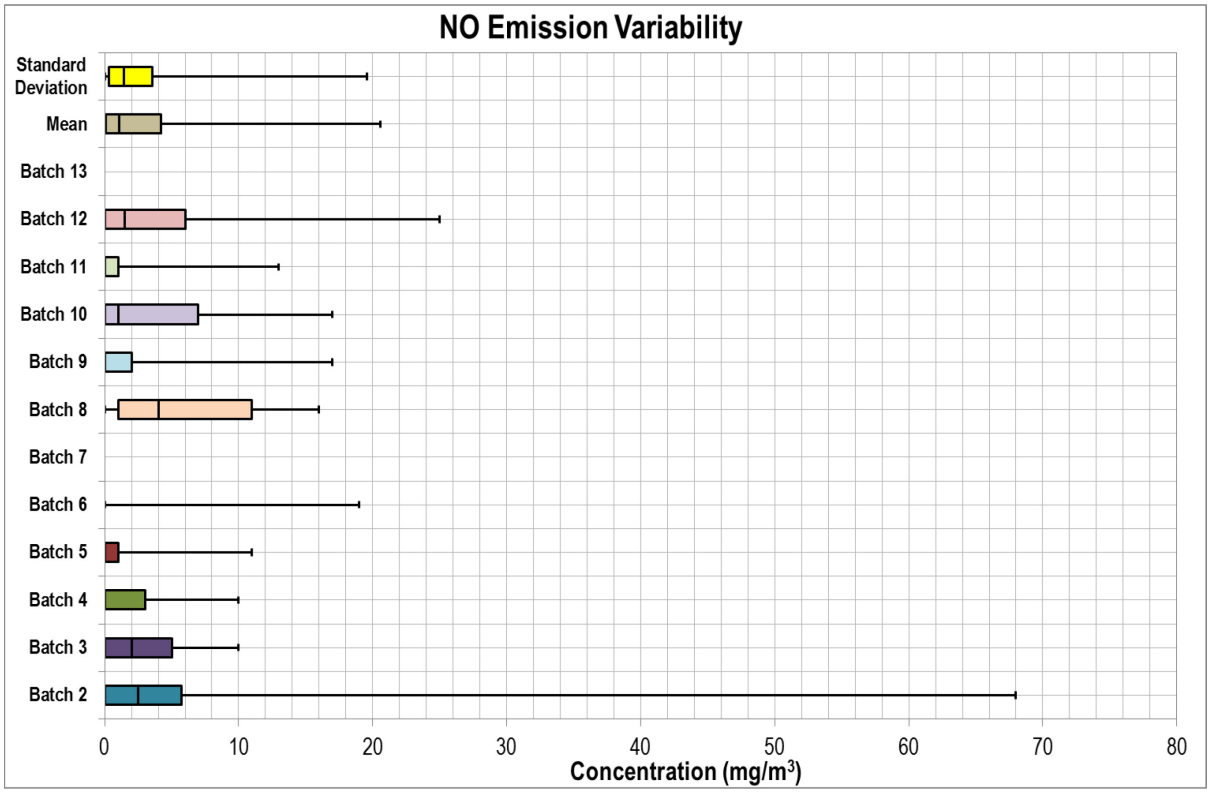


Figure 56: NO emission variability plot – Batches 3 and 8 displayed the best indication of consistent and steadier emissions over the firing period while Batches 2, 6 and 12 show high levels of data inconsistency

4.2.4 SO_2 Emissions

SO_2 concentration time series plots are presented in Figure 57, Figure 58 and Figure 59, excluding Batches 1, 6, 7 and 13; which could not be obtained due to equipment breakdown and power failure. Histograms of SO_2 emissions are also shown in Figure 60 for each firing batch. Measured SO_2 concentration shows similar trends across batches, with concentration initiating at low levels; gradually rising and reaching peak concentrations within 80 – 120 hours (i.e. second and third quarter of firing duration), and gradually falling again to low levels towards the end of the firing cycle. In most cases, the concentrations show a positively skewed histogram (leaning towards lower emissions), also typical of kiln combustion process which gradually ignites fuel and sulfur compounds in the bricks; and burning out over time. Occasional spikes in SO_2 levels are observed at the start of the firing cycle, which is an indication of the release of sulfur from combustion of the fire-box and the external fuel in the 'scintle' layer. Thereafter, consistent zero emission is recorded for a period lasting 3 – 6 days across different batches, and then a sudden and consistent spike in levels is recorded, peaking within 1 – 2 days and

dipping again to ambient levels towards the end of the firing cycle. The sudden spike in SO_2 levels is most likely due to the oxidation of the pyrite component (FeS_2) in the clay material, oxidation of the sulfur component of the internal fuel (coal that is mixed with the clay material during brick processing) and the dissociation of $CaSO_4$ in an oxidizing environment within the clay material to release SO_2 (refer to Section 2.2).

SO_2 maximum, mean and minimum emission concentrations, as well as standard deviation from the mean, are presented in Table 25. The highest average emissions are recorded during Batches 2 and 12; while Batches 3, 4 and 5 recorded the lowest average emissions across the firing period. The minimum concentration recorded was zero for all batches.

Table 25: SO_2 emission summary

	SO_2 Concentration (mg/m^3)											
Batch	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Max.	416	82.0	41.0	84.0	ND	ND	190	124	147	239	396	ND
Mean	34.5	12.0	7.8	10.1	ND	ND	45.1	16.8	43.2	24.2	75.6	ND
SD	72.3	22.4	12.0	18.3	ND	ND	50.9	30.3	47.1	45.2	108	ND
Median	0	0	0	0	0	0	23.5	0	23	0	16.5	ND
Min.	0.0	0.0	0.0	0.0	ND	ND	0.0	0.0	0.0	0.0	0.0	ND

NOTE: "ND" implies "no data"; "SD" implies "standard deviation"; "Max." implies "maximum"; while "Min." implies "minimum"

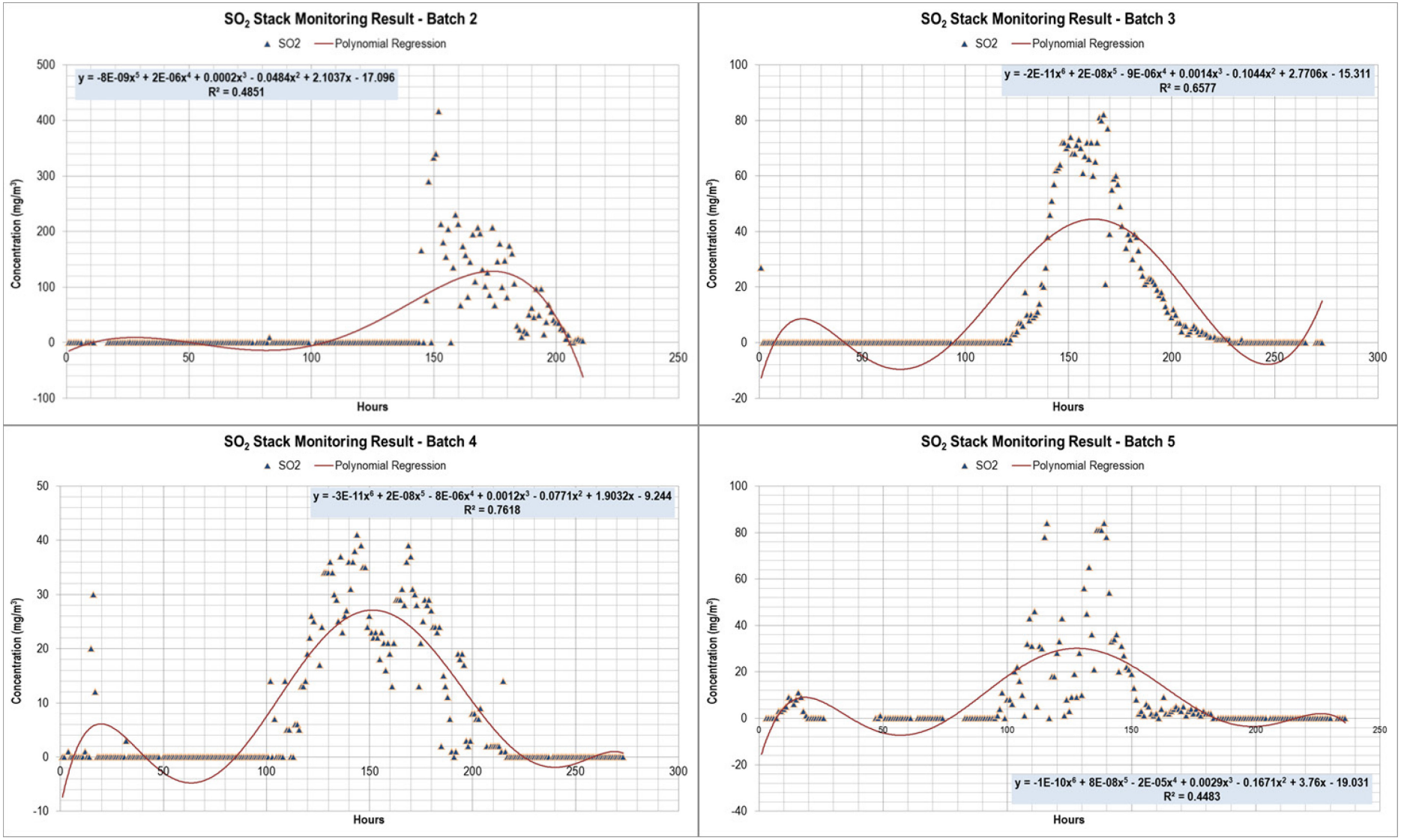


Figure 57: SO_2 emission concentration in mg/m^3 (Batches 2, 3, 4 and 5)

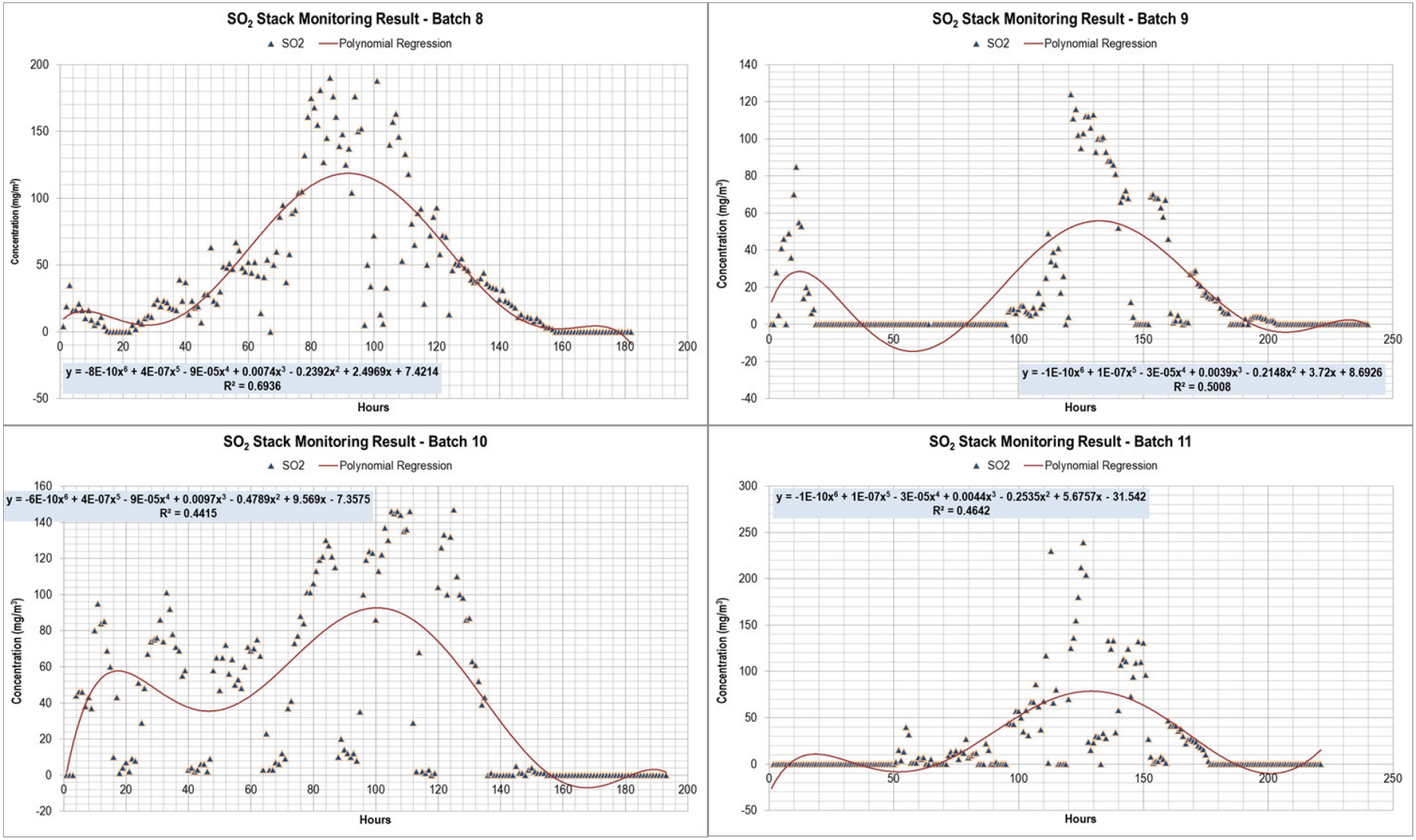


Figure 58: SO_2 emission concentration in mg/m^3 (Batches 8, 9, 10 and 11)

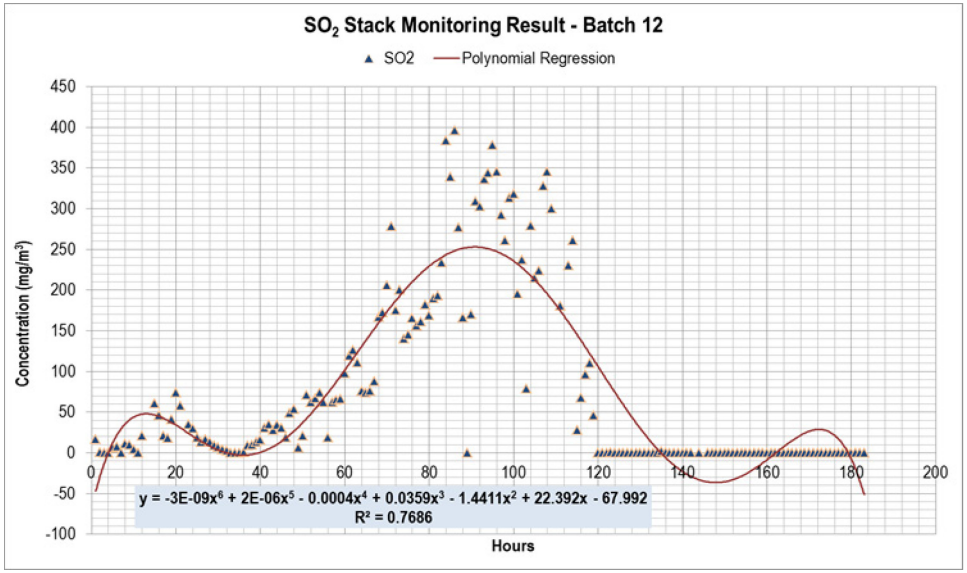


Figure 59: SO_2 emission concentration in mg/m^3 (Batches 12)

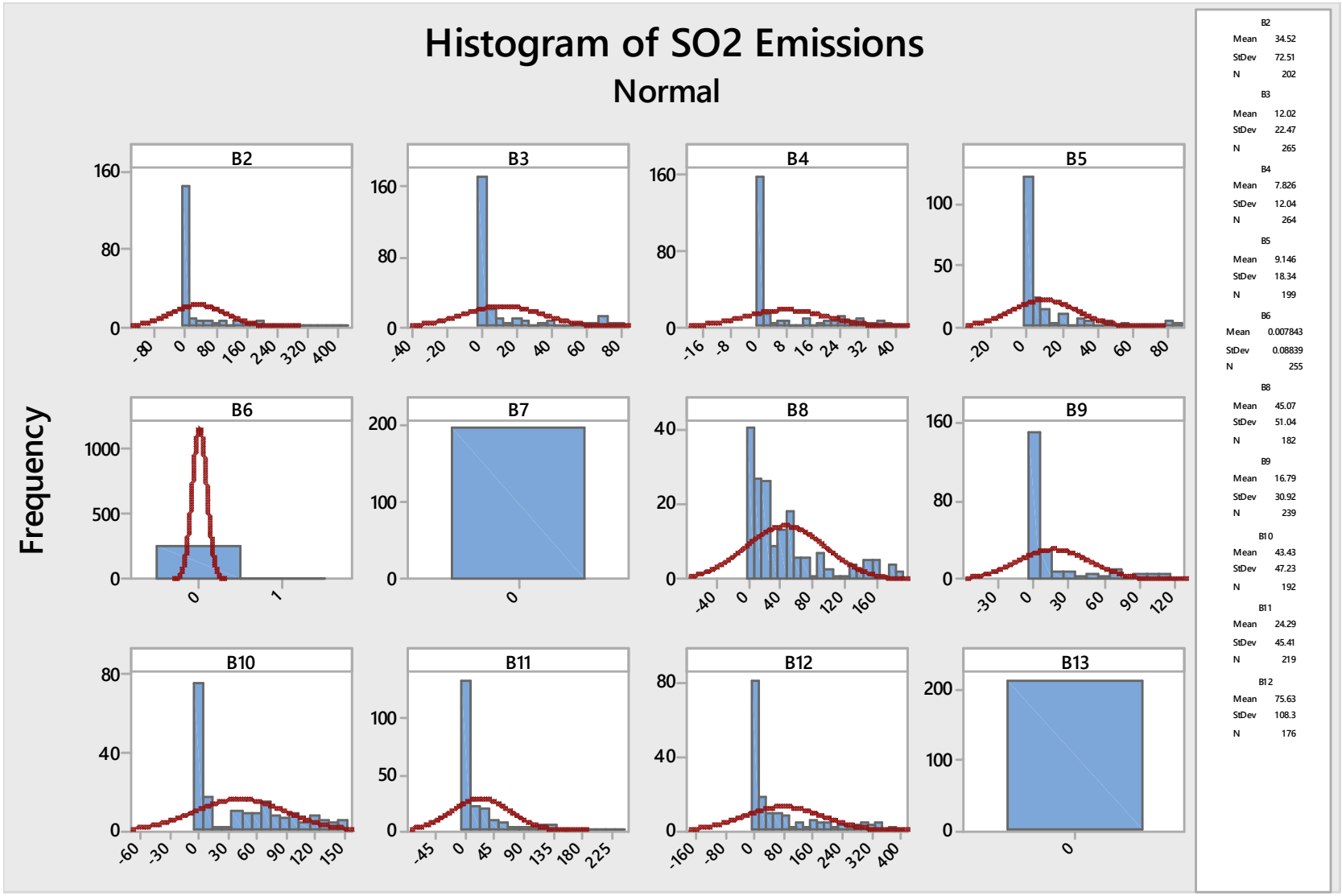


Figure 60: Histogram of SO_2 emission concentrations across Batch 2 to Batch 13

An SO_2 emission variability plot is shown in Figure 61 which indicates positively skewed SO_2 emissions (leaning towards lower SO_2 concentrations). Batch 8 displays the best indication of consistent emissions over the firing period (since shorter bars and a centred median in the variability plot is an indication of lower variability and steadier emissions). Batches 2, 10 and 12 show extreme levels of data variability, which suggest that these batches were inefficiently fired.

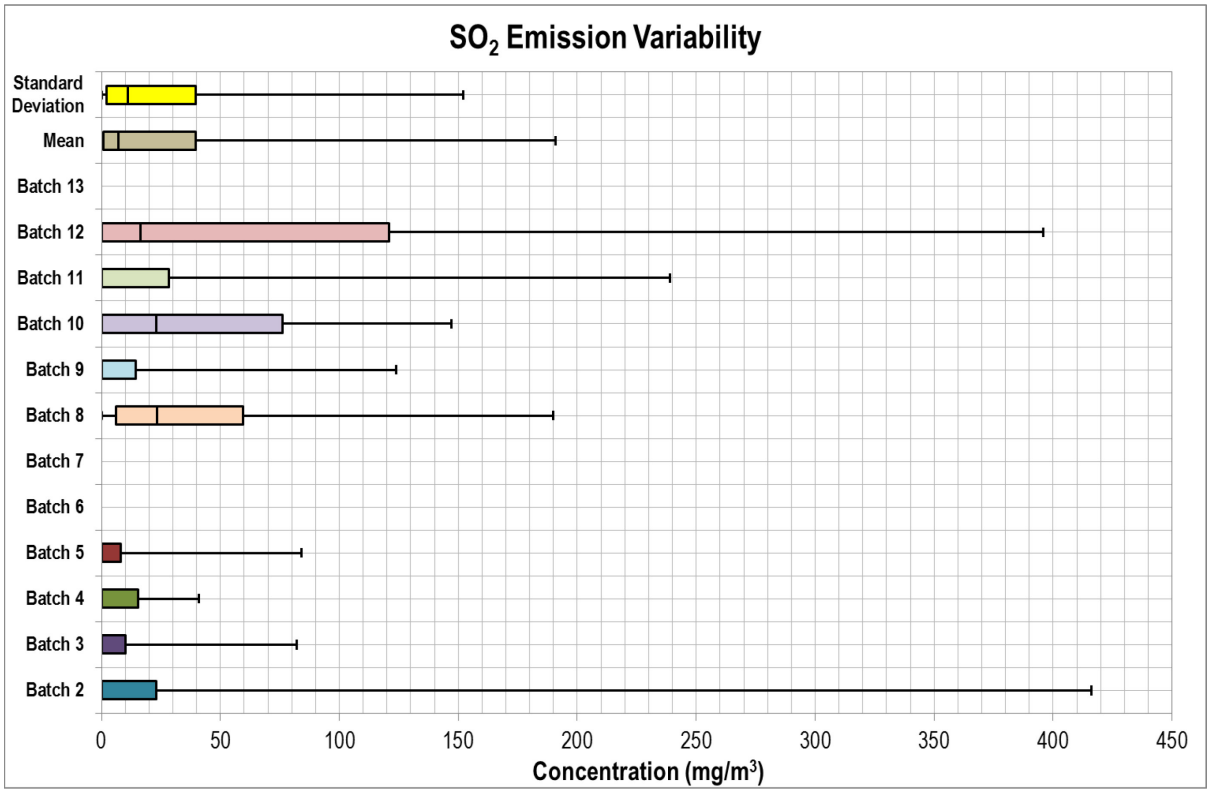


Figure 61: SO_2 emission variability plot – Batch 8 displays the best indication of consistent emissions over the firing period, while Batches 2, 10 and 12 shows an extreme level of data inconsistency

4.2.5 PM Emissions

4.2.5.1 PM_{10} Emissions (SidePak Monitor)

PM_{10} emission measurement for Batch 2 to Batch 13 was taken with the SidePak monitor, as described in Section 3.3.2. Measured PM_{10} concentration time series plots (uncorrected) are presented in Figure 62, Figure 63 and Figure 64, with the exception of Batch 1; which could not be obtained due to equipment breakdown. Histograms of PM_{10} emissions are also shown in Figure 65 for each firing batch.

Measured PM_{10} concentration does not exhibit any consistent trend, with concentration initiating at mid to high levels, rising and falling over the firing period. In most cases, the concentrations show a positively skewed histogram (leaning towards lower emissions), typical of kiln combustion process which gradually ignites fuel and release particulates as combustion proceeds; and burns out over time.

Uncorrected PM_{10} maximum, mean and minimum emission concentrations, as well as standard deviation from the mean, are presented in Table 26. The highest average emissions are recorded during Batches 2, 12 and 13; while Batches 5 and 8 recorded the lowest average emissions across the firing period. The minimum concentration recorded was zero for all batches. It is also noted that since there is no clear trend of high values at the start of the firing cycle indicate that the external fuel does not contribute disproportionally to PM emissions.

Table 26: PM_{10} emission summary

	PM_{10} Concentration (mg/m^3)											
Batch	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Max.	19.0	19.5	17.6	18.3	19.5	17.3	16.8	19.0	11.1	9.8	19.4	18.9
Mean	10.4	4.7	4.1	2.8	3.4	3.9	2.7	3.6	4.9	6.1	6.6	6.6
SD	6.8	4.6	5.0	3.9	5.3	4.3	3.8	4.7	3.9	4.2	4.6	3.8
Median	9.6	3.9	0.3	0.0	0.0	0.2	0.0	0.0	6.3	6.7	10.3	7.2
Min.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

NOTE: **"**ND" implies "no data"; "SD" implies "standard deviation"; "Max." implies "maximum"; while "Min." implies "minimum"

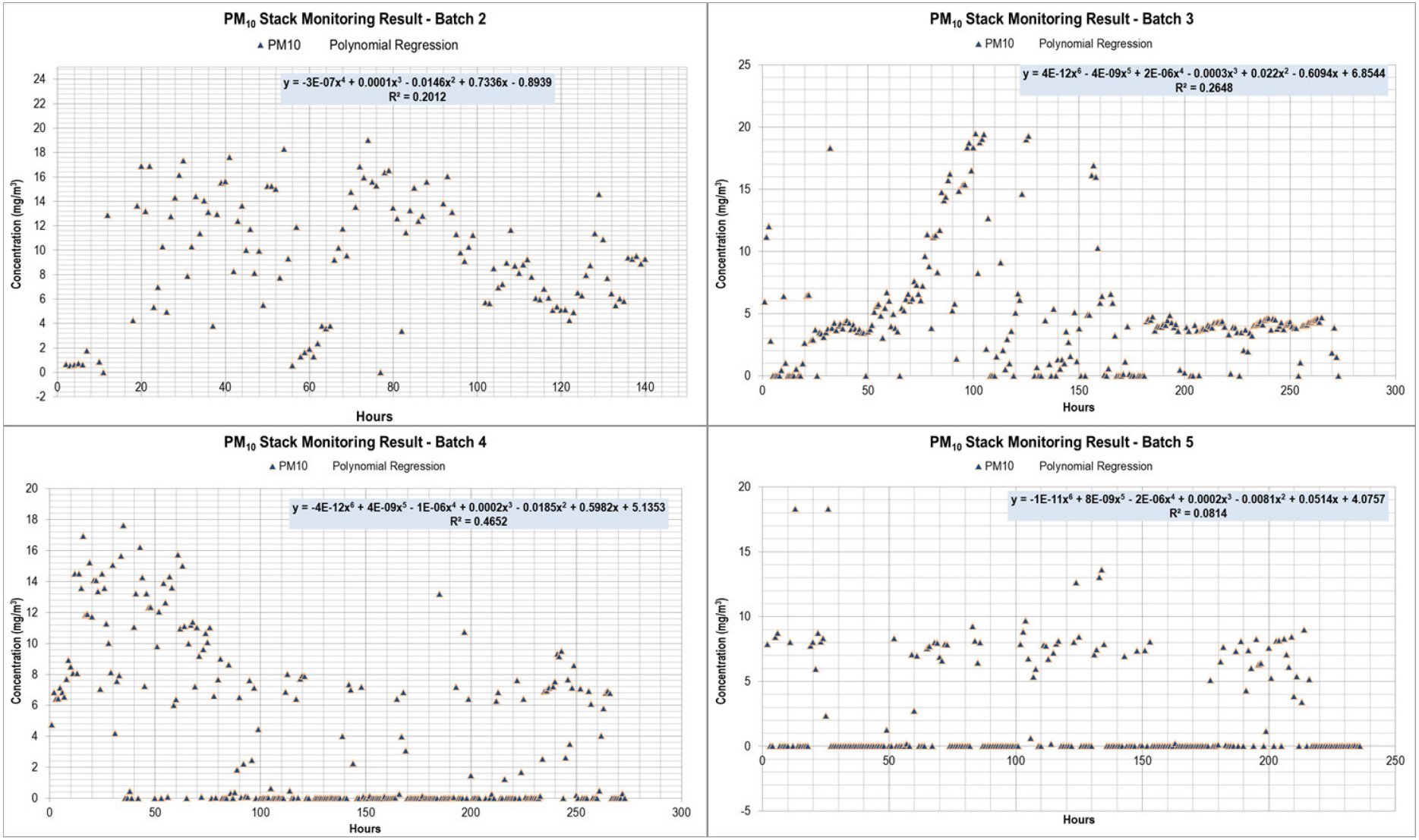


Figure 62: PM_{10} emission concentrations in mg/m^3 – SidePak monitor (Batches 2, 3, 4 and 5)

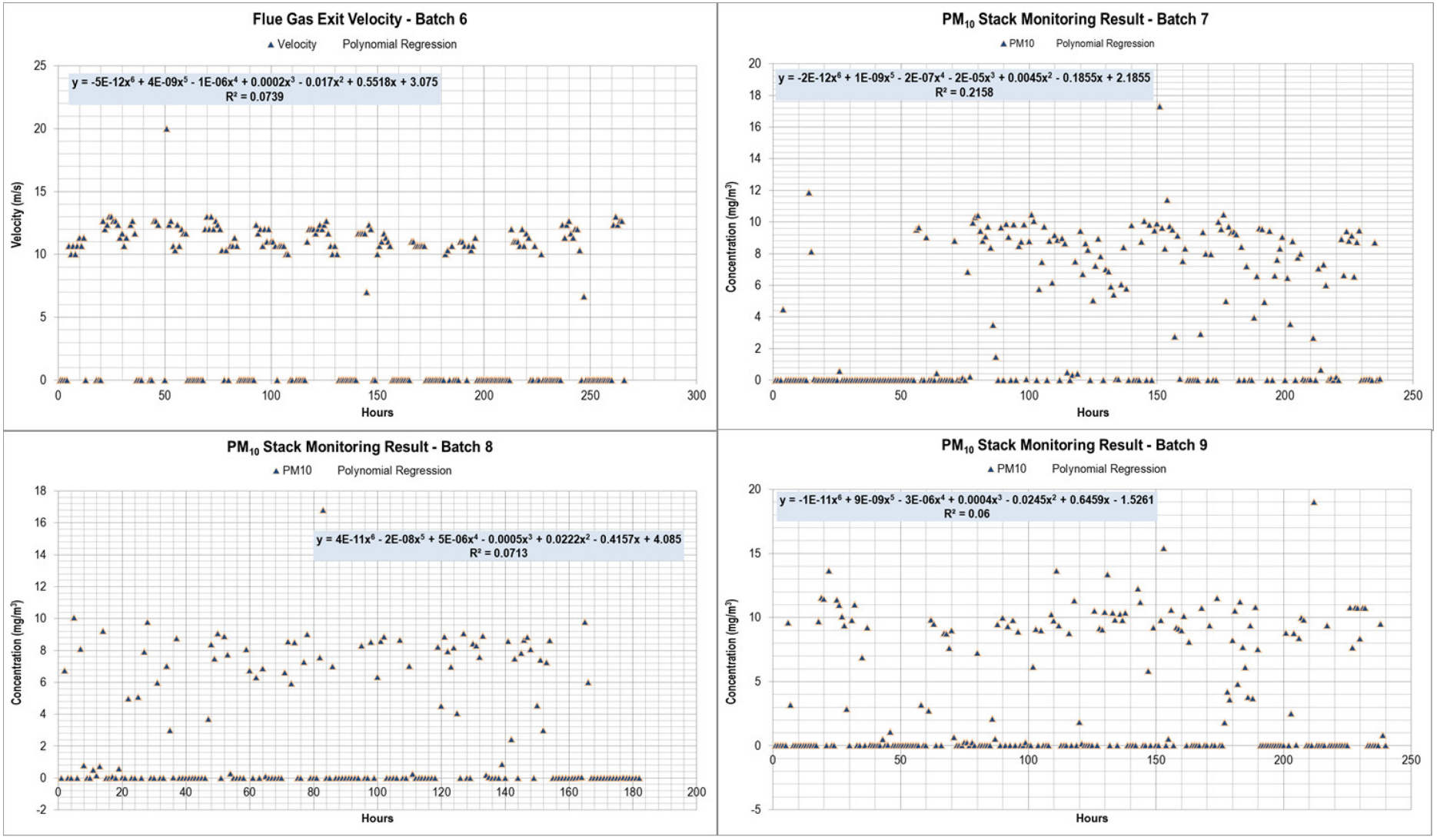


Figure 63: PM_{10} emission concentrations in mg/m^3 – SidePak monitor (Batches 6, 7, 8 and 9)

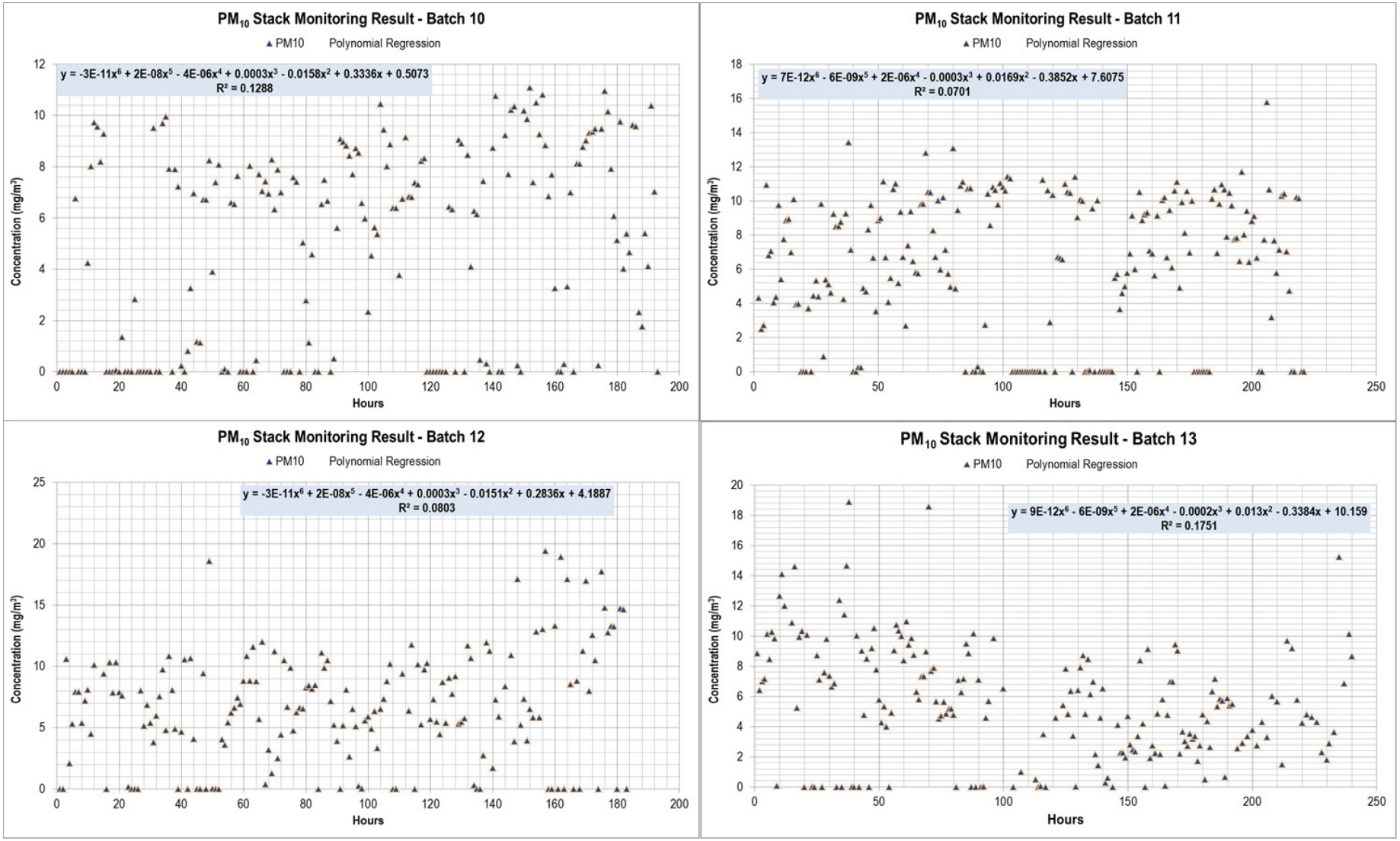


Figure 64: PM_{10} emission concentrations in mg/m^3 – SidePak monitor (Batches 10, 11, 12 and 13)

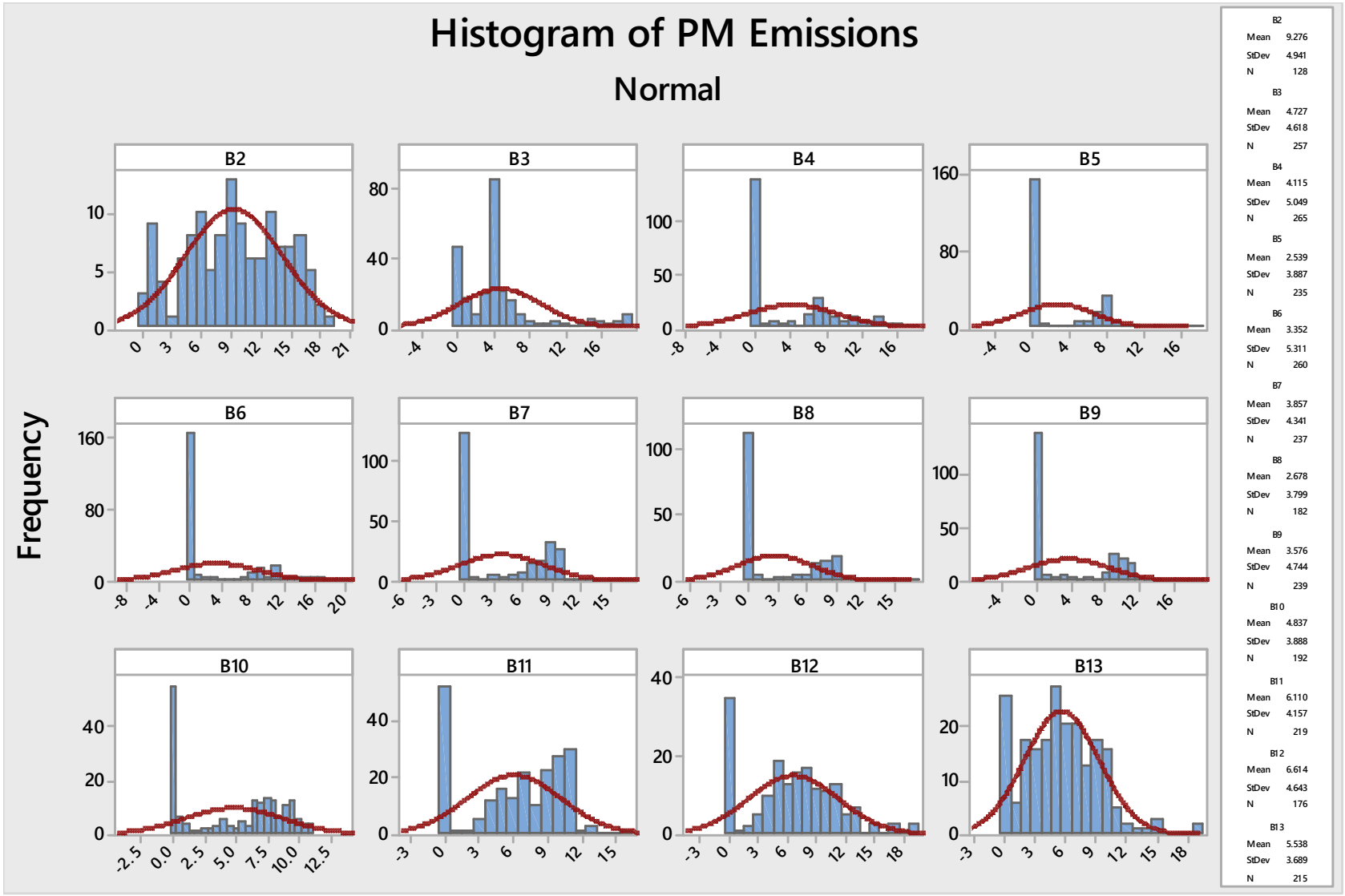


Figure 65: Histogram of PM emission concentrations across Batch 2 to Batch 13

4.2.5.2 PM EMISSIONS (DUSTTRAK MONITOR)

During Batch 13 firing campaign, the DustTrak Monitor (described in Section 3.3.2) was also utilized in measuring PM emissions alongside the SidePak monitor. Measured PM_{10} concentration is presented in Figure 66, comparing the concentrations measured by the DustTrak and SidePak monitors. A positive Spearman rank correlation coefficient of 0.61 suggests a strong rank correlation between the DustTrak and SidePak monitors measurement values. Consequently, a PM_{10} adjustment factor of **7.61** was obtained by comparing PM_{10} results from the SidePak and DustTrak monitors during Batch 13 firing. This was done to account for the lower sampling range of the SidePak (refer to Section 3.3.2).

Also, a concentration/hour chart is presented in Figure 67, demonstrating uncorrected size segregated PM fraction patterns corresponding to PM_1, $PM_{2.5}$, respirable or PM_4, PM_{10}, and PM_{Total} (PM_{15}). The size segregated mass fraction distribution showed similar trends when compared with those in literature (TSI Incorporated, 2014b).

Adjusted PM_{10} maximum, mean and minimum emission concentrations, as well as standard deviation from the mean, are presented in Table 27. PM size-segregated mass fractions measured during Batch 13 using the DustTrak Monitor is presented in Table 28; while the percentages of these PM size-segregated mass fractions are presented in Table 29. The high percentages of PM_1, $PM_{2.5}$, respirable or PM_4 and PM_{10} fractions indicate that combustion-related particulates is composed of extremely fine PM (since it is made up of nucleotides and particles that are yet to coagulate in the atmosphere).

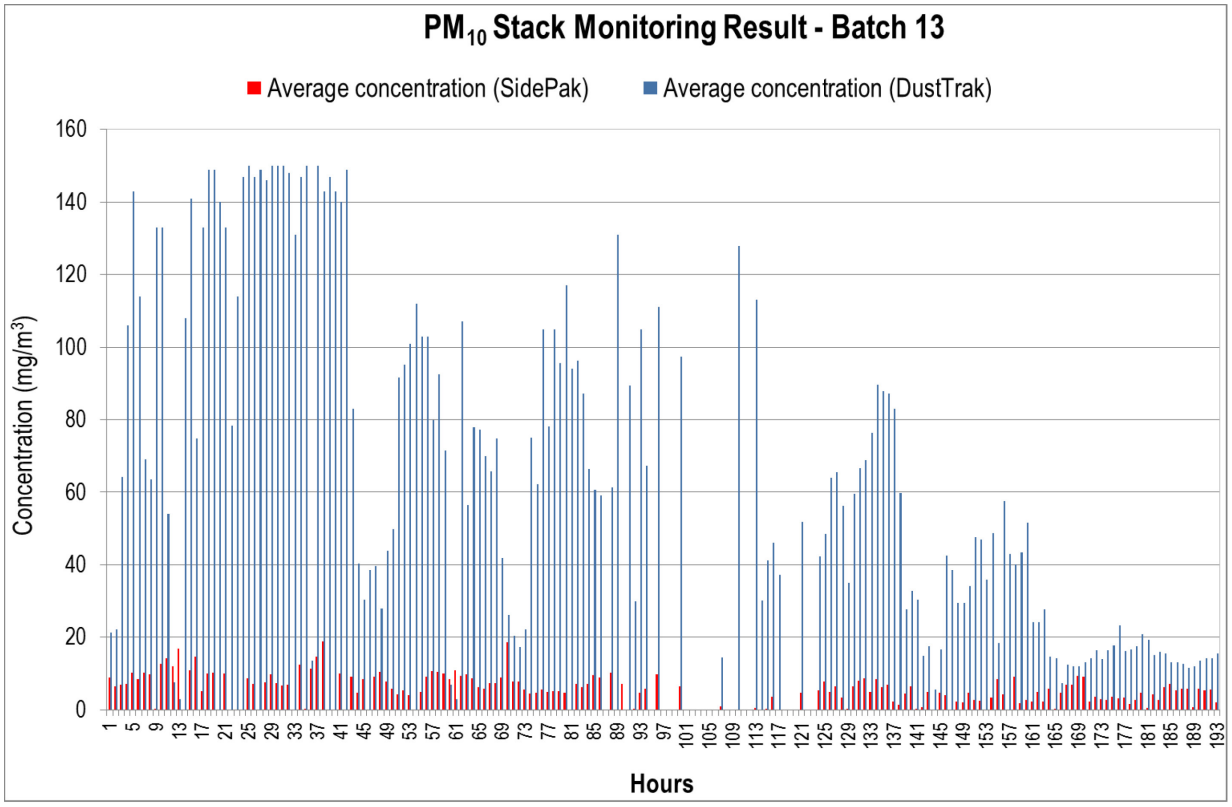


Figure 66: Uncorrected PM_{10} emission concentrations in mg/m³ during Batch 13 (DustTrak and SidePak monitors)

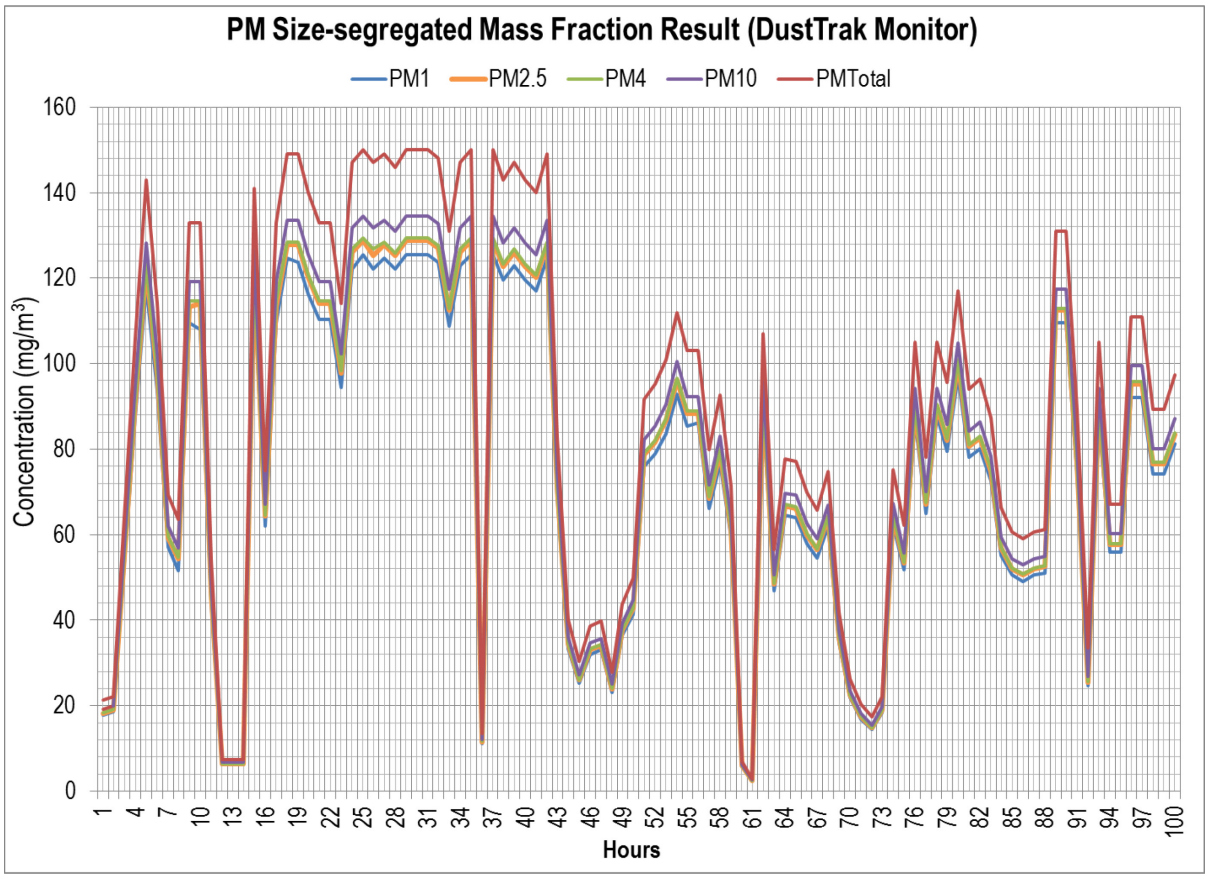


Figure 67: Uncorrected PM Size-segregated mass fraction – Batch 13 (DustTrak Monitor)

Table 27: Adjusted PM_{10} emissions summary based on SidePak to DustTrak adjustment factor of 7.61 (Batch 2 to Batch 13)

	Adjusted PM_{10} Concentration (mg/m^3)											
Batch	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Max.	140.8	144.5	130.4	135.6	144.5	128.2	124.5	140.8	82.3	72.6	143.8	140.1
Mean	77.1	34.8	30.4	20.7	25.2	28.9	20.0	26.7	36.3	45.2	48.9	48.9
SD	50.4	34.1	37.1	28.9	39.3	31.9	28.2	34.8	28.9	31.1	34.1	28.2
Min.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

NOTE: "SD" implies "standard deviation"; "Max." implies "maximum"; while "Min." implies "minimum"

Table 28: PM size-segregated mass fractions – Batch 13 (DustTrak Monitor)

Size-segregated PM Concentrations from DustTrak (mg/m^3) – Batch 13					
	PM_1	**$PM_{2.5}$**	**PM_4**	**PM_{10}**	**PM_{15}**
Maximum	150.00	150.00	150.00	150.00	150.00
Mean	50.28	50.49	50.51	50.51	50.53
SD	46.22	46.44	46.47	46.47	46.46
Minimum	0.00	0.00	0.00	0.00	0.00

NOTE: "SD" implies "standard deviation"

Table 29: PM size-segregated mass fractions as a percentage of Total PM – Batch 13 (DustTrak Monitor)

	Mass Percentage of PM_{15}				
	PM_1	$PM_{2.5}$	PM_4	PM_{10}	PM_{15}
Maximum Concentration	100.00%	100.00%	100.00%	100.00%	100.00%
Mean Concentration	99.51%	99.92%	99.95%	99.96%	100.00%

A PM_{10} emission variability plot is shown in Figure 68 which indicates positively skewed PM_{10} emissions (leaning towards lower PM_{10} concentrations). Batch 3 displays the best indication of consistent emissions over the firing period (shorter bars and a centred median in the variability plot is an indication of lower variability and steadier emissions). Batches 11, 12 and 13 also exhibit a certain level of data consistency. Batches 2, 4, 5, 6, 7, 8, 9 and 10 do not exhibit any form of data consistency.

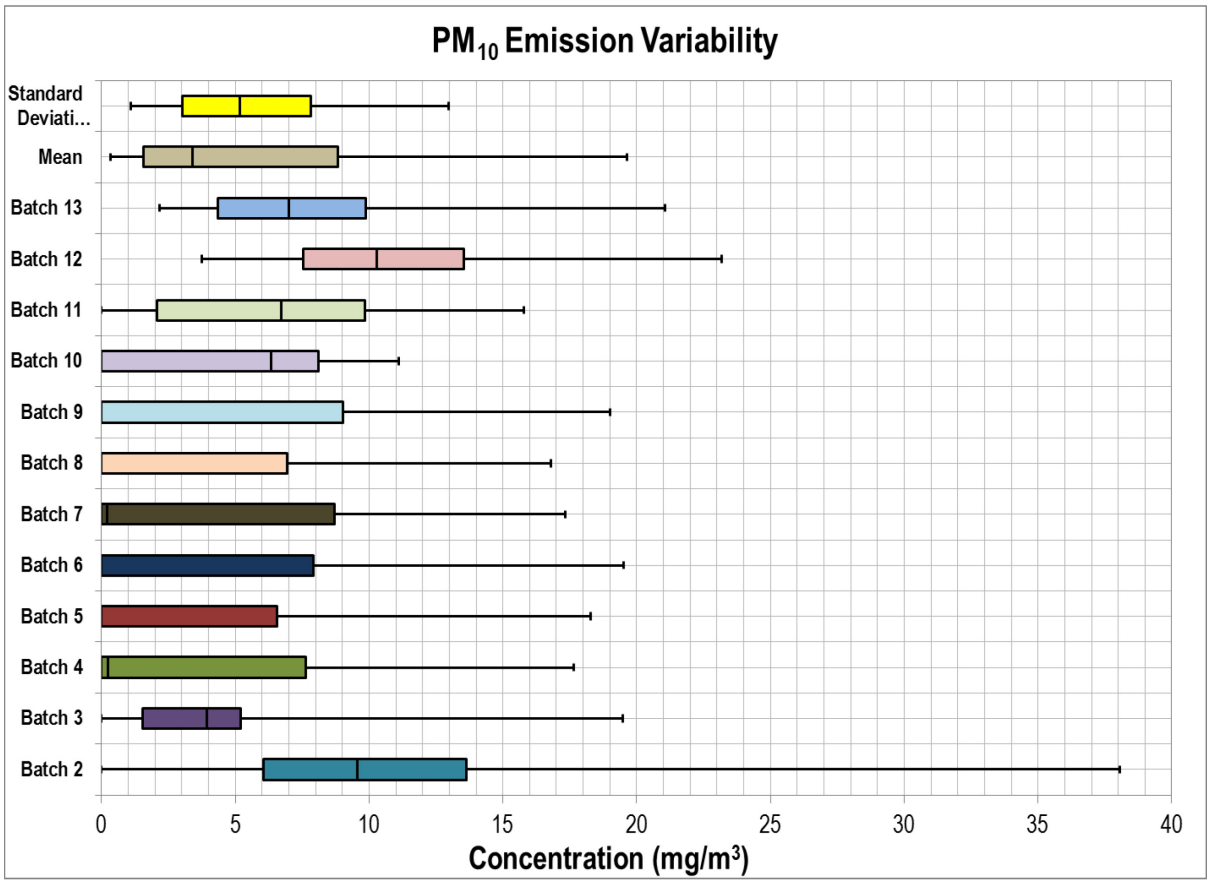


Figure 68: PM_{10} emission variability plot – Batch 3 displays the best indication of consistent emissions, while Batches 11, 12 and 13 also exhibit a certain level of consistency. Batches 2, 4, 5, 6, 7, 8, 9 and 10 do not exhibit any form of data consistency over the firing period

4.2.5.3 Correction of PM Concentration to Gravimetric Measurement

In order to correct PM concentration obtained from the DustTrak and SidePak monitors to gravimetric concentrations, a calibration factor of 0.61 was obtained (refer to Section 3.3.2.1). This calibration factor is used to

correct the PM concentration in Table 27 and Table 28. Corrected PM concentrations are presented in Table 30 and Table 31.

Table 30: PM_{10} emissions summary based on gravimetric correction factor of 0.61 (Batch 2 to Batch 13)

	Adjusted PM_{10} Concentration (mg/m^3)											
Batch	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Max.	85.9	88.1	79.5	82.7	88.1	78.2	75.9	85.9	50.2	44.3	87.7	85.5
Mean	47.0	21.2	18.5	12.6	15.4	17.6	12.2	16.3	22.1	27.6	29.8	29.8
SD	30.7	20.8	22.6	17.6	24.0	19.5	17.2	21.2	17.6	19.0	20.8	17.2
Min.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

NOTE: "SD" implies "standard deviation"; "Max." implies "maximum"; while "Min." implies "minimum".

Table 31: PM size-segregated mass fractions based on gravimetric correction factor of 0.61 (Batch 13)

Size-segregated PM Concentrations from DustTrak (mg/m^3) – Batch 13					
	PM_1	**$PM_{2.5}$**	**PM_4**	**PM_{10}**	**PM_{15}**
Maximum	91.5	91.5	91.5	91.5	91.5
Mean	30.7	30.8	30.8	30.8	30.8
SD	28.2	28.3	28.3	28.3	28.3
Minimum	0.0	0.0	0.0	0.0	0.0

NOTE: "SD" implies "standard deviation"

4.2.6 HYDROCARBON EMISSIONS

During Batch 7 firing campaign, the ENERAC Gas analyser (described in Section 3.3.3) was utilized in measuring hydrocarbon (HC) emissions. The mean and standard deviation of measured HC concentration (calibrated to propane) is presented in Table 32, indicating high concentration variability.

Table 32: Hydrocarbon emissions (calibrated to propane)

Batch 7 – Hydrocarbon emission concentration (calibrated to propane)		
	ppm	**mg/m^3 (calculated)**
Mean	25.0	48.6
Standard deviation	30.0	58.3

4.2.7 FLUE GAS TEMPERATURE

Flue gas temperature time series plots are presented in Figure 69, Figure 70 and Figure 71, excluding Batches 1 and 7; which could not be obtained due to equipment breakdown. Histograms of temperature levels are also shown in Figure 72 for each firing batch. Temperature profiles show similar trends across batches, with temperature levels initially at ambient levels; gradually rising and reaching the peak within 120 – 150 hours (i.e. third quarter of firing duration), and gradually falling again to low levels towards the end of the cycle. Temperature levels show a

positively skewed histogram (leaning towards lower temperature levels), also typical of kiln combustion process. The lower temperature observation at the start of the firing cycle may be attributed to the heat of combustion initially being utilized in drying and heating the layers of brick, until drying is completed and the internal fuel in the brick is ignited. In addition, occasional spike in temperature levels are observed at the start of the firing cycle, which is an indicator to the heat release due to combustion of the external fuel in the 'scintle' layer.

A rise and fall in temperature levels, following a diurnal and nocturnal temperature rise and dip is observed in all the batches. This rise and fall in temperature levels are observed from the start of the firing cycle and follows the flue gas temperature rise and fall over the entire cycle, until ambient temperatures are maintained. Batch 3, again, shows the best indication of the diurnal and nocturnal temperature rise and dip, a trend which is better demonstrated in some batches than the others.

Maximum, mean and minimum flue gas temperatures, as well as standard deviation from the mean, are presented in Table 33. The highest average emissions are recorded during Batches 2 and 12; while Batches 3, 4 and 5 recorded the lowest average emissions across the firing period. The minimum temperatures recorded were at ambient levels, ranging from 7 – 25 ^{o}C for all batches.

Table 33: Flue gas temperature summary

	Flue gas temperature summary (^{o}C)											
Batch	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Max.	409	167	181	217	136	ND	202	143	194	214	344	137
Mean	122	68	86	86	76	ND	90	56	92	80	115	76
SD	103	44	51	53	28	ND	53	38	44	60	84	43
Median	69	49	61	68	76	ND	76.5	44	80	62	77	68.5
Min.	16	17	15	14	25	ND	16	9	20	7	15	20

NOTE: "ND" implies "no data"; "SD" implies "standard deviation"; "Max." implies "maximum"; while "Min." implies "minimum"

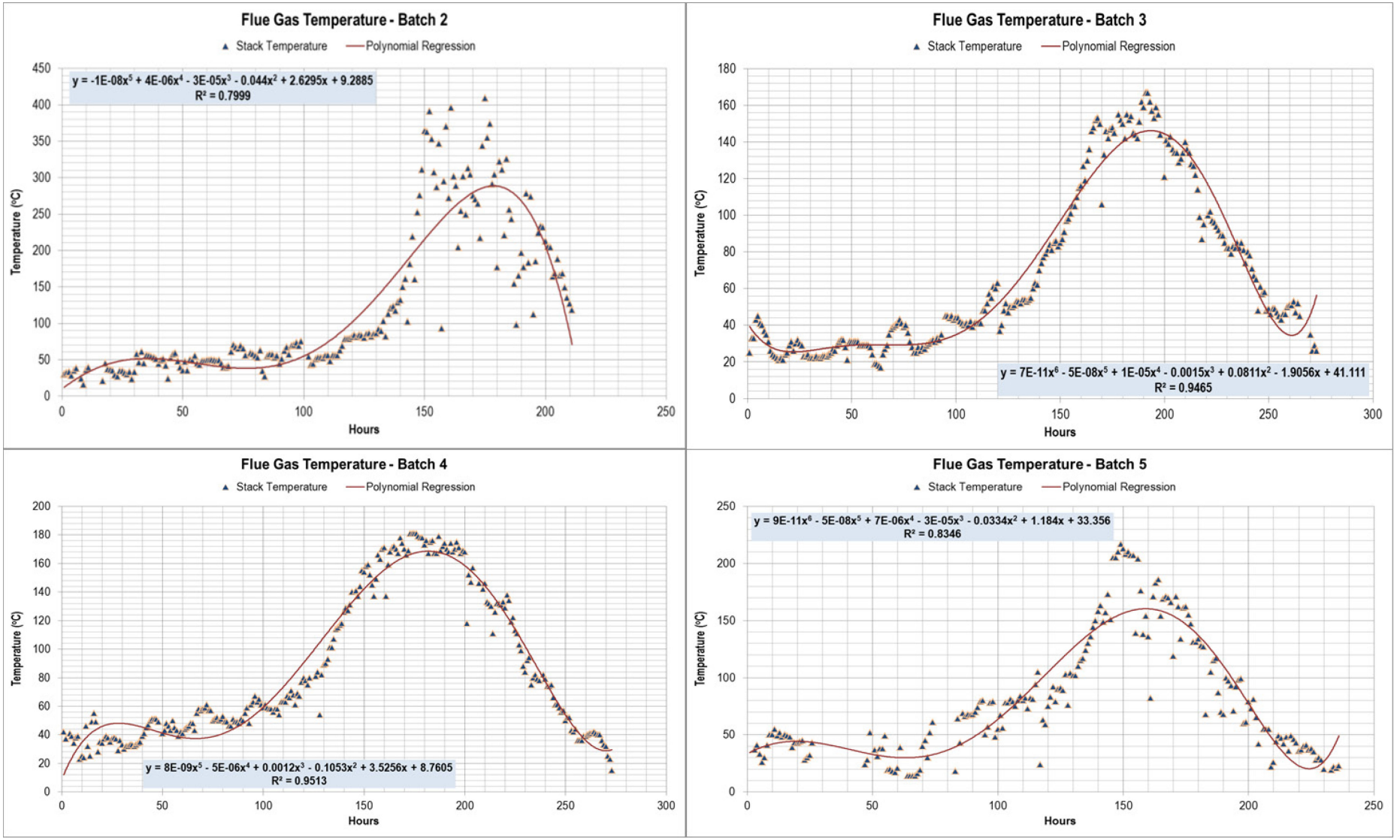


Figure 69: Flue gas temperature in °C (Batches 2, 3, 4 and 5)

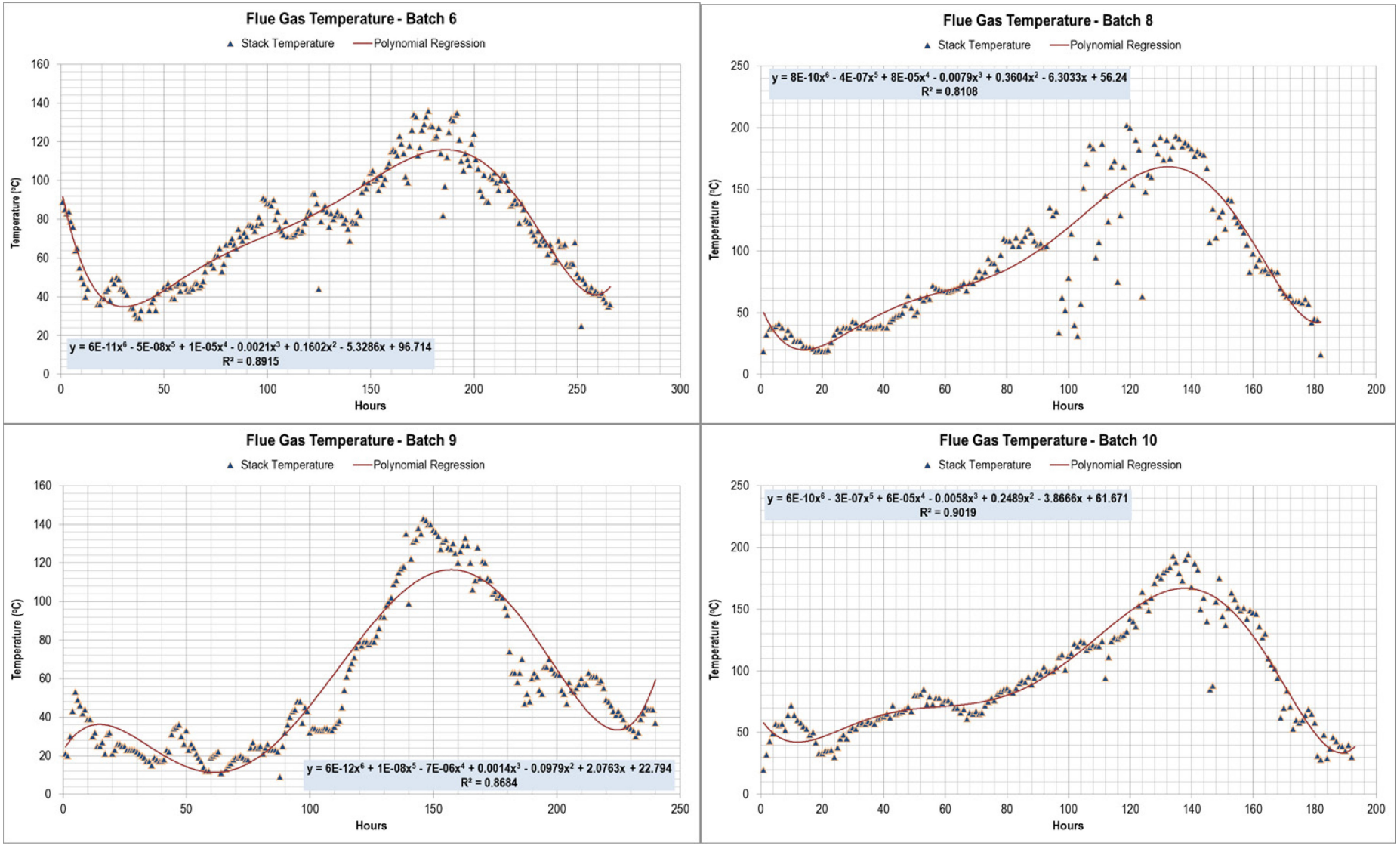


Figure 70: Flue gas temperature in °C (Batches 6, 8, 9 and 10)

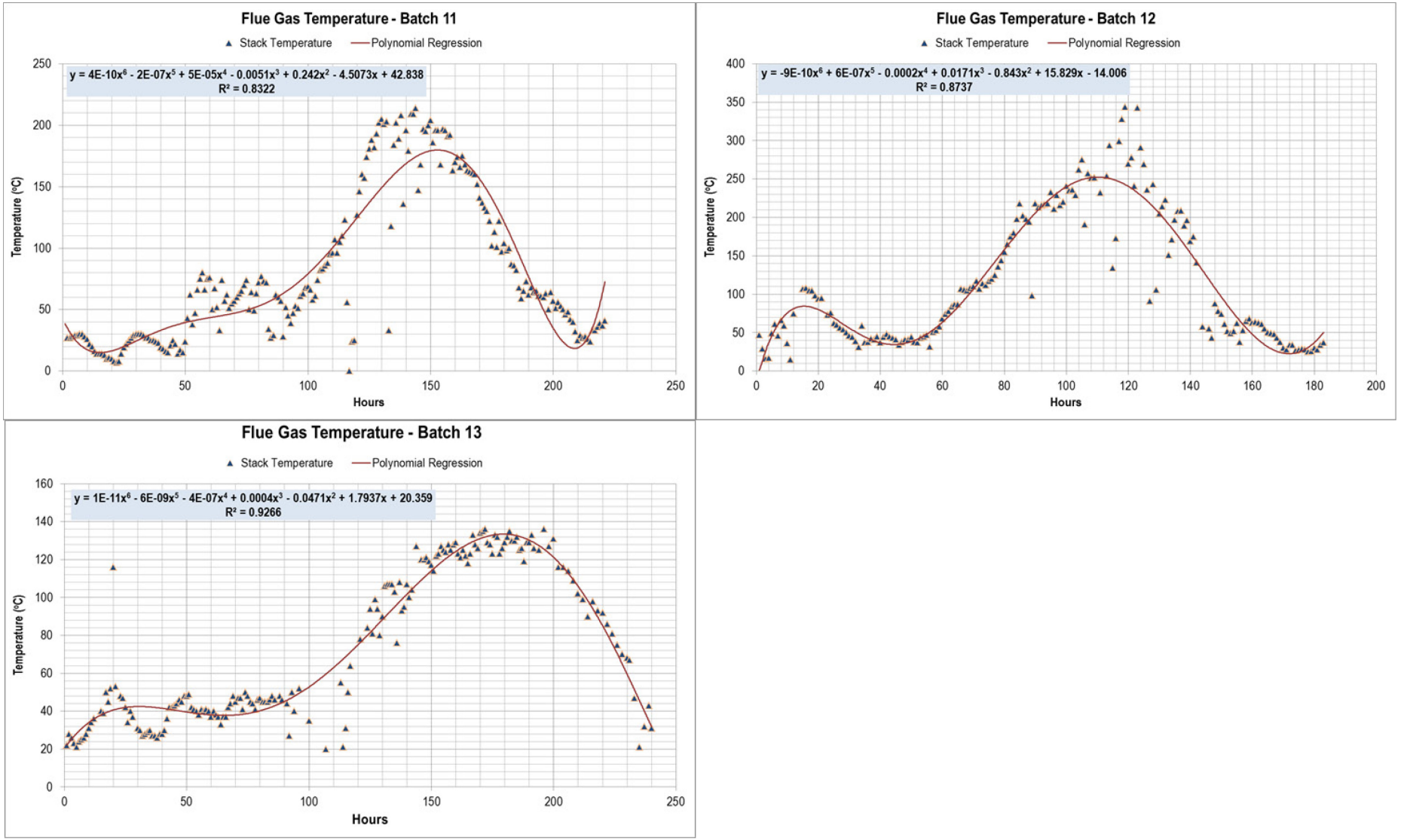


Figure 71: Flue gas temperature in ºC (Batches 11, 12 and 13)

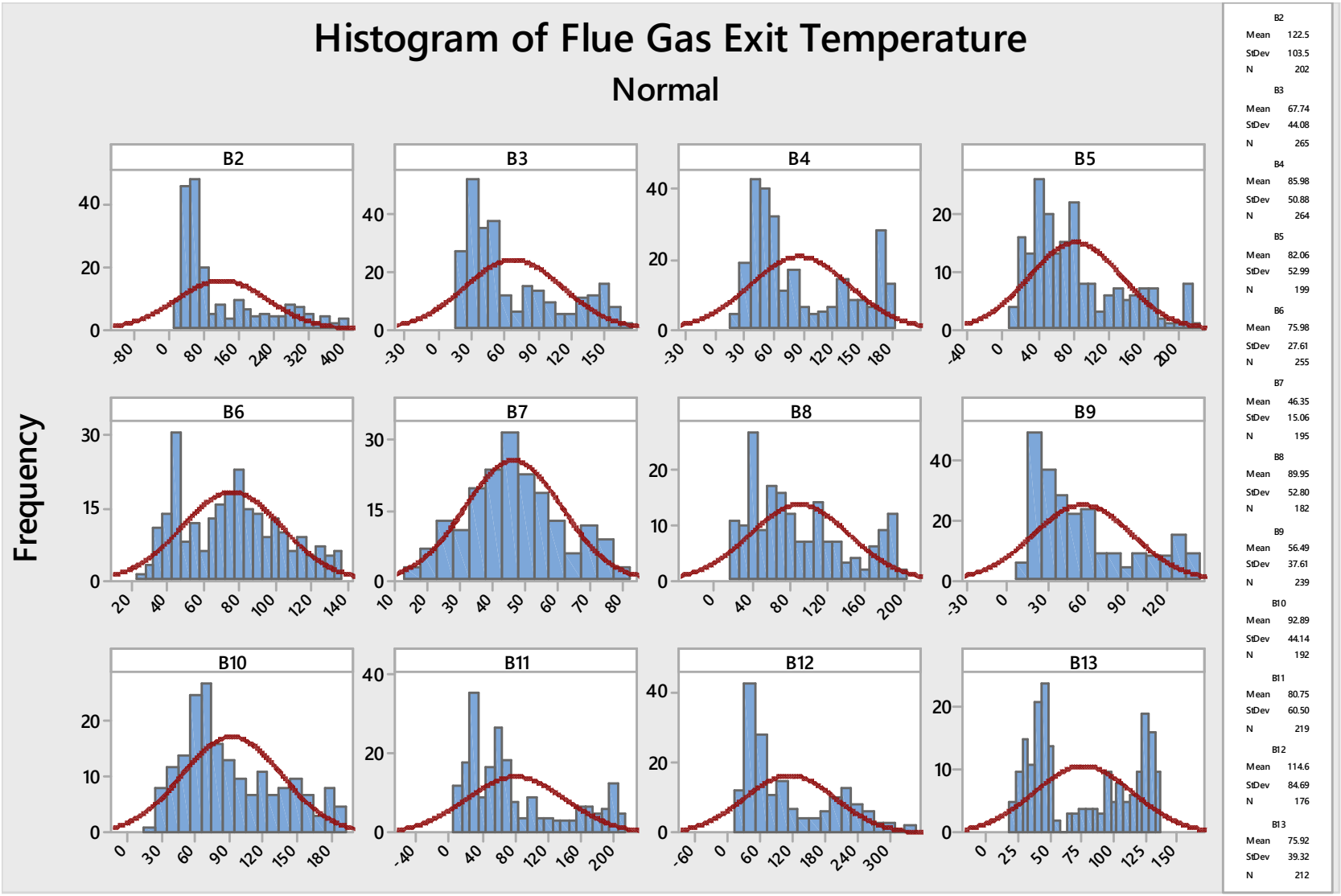


Figure 72: Histogram of flue gas exit temperature across Batch 2 to Batch 13

A flue gas temperature variability plot is shown in Figure 73 which indicates positively skewed temperature levels (leaning towards lower temperature levels). Batches 13 and 6 display the best indication of consistent emissions over the firing period (shorter bars and a centred median in the variability plot is an indication of lower variability and steadier temperature levels). Batches 3 and 4 also show high level of data consistency, while Batches 2 and 12 show extreme levels of data variability, which suggest that these batches were inefficiently fired. As with CO results, these extreme variability could not be linked to the energy input.

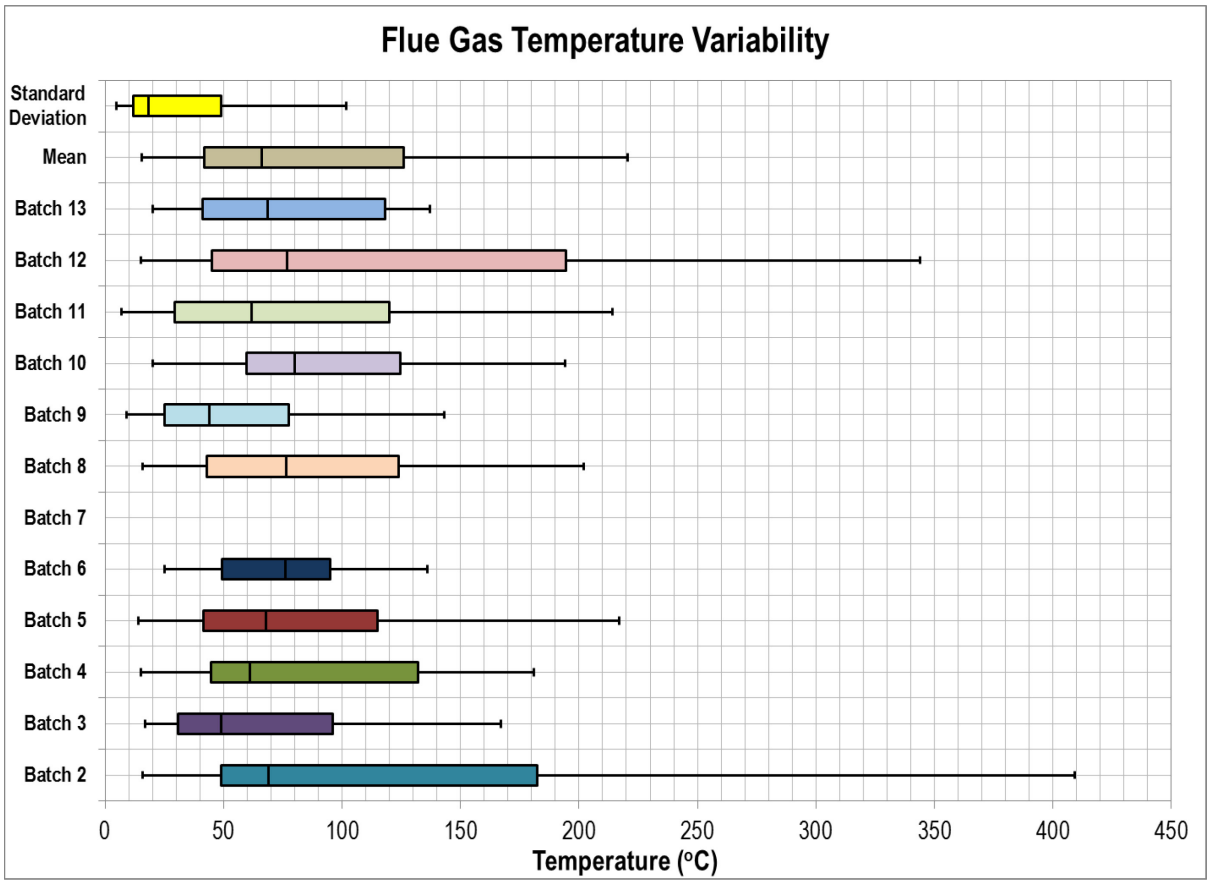


Figure 73: Flue gas temperature variability – Batches 6 and 13 displays the best indication of consistent emissions over the firing period, Batches 3 and 4 also show high level of data consistency; while Batches 2 and 12 show extreme levels of data variability

4.2.8 FLUE GAS VELOCITY

Measured flue gas velocity time series plots are presented in Figure 74, Figure 75 and Figure 76, excluding Batch 1; which could not be obtained due to equipment breakdown. Histograms of temperature levels are also shown in Figure 77 for each firing batch. The measured flue gas velocity does not exhibit any consistent trend, generally initiating at mid to high levels, rising and falling over the firing period. Velocity levels show slight positively skewed histogram (leaning towards lower velocity levels) for Batches 3, 4, 5, 6, 7, 9 and13; and slight negatively skewed histogram (leaning towards higher velocity levels) for Batches 2, 8, 10, 11 and 12. This suggests that flue gas velocity at the stack may be controlled by the extraction fan and meteorological components such as wind speed

and wind direction, rather than by convective processes inside the firing chamber of the kiln. It was observed that at high wind speeds, visible smoke can be seen coming out from under the semi-enclosed air inlet at the opposing side to the direction of the wind, indicating incomplete capture of the emissions by the exhaust fan and duct under these circumstances.

Correlation analysis was conducted using both Pearson and Spearman rank correlation to evaluate the strength and direction of the sensitivity of flue gas emission velocity to external wind speed data obtained from OR Tambo International Airport weather station. Correlation analysis of data was performed using the GNU PSPP™ version 0.9 software at 95% confidence interval. Flue gas emission velocity data for each hour of measurement were paired with the same hourly data from the weather station. Sub-hourly data, which would have provided higher degree of accuracy for the correlation analysis, was not available at the weather station (since measurements were taken for only 5 minutes per time). Both Pearson and Spearman rank correlation indicate poor and very poor correlation between flue gas emission velocity and external wind speed; while both positive and negative relationship are experienced across different batches (Table 34). Therefore, it can be inferred that flue gas emission velocity are not sensitive to external wind conditions.

Table 34: Pearson and Spearman rank correlation to evaluate the strength of the sensitivity of flue gas emission velocity to external wind speed obtained from OR Tambo International Airport weather station data

	Flue gas velocity (m/s)									
Batch	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Pearson	0.12	0.03	-0.13	-0.02	0.10	0.25	-0.11	-0.02	-0.21	-0.19
Spearman	0.14	0.04	-0.01	-0.07	0.14	0.43	-0.02	-0.03	-0.23	-0.29

NOTE: Analyses performed with a 95% confidence interval using GNU PSPP™ version 0.9 software
"0" implies no correlation and "+1" and "-1" implies very strong positive and negative correlation

Maximum, mean and minimum flue gas velocities, as well as standard deviation from the mean, are presented in Table 35. The highest average velocity was recorded during Batches 6, 9 and 10; while Batches 3 and 7 recorded the lowest average velocity across the firing period. The minimum concentration recorded was zero for all batches.

Table 35: Flue gas velocity summary

	Flue gas velocity (m/s)											
Batch	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Max.	19.0	13.0	16.0	16.0	20.0	20.0	11.0	16.0	19.0	16.0	16.0	13.0
Mean	9.1	7.3	10.9	10.6	11.4	7.0	7.7	11.3	12.7	11.5	8.3	9.6
SD	3.6	3.1	3.3	2.1	5.8	3.3	1.8	2.3	3.0	3.0	4.1	2.0
Median	10.3	7.0	10.7	10.0	10.0	6.3	8.0	11.0	13.0	12.0	10.0	9.0
Min.	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0

NOTE: "ND" implies "no data"; "SD" implies "standard deviation"; "Max." implies "maximum"; while "Min." implies "minimum"

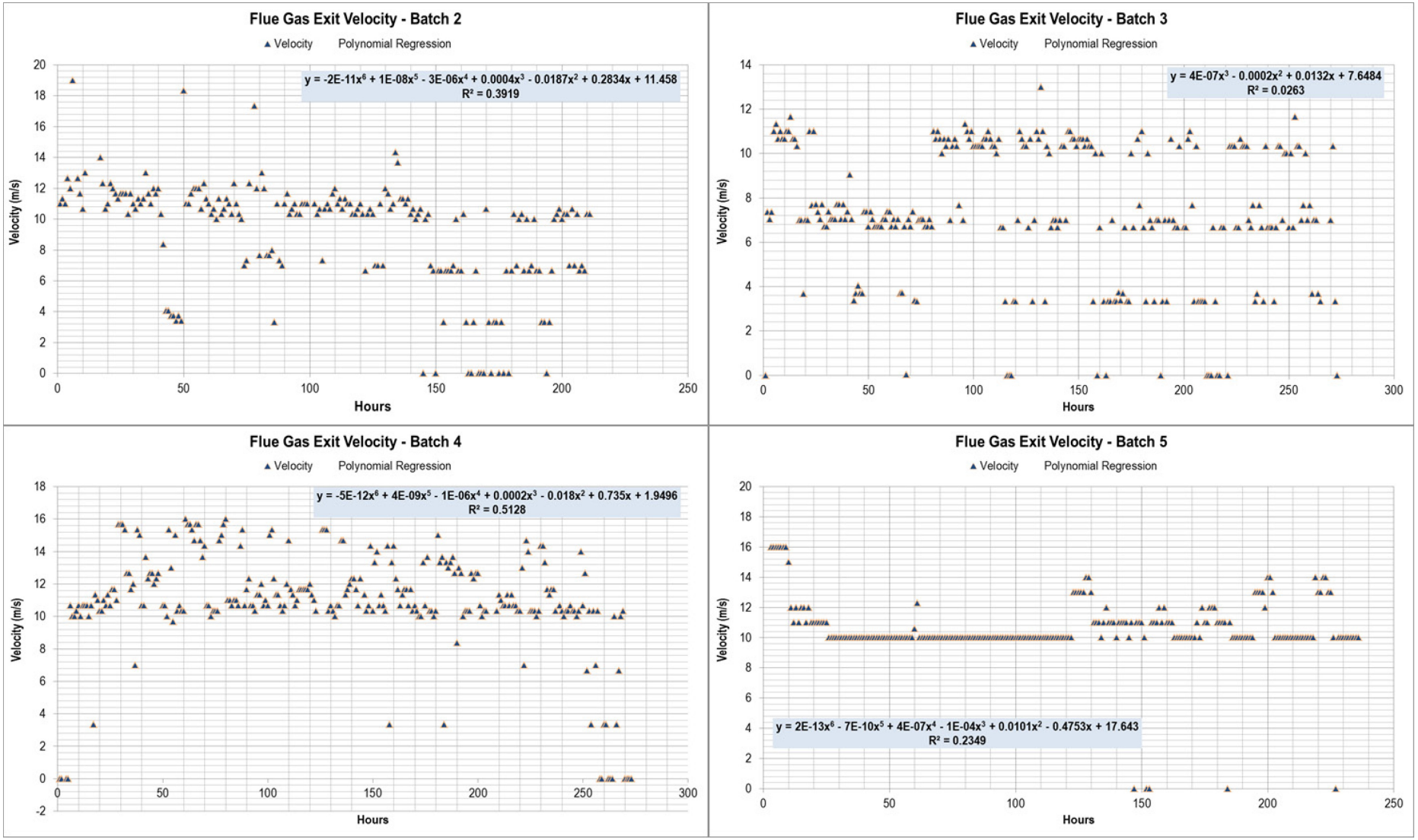


Figure 74: Flue gas velocity in m/s (Batches 2, 3, 4 and 5)

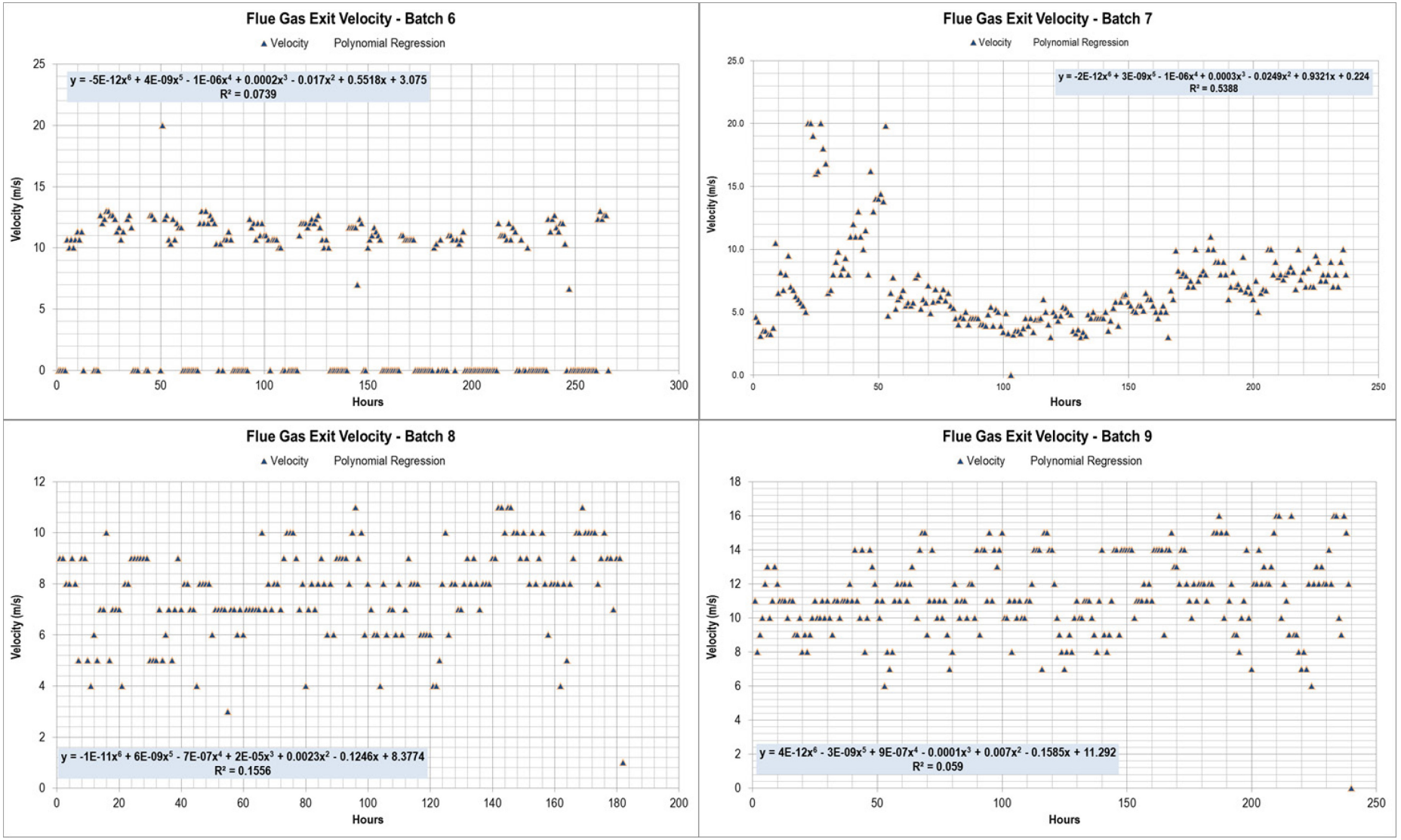


Figure 75: Flue gas velocity in m/s (Batches 6, 7, 8 and 9)

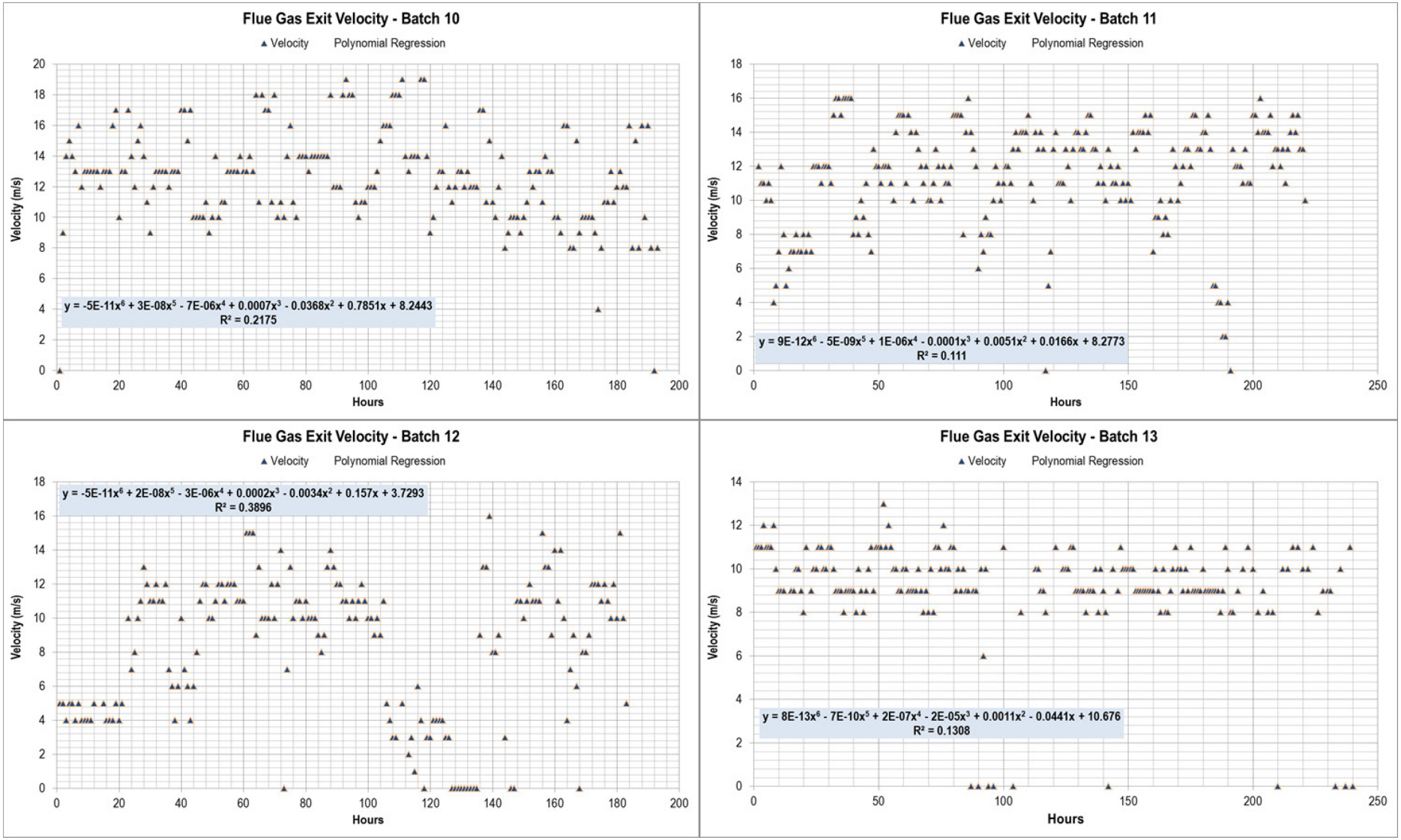


Figure 76: Flue gas velocity in m/s (Batches 10, 11, 12 and 13)

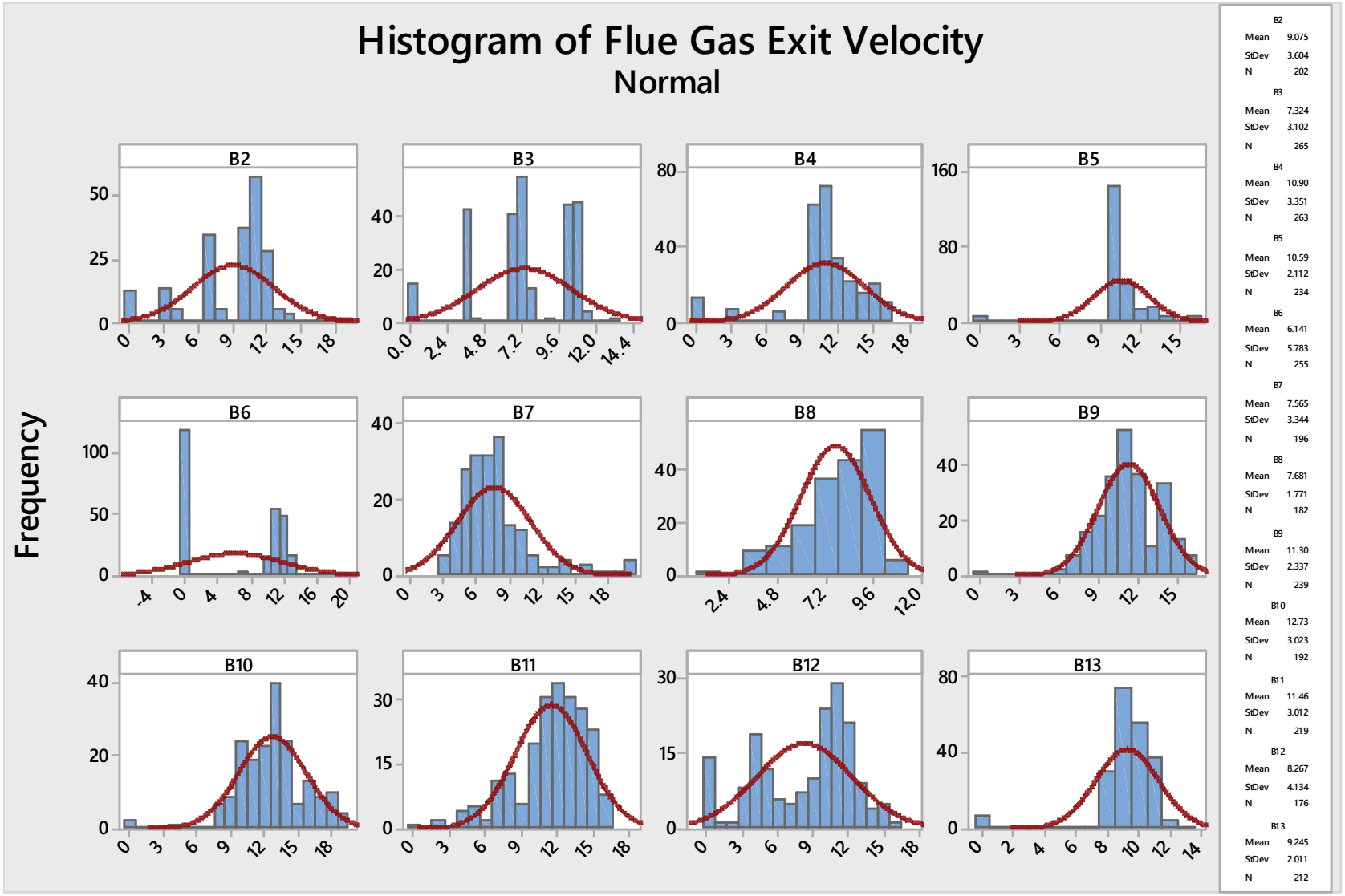


Figure 77: Histogram of flue gas exit velocity across Batch 2 to Batch 13

A flue gas velocity variability plot is shown in Figure 73 which indicates skewed velocities at extreme levels than at lower levels for all batches and for the mean and standard deviation. Batch 8 displays the best indication of consistent and steadier wind velocities over the firing period, a better consistency than the mean of the distribution (since shorter bars and a centred median in the variability plot is an indication of lower variability and steadier emissions). The median of the velocities for all the batches equals 10 m/s.

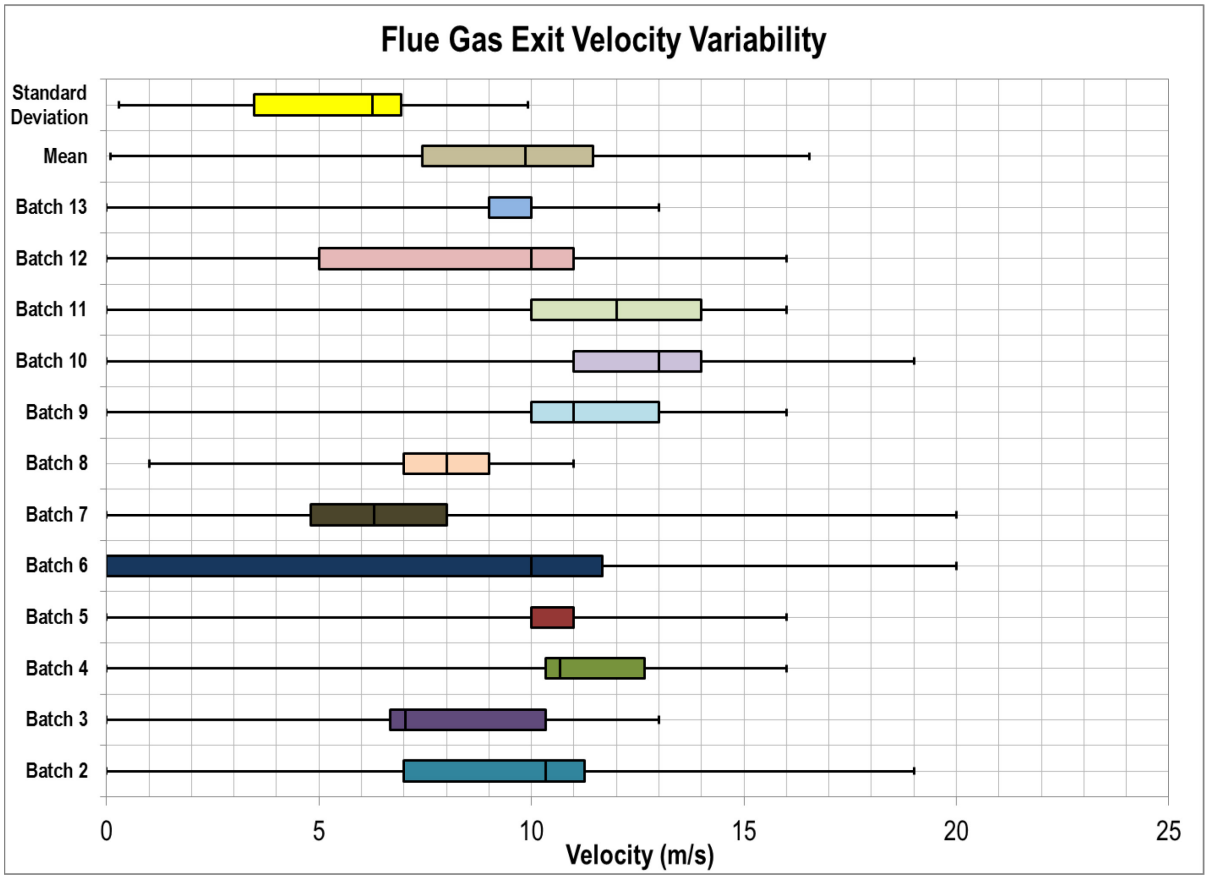


Figure 78: Flue gas velocity variability plot – Batch 8 displays the best indication of consistent and steadier wind velocities

4.2.9 PERCENTAGE OXYGEN REFERENCE

The O_2 reference is a measure of the process oxygen level which the gas analyser utilizes in standardizing the monitoring and reporting of NO_x emissions (Biarnes *et al,* 2013). It is expected to be proximate to the percentage by volume of O_2 in dry air (20.95%). The measured O_2 reference results are presented in Figure 96, Figure 97 and Figure 98 (Appendix B, Section 10.2), with the exception of Batch 1 which could not be obtained due to equipment breakdown.

The measured O_2 references exhibit slight to moderate consistency across the firing cycle, with levels generally oscillating between 19% and 21% across the firing period. The O_2 reference/time plot shows asymmetrical polynomial regression curves with little to moderate consistency across the batches.

The maximum, minimum and mean O_2 references, as well as standard deviation from the mean, are presented in Table 36. Batches 3, 6 and 13 recorded proximate values to 20.95%; while Batches 2 and 8 recorded extreme values.

Table 36: Percentage O_2 reference summary – Batches 3, 6 and 13 recorded proximate values to 20.95%

	Percentage O_2 reference (%)											
Batch	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Max.	22.8	21.9	21.3	21.2	21.2	21.0	21.9	21.8	19.7	23.9	27.0	21.3
Mean	19.8	20.9	20.4	20.6	20.9	20.8	19.9	20.4	20.2	20.5	20.2	20.9
SD	1.2	0.3	0.5	0.4	0.1	0.1	0.8	0.6	0.8	0.6	1.3	5.8
Median	19.9	20.9	20.6	20.8	20.9	20.8	20.05	20.6	20.5	20.7	22.4	20.9
Min.	15.3	19.1	19.3	19.1	20.5	19.3	16.4	19.0	18.5	18.7	17.6	0.0

NOTE: **"**ND" implies "no data"; "SD" implies "standard deviation"; "Max." implies "maximum"; while "Min." implies "minimum"

A percentage O_2 reference variability plot is shown in Figure 79, which indicates moderately steady levels across all batches, with the exception of Batch 12. Batch 3 displays the best indication of consistent and steadier readings, as well as the best proximity in value to 20.95% (shorter bars and a centred median is an indication of lower variability and steadier O_2 reference levels). Since model kiln O_2 reference levels are comparable to ambient O_2 levels, this suggests a favourable validation of the hypothesis that the firing process in the model kiln (such as exchange of cold air and release of flue gases etc.) will simulate the firing process in a full-scale clamp kiln. Batch 13 recorded a minimum percentage O_2 reference of 0.0, an anomalous value. However, since Batch 13 measurements were flawed; it is safe to regard these measurements as erroneous.

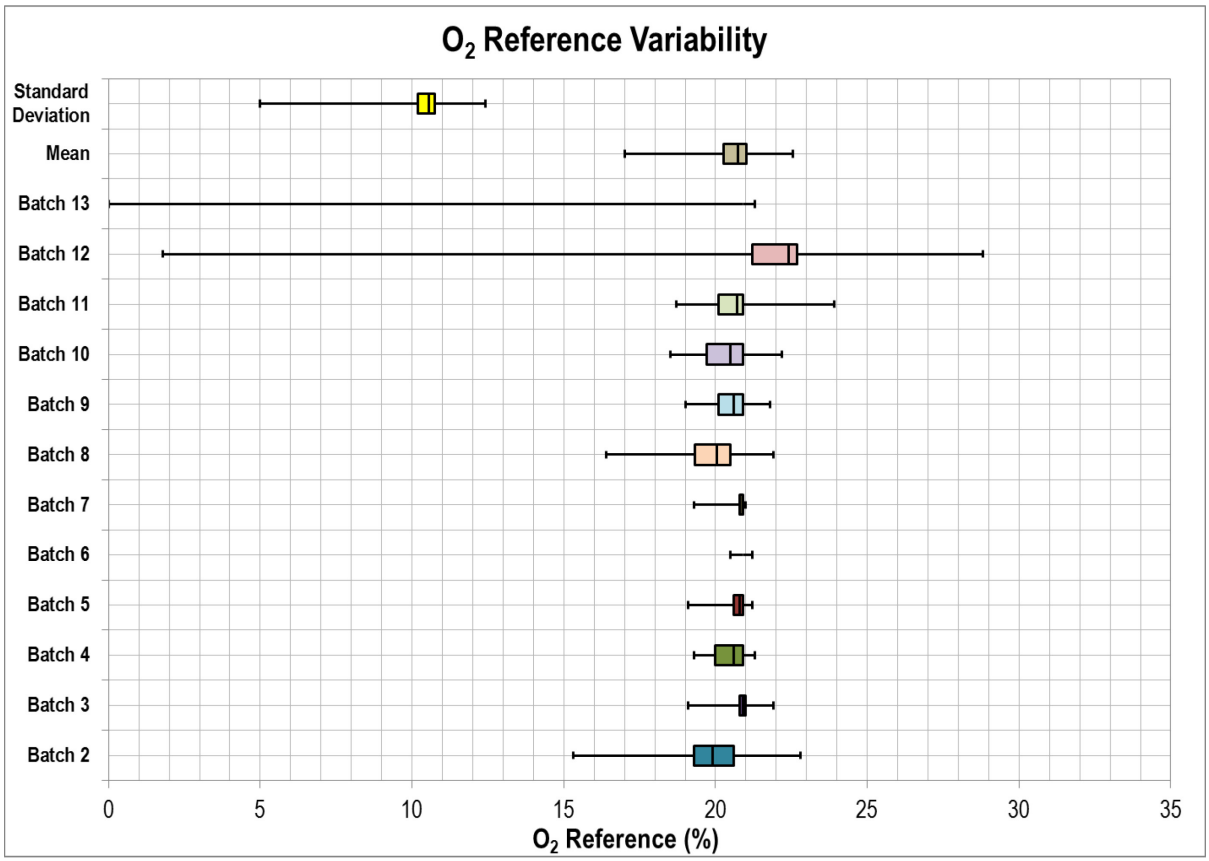


Figure 79: Percentage O_2 reference variability – Batch 3 displays the best indication of consistent and steadier levels, as well as the best proximity to 20.95%

4.2.10 PERCENTAGE CO_2

Percentage CO_2 is calculated by the gas analyser, utilizing a function of the maximum possible stoichiometric amount of CO_2 that can be released by a given fuel and the O_2 concentration, as shown in Equation 16 (Section 3.6.2). The calculated percentage CO_2 results are presented in Figure 102, Figure 103 and Figure 104 (Appendix B, Section 10.2), with the exception of Batch 1 and Batch 13; which could not be obtained due to equipment breakdown.

The calculated percentage CO_2 results exhibit little consistency across the firing cycle; with levels generally maintained between 0 and 8 % over the firing period. The maximum, minimum and mean CO_2 percentages, as well as the standard deviation from the mean, are presented in Table 37. The highest average CO_2 percentages are recorded during Batches 2, 6, 10 and 12. Mean percentage CO_2 across all batches is 0.48%.

Table 37: Model kiln flue gas percentage CO_2 concentration summary

Kiln percentage CO_2 (%) [a]												
Batch	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Max.	5.6	1.6	1.5	1.7	13.0	ND	3.8	1.8	9.0	2.0	3.1	ND
Mean	1.09	0.05	0.40	0.23	0.06	ND	0.78	0.40	0.64	0.38	0.72	ND
SD	1.1	0.2	0.4	0.4	0.8	ND	0.7	0.5	0.9	0.5	0.9	ND
Median	0.9	0	0.2	0	0	ND	0.7	0.2	0.3	0.1	0.3	ND
Min.	0.0	0.0	0.0	0.0	0.0	ND	0.0	0.0	0.0	0.0	0.0	ND
Calculated Mean CO_2 Concentration (ppm)												
Mean	10900	500	4000	2300	600	ND	7800	4000	6400	3800	7200	ND
Calculated CO_2 Concentration (mg/m^3)												
Mean	21146	970	7760	4462	1164	ND	15132	7760	12416	7372	13968	ND
SD	21340	3880	7760	7760	15520	ND	13580	9700	17460	9700	17460	ND

NOTE: "ND" implies "no data"; "SD" implies "standard deviation"; "Max." implies "maximum"; while "Min." implies "minimum"

[a] Percentage CO_2 levels are likely to be overestimated by the gas sampler due to dilution effect of the bifurcated fan

A percentage CO_2 distribution plot is provided in Figure 80 showing the distribution of percentage occurrence of percentage CO_2 in various ranges. CO_2 at 0 – 0.24 % is calculated to occur about 25% – 100% of the firing time across Batch 2 to Batch 13, indicating that the percentage CO_2 level within the model kiln is often near ambient levels (0.03 %), similar to levels expected for full-scale kiln (due to its pseudo-enclosed firing chamber). This further suggests favourable validation of the hypothesis that firing conditions in the model kiln will simulate the firing process in a full-scale clamp kiln.

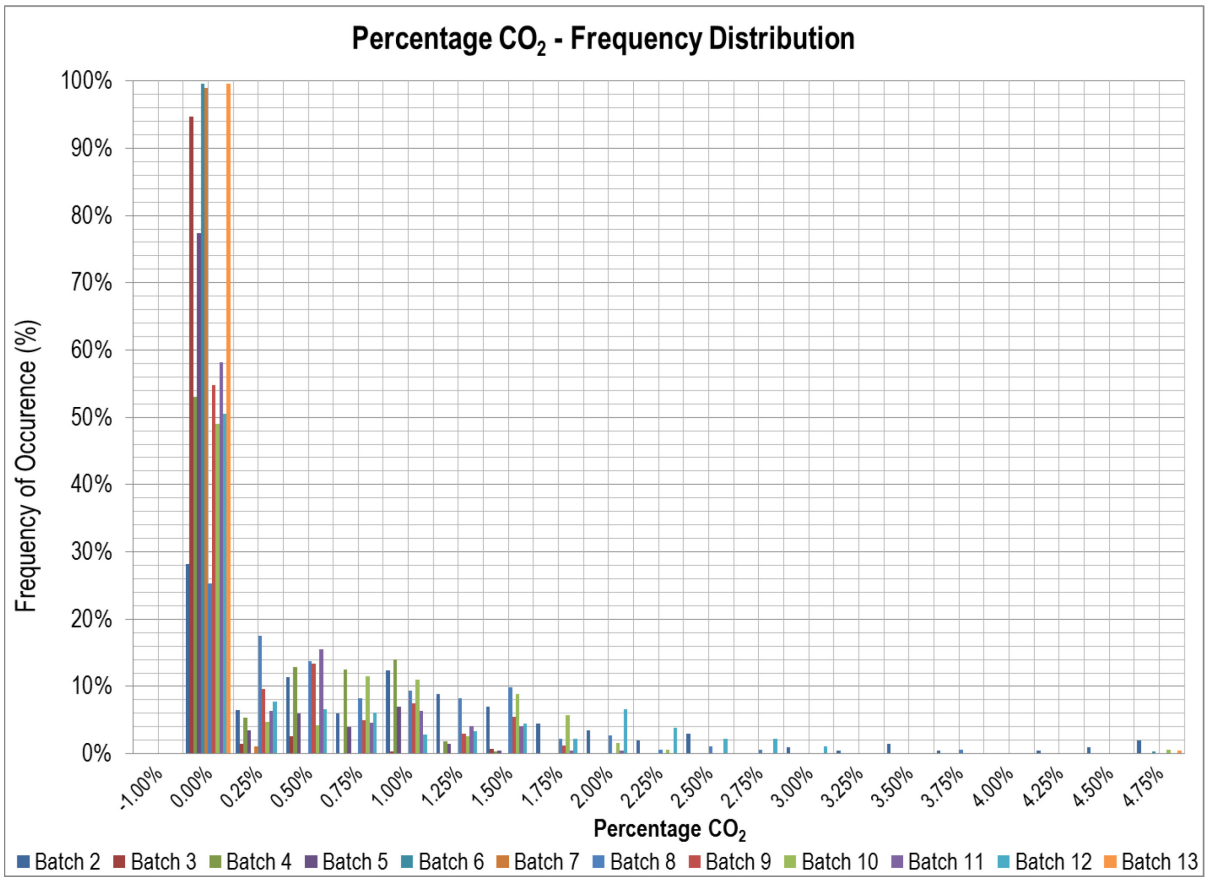


Figure 80: Percentage CO_2 frequency distribution. CO_2 at 0 – 0.24 % is calculated to occur about 25% – 100% of the firing time across Batch 2 to Batch 13, indicating that the percentage CO_2 level within the model kiln is often near ambient levels (0.03 %)

4.2.11 Combustion Efficiency and Percentage Excess Air

Combustion efficiency is calculated by the gas analysers, utilizing the total heat loss from the kiln and the fuel heating value in Equation 14 (Section 3.6.1). Percentage excess air is calculated by the gas analyser, utilizing the difference in the O_2 level in the firing chamber and the of O_2 level in dry air (20.95%) as shown in Equation 15 (Section 3.6.2). These calculations are based on assumption of the fuel type and calorific value of the fuel utilised in the combustion process. Consequently, calculated combustion efficiency and percentage excess air results obtained from the gas sampler are not deemed applicable to clamp kiln or model kiln firing, due to the pseudo-enclosed nature of the firing chamber. Combustion efficiency and percentage excess air results are therefore, not analysed in this report.

Combustion efficiency results obtained from the gas sampler are presented in Figure 93, Figure 94 and Figure 95 (Section 10.2 – Appendix B), while percentage excess air results are presented in Figure 99, Figure 100 and Figure 101 for record purposes (Appendix B, Section 10.2).

4.2.12 EMISSIONS SUMMARY

A summary of emission concentration and process metrics is presented in Table 38 and Table 39 respectively. It can be concluded that model kiln emission concentrations and process metric results exhibit a wide range of data variability during each firing cycle, indicating that they are sensitive to the various reactions and processes occurring within the kiln at a particular period (refer to Sections 2.2 and 4.2).

In addition, emission concentrations and process metric results exhibit little or no similarity across various batches; which may be attributed to the significantly varying input, packing and firing conditions applied to each batch. High standard deviations, as well as a high range of data spread across the batches, suggest that emissions and process metrics from the kiln are sensitive to these input and firing variables.

Table 38: Summary of emission concentrations – emission concentrations exhibit little or no similarity across various batches; which may be attributed to the significantly varying input, packing and firing conditions applied to each batch. Also, emission concentrations exhibit a wide range of variability during each firing cycle, suggesting that they are sensitive to the various reactions and processes occurring within the kiln

Batch	Emission concentration (mean ± standard deviation in mg/m³)												Average Range
	2	3	4	5	6	7	8	9	10	11	12	13	
CO	1809 ± 1733	190 ± 191	458 ± 540	113 ± 214	196 ± 161	ND	685 ± 767	157 ± 210	414 ± 554	558 ± 909	786 ± 1070	ND	113 – 1809
NO_x	6 ± 11.5	2.8 ± 2.9	1.5 ± 2.1	1.2 ± 2.1	3.8 ± 1.2	ND	5.6 ± 5.0	1.2 ± 2.4	3.8 ± 4.4	1.1 ± 2.1	3.5 ± 4.6	ND	1.1 – 6.0
NO	6 ± 11.5	2.8 ± 2.9	1.5 ± 2.1	1.2 ± 2.1	3.8 ± 1.2	ND	5.6 ± 5.0	1.2 ± 2.4	3.8 ± 4.4	1.1 ± 2.1	3.5 ± 4.6	ND	1.1 – 6.0
NO_2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SO_2	34.5 ± 72.3	12 ± 22.4	7.8 ± 12	10.1 ± 18.3	ND	ND	45.1 ± 50.9	16.8 ± 30.9	43.2 ± 47.1	24.3 ± 45.3	75.6 ± 108.0	ND	7.8 – 75.6
PM_{10}	47.0 ± 37	21.2 ± 21	18.5 ± 23	12.6 ± 18	15.4 ± 24	17.6 ± 19	12.2 ± 17	16.3 ± 21	22.1 ± 18	27.6 ± 19	29.8 ± 21	30.8 ± 28	12.6 – 47.0
PM_{15}	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	30.8 ± 28	50.5 ± 46
PM_4	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	30.8 ± 28	50.5 ± 46
$PM_{2.5}$	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	30.8 ± 28	50.5 ± 46
PM_1	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	30.7 ± 28	50.3 ± 46
HC	ND	ND	ND	ND	ND	48.6 ± 58.3	ND	ND	ND	ND	ND	ND	48.6 ± 58
Emission concentration (mean ± standard deviation in g/m³)													
CO_2	21.1 ± 21.3	1.0 ± 3.9	7.8 ± 7.8	4.5 ± 7.8	1.2 ± 15.5	ND	15.1 ± 13.6	7.8 ± 9.7	12.4 ± 17.5	7.4 ± 9.7	14.0 ± 17.5	21.1 ± 21.3	1.0 – 21.1

NOTE: **"**ND" implies "no data"; "SD" implies Standard deviation; HC emission is calibrated to propane

Table 39: Summary of flue gas process metrics – model kiln process metrics exhibit a wide range of variability during each firing cycle, indicating that they are sensitive to the various reactions and processes occurring within the kiln

Process Metrics (mean ± standard deviation)													
Batch	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**Range**
Temperature (°C)	123 ± 103	67.7 ± 44	86.0 ± 51	86.9 ± 53	76.0 ± 28	46.4 ± 15	90.0 ± 53	56.5 ± 38	92.9 ± 44	80.8 ± 60	115 ± 85	75.9 ± 39	46.4 – 122.5
Velocity (m/s)	9.1 ± 3.6	7.3 ± 3.1	10.9 ± 3.3	10.6 ± 2.1	11.4 ± 5.8	7.0 ± 3.3	7.7 ± 1.8	11.3 ± 2.3	12.7 ± 3	11.5 ± 3	8.3 ± 4.1	9.6 ± 2	7.0 – 12.7
Oxygen Reference (%)	19.8 ± 1.2	20.9 ± 0.3	20.4 ± 0.5	20.6 ± 0.4	20.9 ± 0.1	20.8 ± 0.1	19.9 ± 0.8	20.4 ± 0.6	20.2 ± 0.8	20.5 ± 0.6	20.2 ± 1.3	ND	19.8 – 20.9
Percentage CO_2 (%) [a]	1.1 ± 1.1	0.1 ± 0.2	0.4 ± 0.4	0.2 ± 0.4	0.1 ± 0.8	ND	0.8 ± 0.7	0.4 ± 0.5	0.6 ± 0.9	0.4 ± 0.5	0.7 ± 0.9	ND	0.1 – 1.1

NOTE: **"**ND" implies "no data"

[a] Percentage CO_2 levels are likely to be overestimated by the gas sampler due to dilution effect of the bifurcated fan

Table 40: Summary of emission concentrations standardized to normal conditions (mg/Nm^3)

Batch	Mean Emission Concentration (mg/Nm^3)												Mean ± SD
	2	3	4	5	6	7	8	9	10	11	12	13	
CO	1120	137	314	77.2	138	ND	464	117	278	388	498	ND	353 ± 293
NO_x	3.7	2.0	1.0	0.8	2.7	ND	3.8	0.9	2.6	0.8	2.2	ND	2.0 ± 1.1
NO	3.7	2.0	1.0	0.8	2.7	ND	3.8	0.9	2.6	0.8	2.2	ND	2.0 ± 1.1
NO_2	0.0	0.0	0.0	0.0	0.0	ND	0.0	0.0	0.0	0.0	0.0	ND	0.0
SO_2	21.4	8.7	5.3	6.9	0.0	ND	30.5	12.5	29.0	16.9	47.9	ND	17.9 ± 13.8
PM_{10}	29.2	15.3	12.7	8.6	10.8	ND	8.3	12.2	14.8	19.2	18.9	21.7	21.7 ± 6.0
PM_{15}	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	30.8	21.7
PM_4	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	30.8	21.7
$PM_{2.5}$	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	30.8	21.7
PM_1	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	30.7	21.7
HC	ND	ND	ND	ND	ND	37.4	ND	ND	ND	ND	ND	ND	ND
Emission concentration (mean ± standard deviation in g/m^3)													
CO_2	13130	700	5310	3050	820	ND	10250	5790	8340	5120	8850	ND	6136 ± 3836

NOTE: "ND" implies "no data"; HC emission is calibrated to propane

4.3 RELATIONSHIPS BETWEEN EMISSION METRICS

Various flue gas emission metrics were analysed in order to determine their relationships and relate this to the chemical and thermodynamic processes occurring within the firing chamber of the kiln. Correlation analysis was conducted using both Pearson and Spearman rank correlation to evaluate the relationships between the following emission metrics: flue gas temperature and CO emissions; flue gas temperature and SO_2 emissions; NO_x and SO_2 emissions; flue gas temperature and NO_x emissions; flue gas velocity and temperature; and flue gas velocity and temperature. Correlation analysis of data was performed using the GNU PSPP™ version 0.9 software at 95% confidence interval. Correlation results are presented in Table 41. The relationships between these metrics are discussed below:

- **Flue gas temperature and CO emissions**

  Both Pearson and Spearman rank correlation indicate weak and very weak negative correlation between flue gas temperature and CO emissions across various batches (with the exception of Batch 12 showing a very poor positive correlation). This agrees with literature in that the carbonaceous compounds are burnt off at the early stages of firing before optimum temperature is reached (i.e. before 300 ^oC).

- **Flue gas temperature and SO_2 emissions**

  Both Pearson and Spearman rank correlation indicate medium to very strong positive correlation between flue gas temperature and SO_2 emissions across batches (with the exception of Batch 5 showing a poor positive correlation). This also agrees with literature since SO_2 is retained in the brick at lower firing temperatures, hence the higher the temperature, the higher the quantity of SO_2 released.

- **Flue gas temperature and NO_x emissions**

  Both Pearson and Spearman rank correlation indicate very poor to strong positive correlation between flue gas temperature and NO_x emissions across batches (with the exception of Batch 8 showing a poor negative correlation). Although the correlation results across various batches suggests a slight linear relationship between flue gas temperature and NO_x emissions, a distinct relationship has not been established in literature and the correlation results do not provide conclusive evidence of a linear relationship between flue gas temperature and NO_x emissions.

- **NO_x emissions and SO_2 emissions**

  Both Pearson and Spearman rank correlation indicate medium to very strong positive correlation between NO_x and SO_2 emissions across batches. Though a distinct relationship between NO_x and SO_2 emissions have not been established in literature, a medium to very strong positive correlation suggests a linear relationship between the release of NO_x and SO_2 emissions. This is probably due to NO_x and SO_2 emissions being released at higher temperatures as described above.

- **Flue gas velocity and Flue gas temperature**

  Both Pearson and Spearman rank correlation indicate very poor to strong positive and negative correlation between flue gas velocity and temperature across batches, suggesting that the relationship between these two metrics are not linear or non-existent.

- **CO emissions and PM emissions**

  Both Pearson and Spearman rank correlation indicate very poor to strong positive and negative correlation between CO and PM emissions across batches, also suggesting that the relationship between these two metrics are not linear or non-existent.

Table 41: Pearson and Spearman rank correlation evaluating the relationships between emission metrics across Batch 2 to Batch13

Batch		CO / Temperature	SO_2 / Temperature	NOx / SO_2	NOx / Temperature	Velocity / Temperature	CO / PM
2	Pearson	-0.30	0.82	0.83	0.63	-0.60	0.00
	Spearman	-0.18	0.77	0.39	0.39	-0.62	0.14
3	Pearson	-0.29	0.53	0.63	0.23	-0.24	0.42
	Spearman	-0.15	0.77	0.43	0.30	-0.26	0.30
4	Pearson	-0.40	0.63	0.41	0.13	0.17	0.29
	Spearman	-0.21	0.71	0.35	0.22	0.12	0.25
5	Pearson	-0.09	0.37	0.85	0.23	-0.18	0.15
	Spearman	ND	ND	ND	ND	ND	ND
6	Pearson	-0.54	ND	ND	ND	-0.14	0.51
	Spearman	ND	ND	ND	ND	ND	ND
7	Pearson	-0.12	ND	ND	ND	-0.16	-0.22
	Spearman	ND	ND	ND	ND	ND	ND
8	Pearson	-0.50	0.42	0.66	-0.06	0.15	-0.08
	Spearman	-0.39	0.52	0.72	-0.01	0.15	0.01
9	Pearson	-0.36	0.49	0.72	0.13	0.15	-0.07
	Spearman	-0.39	0.58	0.67	0.17	0.17	-0.05
10	Pearson	-0.33	0.12	0.93	0.02	0.07	-0.14
	Spearman	-0.16	0.12	0.90	0.07	0.03	-0.16
11	Pearson	-0.31	0.62	0.66	0.26	0.16	-0.04
	Spearman	-0.16	0.77	0.59	0.30	0.20	-0.02
12	Pearson	0.01	0.55	0.43	0.05	-0.26	-0.14
	Spearman	0.18	0.48	0.70	0.15	-0.24	-0.19
13	Pearson	-0.37	ND	ND	0.04	-0.03	0.18
	Spearman	-0.15	ND	ND	0.01	0.01	0.31

NOTE: Analyses were performed with a 95% confidence interval using GNU PSPP™ version 0.9 software
"0" implies no correlation and "+1" and "-1" implies very strong positive and negative correlation

4.4 EMISSION RATES AND EMISSION FACTORS

Emission rates were calculated from hourly emission concentration over each firing cycle, and are given in g/s (Table 42) and g/s brick (Table 43). Similarly, emission factors were calculated from hourly emission concentration over each firing cycle, and are given in g/brick (Table 44) and kg/Mg or g/kg (Table 45). The mean concentration and standard deviation over each firing period was used in calculating emission rates and emission factors, with standard deviation indicating high data variability across all batches. Since PM_{15}, PM_4, $PM_{2.5}$ and PM_1 concentration were only obtained for Batch 13 run, their mean was taken as a percentage fraction (refer to Table 29) of the mean of PM_{10}.

Table 42: Emission rates in g/s

Batch	g/s									
	CO	NO_x/NO	CO_2	SO_2	PM_{10}	PM_{15}	PM_4	$PM_{2.5}$	PM_1	HC
2	2.2×10^{0}	5.2×10^{-3}	2.48×10^{1}	2.2×10^{-2}	5.6×10^{-2}	ND	ND	ND	ND	ND
3	1.9×10^{-1}	2.7×10^{-3}	9.21×10^{-1}	1.1×10^{-2}	2.2×10^{-2}	ND	ND	ND	ND	ND
4	6.8×10^{-1}	2.2×10^{-3}	1.10×10^{1}	1.2×10^{-2}	2.7×10^{-2}	ND	ND	ND	ND	ND
5	1.8×10^{-1}	1.6×10^{-3}	6.30×10^{0}	1.4×10^{-2}	1.8×10^{-2}	ND	ND	ND	ND	ND
6	2.8×10^{-1}	7.7×10^{-3}	1.60×10^{0}	ND	1.1×10^{-2}	ND	ND	ND	ND	ND
7	ND	ND	ND	ND	1.4×10^{-2}	ND	ND	ND	ND	4.4×10^{-2}
8	6.5×10^{-1}	5.4×10^{-3}	1.51×10^{1}	4.4×10^{-2}	1.3×10^{-2}	ND	ND	ND	ND	ND
9	2.2×10^{-1}	1.7×10^{-3}	1.15×10^{1}	2.3×10^{-2}	2.4×10^{-2}	ND	ND	ND	ND	ND
10	6.9×10^{-1}	6.5×10^{-3}	2.07×10^{1}	7.4×10^{-2}	3.7×10^{-2}	ND	ND	ND	ND	ND
11	8.2×10^{-1}	1.6×10^{-3}	1.10×10^{1}	3.7×10^{-2}	4.2×10^{-2}	ND	ND	ND	ND	ND
12	1.0×10^{0}	3.8×10^{-3}	1.49×10^{1}	8.9×10^{-2}	3.4×10^{-2}	ND	ND	ND	ND	ND
13	ND	ND	ND	ND	3.8×10^{-2}	3.8×10^{-2}	3.8×10^{-2}	3.8×10^{-2}	3.8×10^{-2}	ND
Mean [a]	6.9×10^{-1}	3.9×10^{-3}	1.30×10^{1}	3.6×10^{-2}	2.8×10^{-2}	2.8×10^{-2}	2.8×10^{-2}	2.8×10^{-2}	2.8×10^{-2}	4.4×10^{-2}
SD	5.7×10^{-1}	2.1×10^{-3}	6.60×10^{0}	2.7×10^{-2}	1.3×10^{-2}	ND	ND	ND	ND	ND

NOTE: "ND" implies "no data" and "SD" implies "standard deviation"

[a] Mean of PM_{15}, PM_4, $PM_{2.5}$ and PM_1 was taken as a percentage fraction (refer to Table 29) of the mean of PM_{10}

Table 43: Emission rates in g/s brick

Batch	g/s brick									
	CO	NO_x/NO	CO_2	SO_2	PM_{10}	PM_{15}	PM_4	$PM_{2.5}$	PM_1	HC
2	6.8×10^{-5}	1.6×10^{-7}	9.57×10^{-4}	6.8×10^{-7}	2.1×10^{-6}	ND	ND	ND	ND	ND
3	6.6×10^{-6}	9.6×10^{-8}	3.23×10^{-5}	3.9×10^{-7}	7.7×10^{-7}	ND	ND	ND	ND	ND
4	2.3×10^{-5}	7.4×10^{-8}	3.67×10^{-4}	3.9×10^{-7}	9.1×10^{-7}	ND	ND	ND	ND	ND
5	5.5×10^{-6}	4.9×10^{-8}	1.95×10^{-4}	4.2×10^{-7}	5.5×10^{-7}	ND	ND	ND	ND	ND
6	1.3×10^{-5}	3.7×10^{-7}	7.73×10^{-5}	ND	5.3×10^{-7}	ND	ND	ND	ND	ND
7	ND	ND	ND	ND	4.8×10^{-7}	ND	ND	ND	ND	1.5×10^{-6}
8	2.3×10^{-5}	1.9×10^{-7}	5.28×10^{-4}	1.6×10^{-6}	4.4×10^{-8}	ND	ND	ND	ND	ND
9	7.4×10^{-6}	5.8×10^{-8}	3.96×10^{-4}	7.9×10^{-7}	8.4×10^{-7}	ND	ND	ND	ND	ND
10	2.3×10^{-5}	2.2×10^{-7}	6.94×10^{-4}	2.5×10^{-6}	1.2×10^{-6}	ND	ND	ND	ND	ND
11	3.2×10^{-5}	6.2×10^{-8}	5.26×10^{-4}	1.4×10^{-6}	2.0×10^{-6}	ND	ND	ND	ND	ND
12	3.9×10^{-5}	1.4×10^{-7}	5.63×10^{-4}	3.4×10^{-6}	1.3×10^{-6}	ND	ND	ND	ND	ND
13	ND	ND	ND	ND	1.6×10^{-6}	1.6×10^{-6}	1.6×10^{-6}	1.6×10^{-6}	1.6×10^{-6}	ND
Mean	2.4×10^{-5}	1.4×10^{-7}	4.34×10^{-4}	1.3×10^{-6}	1.1×10^{-6}	1.1×10^{-6}	1.1×10^{-6}	1.1×10^{-6}	1.1×10^{-6}	1.5×10^{-6}
SD	1.8×10^{-5}	9.5×10^{-8}	2.70×10^{-4}	1.0×10^{-6}	5.6×10^{-7}	ND	ND	ND	ND	ND

NOTE: "ND" implies "no data" and "SD" implies "standard deviation".
[a] Mean of PM_{15}, PM_4, $PM_{2.5}$ and PM_1 was taken as a percentage fraction (refer to Table 29) of the mean of PM_{10}.

Table 44: Emission factors in g/brick

Batch	g/brick									
	CO	NO_x/NO	CO_2	SO_2	PM_{10}	PM_{15}	PM_4	$PM_{2.5}$	PM_1	HC
2	63.52	0.15	726.62	0.64	1.63	ND	ND	ND	ND	ND
3	5.97	0.09	29.20	0.35	0.69	ND	ND	ND	ND	ND
4	22.24	0.07	360.85	0.38	0.89	ND	ND	ND	ND	ND
5	4.71	0.04	165.48	0.36	0.46	ND	ND	ND	ND	ND
6	12.79	0.36	74.04	ND	0.51	ND	ND	ND	ND	ND
7	ND	ND	ND	ND	0.41	ND	ND	ND	ND	1.32
8	14.84	0.12	346.04	1.02	0.29	ND	ND	ND	ND	ND
9	6.42	0.05	342.49	0.68	0.73	ND	ND	ND	ND	ND
10	16.32	0.15	482.13	1.75	0.86	ND	ND	ND	ND	ND
11	24.88	0.05	412.55	1.12	1.56	ND	ND	ND	ND	ND
12	22.52	0.08	328.38	1.97	0.75	ND	ND	ND	ND	ND
13	ND	ND	ND	ND	1.19	1.19	1.19	1.18	1.18	ND
Mean	19.42	0.12	326.78	0.92	0.83	0.83	0.83	0.83	0.83	1.32
SD	16.23	0.09	192.77	0.57	0.41	ND	ND	ND	ND	ND

NOTE: "ND" implies "no data" and "SD" implies "standard deviation".
[a] Mean of PM_{15}, PM_4, $PM_{2.5}$ and PM_1 was taken as a percentage fraction (refer to Table 29) of the mean of PM_{10}.

Table 45: Emission factors in kg/Mg

Batch	kg/Mg or g/kg of fired bricks									
	CO	NO_x/NO	CO_2	SO_2	PM_{10}	PM_{15}	PM_4	$PM_{2.5}$	PM_1	HC
2	22.07	0.05	253.15	0.22	0.57	ND	ND	ND	ND	ND
3	2.01	0.03	9.85	0.12	0.23	ND	ND	ND	ND	ND
4	8.34	0.03	134.44	0.14	0.33	ND	ND	ND	ND	ND
5	1.54	0.01	54.15	0.12	0.15	ND	ND	ND	ND	ND
6	3.76	0.11	21.77	ND	0.15	ND	ND	ND	ND	ND
7	ND	ND	ND	ND	0.12	ND	ND	ND	ND	0.39
8	4.37	0.04	101.78	0.30	0.09	ND	ND	ND	ND	ND
9	2.29	0.02	122.32	0.24	0.26	ND	ND	ND	ND	ND
10	5.83	0.05	172.19	0.63	0.31	ND	ND	ND	ND	ND
11	8.70	0.02	144.25	0.39	0.54	ND	ND	ND	ND	ND
12	8.74	0.03	127.40	0.76	0.29	ND	ND	ND	ND	ND
13	ND	ND	ND	ND	0.40	0.40	0.40	0.39	0.39	ND
Mean	6.76	0.04	114.13	0.33	0.29	0.29	0.29	0.29	0.29	0.39
SD	5.74	0.03	68.86	0.22	0.15	ND	ND	ND	ND	ND

NOTE: "ND" implies "no data" and "SD" implies "standard deviation"

[a] Mean of PM_{15}, PM_4, $PM_{2.5}$ and PM_1 was taken as a percentage fraction (refer to Table 29) of the mean of PM_{10}

A dendrogram of cluster analysis for pollutants emission factors is presented in Figure 81 showing associations among various pollutants across Batch 2 to Batch 13. The relationship or association among the various pollutants can be linked to the processes and mechanisms of the pollutant generation (in this case, mainly combustion conditions and/or properties of fuel and clay material used. A strong association is observed between high-temperature releasing pollutants such as SO_2 and NO_x/NO_2, while a weak association is observed between CO and CO_2 emissions, since CO is released by incomplete combustion, while CO_2 release is mostly fuel (carbon) dependent under complete combustion conditions. For PM emission, the weak association relative to other pollutants suggests that its release is not directly linked to the mechanisms associated with other pollutants (incomplete combustion, high temperature or fuel content).

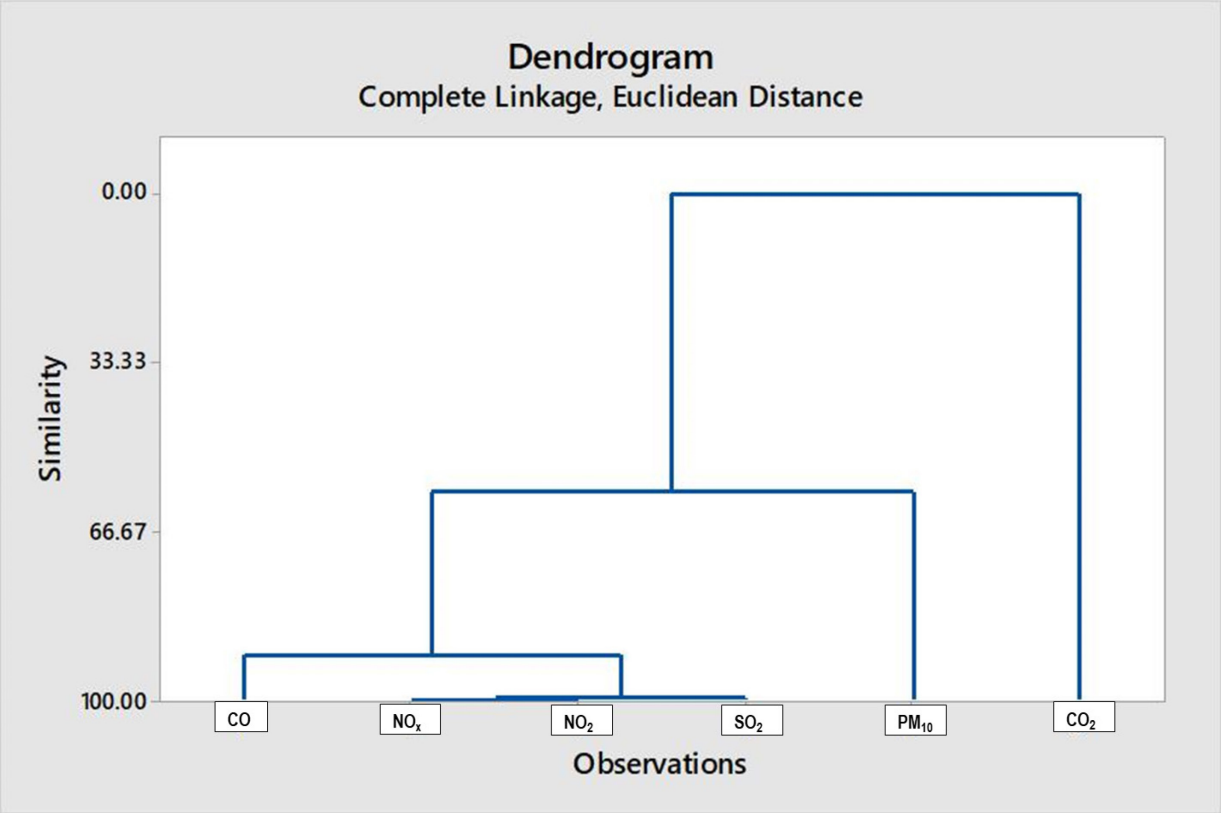


Figure 81: Dendrogram of cluster analysis for pollutant emission factors showing associations among various pollutants across Batch 2 to Batch 13

CHAPTER FIVE

5 ENERGY ANALYSIS FOR CLAMP KILNS

This section evaluates the energy input utilized in model kiln firing across Batch 2 to Batch 13. The evaluation of energy input is essential in determining how efficient the model kiln is fired, and by implication determining the efficiency of South African kiln firing practices.

5.1 ENERGY CONSUMPTION

The energy utilized in the model kiln firing is derived from the following sources:

- Internal or body fuel – the energy from coal mixed into the raw bricks during processing;
- 'Scintle' fuel – the energy from coal in the 'scintle' layer of the kiln; and
- Ignition or 'fire-box' fuel – the energy from coal, diesel or gas used to start the firing process.

For the purpose of this study, a combination of the 'scintle' and the fire-box fuel makes up the external fuel, while a combination of these two plus the body fuel make up the total firing energy for the kiln.

Table 46 presents the breakdown of the energy input utilized in model kiln firing. Intrinsic properties, such as percentage ash, percentage volatile matter, specific energy, etc., were obtained from laboratory analysis of the internal and external coal. Specific energy consumption (MJ/kg) was then calculated from the total energy utilized and the total weight of clay material fired.

Table 46: Analysis of energy input and firing metrics

Colour Legend (source of data)	Provided by source factory			Field data			Calculation			Laboratory analysis		
Input and Firing Metrics	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Quantity of body fuel (kg)	5933	7886	19800	10720	7632	6000	6000	5800	14504	3000	8529	5000
Quantity of 'scintle' fuel (kg)	2543	1980	3000	1650	1663	1800	1800	2100	2500	6230	3600	1300
Quantity of coal in fire-box (kg)	50	70	0	60	200	200	200	500	0	200	0	200
Specific Energy of body fuel (MJ/kg)	22.87	22.87	12.36	22.87	22.87	19.00	19.00	22.87	21.89	18.23	11.76	19.00
Specific Energy of 'scintle' fuel (MJ/kg)	17.50	17.50	22.60	17.50	28.45	20.00	20.00	17.50	22.15	17.50	28.76	20.00
% volatile matter (body fuel)	21.5	23.6	0.3	23.04	23.6	20.8	20.8	23.6	18.9	21.5	2.4	20.8
% volatile matter ('scintle' fuel)	20.3	20.3	25.6	22.71	24.8	23.1	23.1	20.30	20.9	20.3	36.3	23.1
Energy applied – body (GJ)	135.7	180.3	244.7	245.2	174.5	114.0	114.0	132.6	317.5	54.7	100.3	95.0
Energy applied – 'scintle' (GJ)	44.5	34.7	67.8	28.9	47.3	36.0	36.0	36.8	55.4	109.0	103.5	26.0
% 'scintle' to body energy (%)	32.8%	19.2%	27.7%	11.8%	27.1%	31.6%	31.6%	27.7%	17.4%	199.4%	103.2%	27.4%
Energy applied – fire-box (GJ)	0.88	1.23	0.00	1.05	5.69	4.00	4.00	8.75	0.00	3.50	0.00	4.00
Total energy used (GJ)	181	216	313	275	228	154	154	178	373	167	204	125
Weight per green brick (g)	3024	3074	3105	3056	3400	3351	3270	3018	3015	3480	2968	3573
Number of green bricks fired	26000	28500	30000	32356	20700	24000	24000	29000	29500	21000	26500	20000
Total weight of bricks fired (kg)	78624	87618	93152	98870	70385	80420	78480	87508	88943	73080	78661	71467
Energy Consumption - total (MJ/kg)	2.30	2.47	3.36	2.78	3.23	1.91	1.96	2.04	4.19	2.29	2.59	1.75
Energy Consumption - internal (MJ/kg)	1.73	2.06	2.63	2.48	2.48	1.42	1.45	1.52	3.57	0.75	1.28	1.33
Energy Consumption - scintle (MJ/kg)	0.57	0.40	0.73	0.29	0.67	0.45	0.46	0.42	0.62	1.49	1.32	0.36
Energy Consumption - scintle + firebox (MJ/kg)	0.58	0.41	0.73	0.30	0.75	0.50	0.51	0.52	0.62	1.54	1.32	0.42

5.2 RELATIONSHIP BETWEEN FUEL INPUT PARAMETERS AND EMISSION METRICS

Various fuel input parameters were analysed in order to determine their relationships with emission metrics. Correlation analysis was conducted using both Pearson and Spearman rank correlation to evaluate the relationships between fuel input parameters (including total sulfur, percentage total carbon, percentage total volatiles, percentage total ash); and emissions (including CO, NO_2, NO_x, SO_2 and PM_{10} emission factors). Correlation analysis was performed using the GNU PSPP™ version 0.9 software at 95% confidence interval, and is presented in Table 47. Significant relationships worthy of note are discussed below:

- A strong positive correlation is observed between total ash content in external fuel and PM emissions, indicating that higher ash content in external fuel yields higher PM emissions. No distinct relationship is observed between percentage ash content in internal fuel and PM emissions.
- A strong negative correlation is observed between sulfur content in internal fuel and SO_2 emissions, suggesting lower release of SO_2 emission with higher internal sulfur content. This indicates that more sulfur is captured within the brick with higher internal sulfur content and may be attributed to the complex reaction that occurs within the bricks, causing retention (rather than release) of sulfur in the bricks as $CaSO_4$ (Akinshipe & Kornelius, 2017a).
- A strong positive correlation is also observed between carbon content (both internal and external fuels) and CO emissions, indicating that higher carbon content in the fuels yields higher CO emissions, which is suggestive of inefficient combustion.
- A strong positive correlation is also observed between volatile compounds in external fuels and CO emissions, indicating that higher volatile compounds in the fuels also yield higher CO emissions, which is also suggestive of inefficient combustion.
- A strong positive correlation was also observed between the following: volatile compounds in external fuels and SO_2 emissions; total carbon in external fuel and SO_2 emissions.

Table 47: Correlation analysis evaluating the relationships between fuel input parameters and emission metrics

Emission Metrics / Fuel Parameters	Pearson Correlation					Spearman Rank Correlation				
	CO	NO_x	NO	SO_2	PM_{10}	CO	NO_x	NO	SO_2	PM_{10}
total sulfur (internal fuel)	-0.22	0.12	0.12	-0.69	-0.22	-0.48	0.19	0.19	-0.77	-0.13
total sulfur (external fuel)	-0.10	-0.23	-0.23	0.20	-0.15	0.17	-0.22	-0.22	0.35	0.03
total carbon (internal fuel)	-0.19	0.01	0.01	-0.02	-0.19	-0.22	0.06	0.06	-0.22	-0.01
total carbon (external fuel)	0.32	-0.17	-0.17	0.58	0.48	0.70	0.06	0.06	0.69	0.41
volatile compounds (internal fuel)	-0.35	0.25	0.25	-0.13	-0.30	-0.62	0.24	0.24	-0.31	-0.30
volatile compounds (external fuel)	0.28	-0.29	-0.29	0.63	0.38	0.75	-0.11	-0.11	0.62	0.47
total ash (internal fuel)	-0.02	-0.19	-0.19	-0.12	-0.08	-0.05	0.07	0.07	0.05	-0.26
total ash (external fuel)	0.32	-0.41	-0.41	0.14	0.61	0.33	-0.30	-0.30	-0.07	0.49

NOTE: "Very weak" = 0.0 – 0.19; "Weak" = 0.20 – 0.39; "Medium" = 0.40 – 0.59; "Strong" = 0.60 – 0.79; "Very strong" = 0.80 – 0.99

5.3 Evaluation of Energy Consumption and Output Metrics

A ranking of the specific energy consumption for each type of fuel (total, internal and external) is shown in Table 48. Ranking was done in ascending order of magnitude since lower values indicates higher energy efficiency. Batch 13 utilized the lowest total energy input per brick while Batch 10 utilized the highest energy input per brick.

Table 48: Ranking in ascending order of energy consumption

Batch	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13
Energy Consumption (External)	8	3	11	1	10	5	6	4	9	7	12	2
Energy Consumption (Internal)	7.5	7.5	11	10	9	3	4	5	12	6	1	2
Energy Consumption (Total)	8	7	11	9	10	2	3	4	12	5	6	1

In addition, a ranking of mean emission factors and process metrics published in Table 44 and Table 39 was also conducted and is presented in Table 49. Flue gas emission factors, including CO, NO_x, SO_2 and PM_{10}, as well as process metrics including, temperature, oxygen reference and percentage CO_2 were ranked in ascending order of magnitude.

Table 49: Ranking of output metrics' by batch

Batch	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13
Average CO concentration	10	3	7	1	4	ND	5	2	6	8	9	ND
Average NO_x concentration	7	5	4	1	10	ND	8	3	9	2	6	ND
Average SO_2 concentration	4	3	2	1	ND	ND	6	5	8	7	9	ND
Average PM_{10} concentration	12	6	9	3	4	2	1	5	8	10	7	11
Average temperature	12	3	7	8	5	1	9	2	10	6	11	4
Average percentage oxygen reference	11	1	6	4	2	3	10	7	9	5	8	ND
Average percentage CO_2	10	1	3	2	9	ND	6	4	7	5	8	ND

Correlation analysis was conducted using both Pearson and Spearman rank correlation to evaluate the strength of the sensitivity of flue gas emission concentration and process metrics to energy inputs across Batch 2 to Batch 13. Correlation analysis of data was performed using the GNU PSPP™ version 0.9 software. Spearman rank correlation utilized the rankings from Table 48 and Table 49, while the Pearson correlation utilized the energy consumption result from Table 46, emission factors from Table 44 and process metrics from Table 39. Analyses were performed with a 95% confidence interval.

The outcome of the correlation analysis is presented in Table 50, indicating that flue gas output metrics, including temperature, velocity, combustion efficiency, oxygen reference, excess air, percentage CO_2, as well as CO, NO_x, SO_2 and PM_{10} concentrations are most sensitive to the external energy input. Moderate to strong correlation is observed between the external energy and flue gas output metrics such as temperature, combustion efficiency,

percentage CO_2, as well as CO, NO_x and SO_2 concentrations. A weak correlation is observed with velocity, oxygen reference, excess air and PM_{10} concentration.

Output metrics are only slightly sensitive to internal and total energy. Velocity is the only metric that indicated a strong correlation, while temperature and SO_2 concentration exhibit slightly weak correlation with internal and total energy. Consequently, efforts to evaluate the correlation between energy input and output metrics were focused on the external energy.

A weighting was assigned to output metrics in Table 50 to indicate the sensitivity of each parameter to energy input (refer to last line in Table 50). The weighting assigned to each pollutant or process metric is based on the range which the highest correlation value falls. For instance, the highest correlation value obtained for temperature (0.50) falls under the 0.41 – 0.60, hence, a weighting of 3 was assigned to temperature.

A series of charts showing the rank correlation between the external energy and output metrics (including temperature, oxygen reference, percentage CO_2, as well as CO, NO_x and SO_2 concentrations) is depicted in Figure 82. It can be inferred that, while the rest of the batches show moderate to strong correlation, Batches 6, 7 and 13 exhibit poor correlations across all output metrics. These analyses are consistent with measurement outcomes, since it was established in Section 4.2 that Batches 5, 6, 7 and 13 firing campaigns were characterized with malfunction of the gas samplers as well as power failure. Also, Batch 5 and 6 yielded low data availability (in comparison with other batches) due to power failure issues. Therefore, it was concluded that Batches 5, 6, 7 and 13 gaseous emission results should be excluded in the final concentration and emission factor calculation.

Table 50: Correlation analysis of energy input and output metrics across Batches 2 − 13

Output metrics	Pearson correlation			Spearman rank correlation				
	Energy (external)	Energy (internal)	Energy (total)	Energy (external)	Energy (internal)	Energy (total)	Range [1]	Weighting
Average temperature	0.47	0.22	0.38	0.50	0.22	0.46	0.41 – 0.6	3
Oxygen reference	0.18	0.12	0.01	0.09	0.27	0.13	0.21 – 0.4	4
Percentage CO_2	0.55	0.29	0.51	0.71	0.21	0.31	0.61 – 0.8	2
CO	0.29	0.03	0.09	0.70	0.18	0.04	0.61 – 0.8	2
NO_x	0.23	0.28	0.03	0.49	0.08	0.26	0.41 – 0.6	3
SO_2	0.75	0.12	0.20	0.55	0.46	0.30	0.61 – 0.8	2
PM_{10}	0.06	0.10	0.12	0.23	0.09	0.16	0.21 – 0.4	4
Range and designated weighting								
"Very weak" (0.0 – 0.19) = 5	"Weak" (0.20 – 0.39) = 4		"Medium" (0.40 – 0.59) = 3		"Strong" (0.60 – 0.79) = 2		"Very strong" (0.80 – 1.00) = 1	

NOTE: [1] The weighting assigned to each pollutant or process metric is based on the range which the highest correlation value falls. For instance, the highest correlation value obtained for temperature (0.50) falls under the 0.40 – 0.59, hence, a weighting of 3 was assigned.

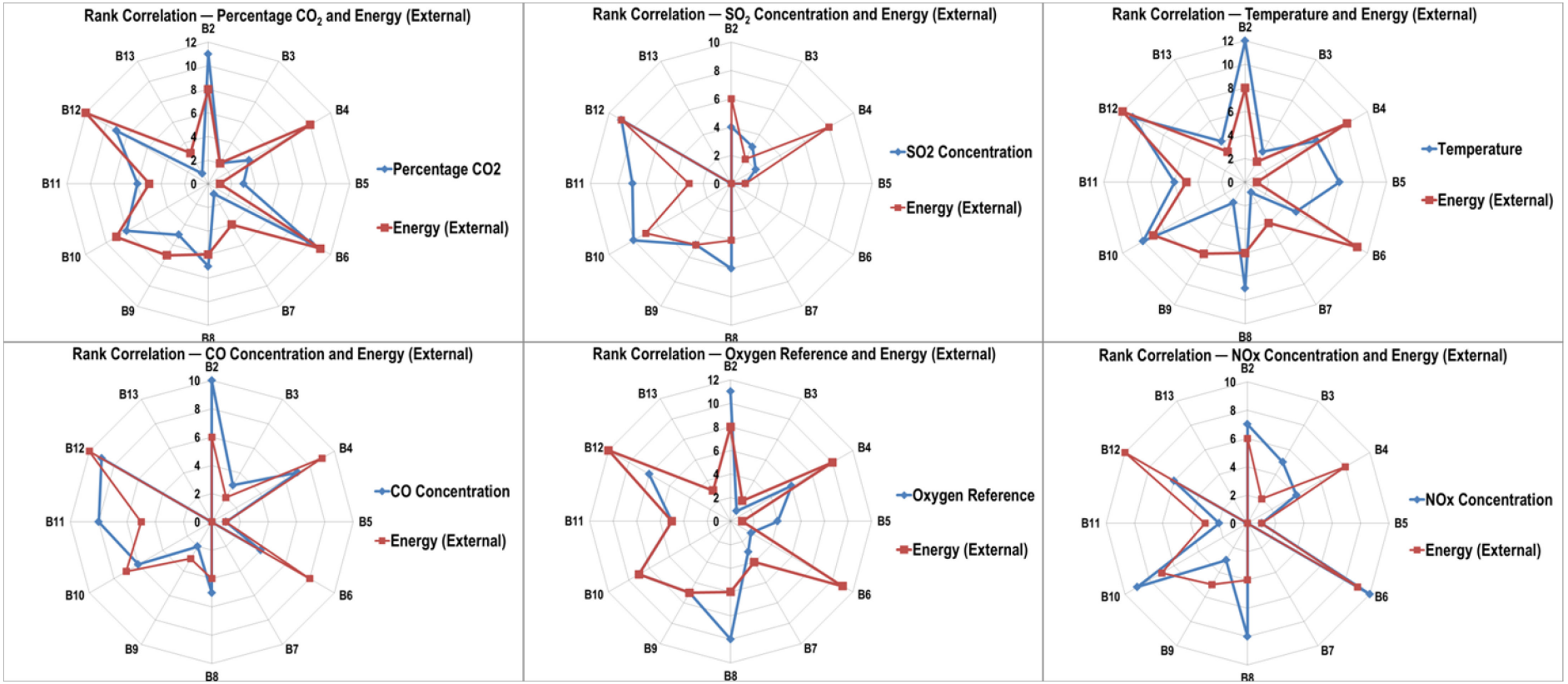


Figure 82: Rank correlation – External energy against output metrics (all batches show moderate to strong correlation, while Batches 6, 7 and 13 exhibit poor correlations)

Applying the assigned weighing in Table 50 to the rankings obtained in Table 49 produces a weighted ranking for all output metrics across Batch 2 to Batch 13. The mean of these weighted rankings is further calculated and ranked to produce a final ranking that is an indicator to the energy performance of each batch of firing.

Batch 3 produced the best performance in terms of external energy to output metrics sensitivity, while Batch 2 performed the poorest. Comparing the current South African industry SEC – 3.4 MJ/kg (Akinshipe and Kornelius, 2017b) to batch 3 SEC – 2.5 MJ/kg (since batch 3 produced the best energy performance) and to the average SEC from this study – 2.6 MJ/kg; the significant reduction of 0.8 – 0.9 MJ/kg (32% – 36%) indicates that the industry could achieve significant reduction in energy use, thereby potentially reducing cost of energy input, and also, significantly reducing the quantity of atmospheric emissions.

Table 51: Weighted rankings (WR) of output metrics' sensitivity to energy input – Batch 3 produced the best performance in terms of external energy sensitivity to output metrics, while Batch 2 performed the poorest

Output Metrics	**Weight**	**Weighted Rankings (WR)**											
		B2	**B3**	**B4**	**B5**	**B6**	**B7**	**B8**	**B9**	**B10**	**B11**	**B12**	**B13**
CO Concentration	2	6	7	11	ND	ND	ND	10	6	12	18	16	ND
NO_x Concentration	3	7	8	11	ND	ND	ND	21	6	27	9	15	ND
SO_2 Concentration	2	7	2	9	ND	ND	ND	12	10	16	14	18	ND
PM_{10} Concentration	4	20	4	14	ND	ND	ND	4	24	32	44	28	ND
Temperature	3	24	18	12	ND	ND	ND	27	6	30	18	33	ND
Oxygen Reference	4	8	2	6	ND	ND	ND	40	28	36	20	32	ND
Percentage CO_2	2	48	20	36	ND	ND	ND	12	8	14	10	16	ND
Mean of all WR	–	28.6	8.4	17.0	ND	ND	ND	18.0	12.6	23.9	19.0	22.6	ND
Ranking of mean of WR	–	8	1	3	ND	ND	ND	4	2	7	5	6	ND

NOTE:
ND implies "no data".
Batches 5, 6, 7 and 13 were excluded from the final ranking due to anomalies during measurement.

CHAPTER SIX

6 EMISSIONS CORRECTION AND MANAGEMENT MECHANISMS

6.1 MODEL KILN EVALUATION USING SULFUR MASS BALANCE

Sulfur mass balance analysis was conducted by accounting for the quantity of sulfur entering (sulfur input) and exiting (sulfur output) the firing system. The sulfur mass balance is based on the conservation law, which, for this study, is premised on the following equation:

$$S_{cm} + S_{bf} + S_{ef} = S_{fb} + S_{ra} + S_{em} \qquad \text{Equation 16}$$

Where:

S_{cm} = sulfur inherent in the clay material

S_{bf} = sulfur inherent in the body fuel

S_{ef} = sulfur inherent in the external fuel

S_{fb} = sulfur residue in the fired brick

S_{ra} = sulfur residue in the ash left over

S_{em} = sulfur emitted into the atmosphere as SO_2

Samples were collected from the body fuel, green bricks, fired bricks and left over ash for Batch 2 to Batch 13 firing runs and sent to the laboratory for sulfur content analysis. Laboratory results and analyses are given in Appendix C (Section 10.3), while the final analysis based on Equation 16, is presented in Table 52. The sulfur mass balance analysis provides a reference technique for assessing the model kiln's efficiency in capturing the sulfur emitted to the atmosphere (S_{em}). S_{em} is comprised of the emissions captured into the stack monitoring duct and emissions that escape from underneath the semi-enclosed sliding doors. In an ideal system, the percentage of output sulfur to input sulfur in the firing system will approach 100%, with the unaccounted percentage equivalent to the emissions that escapes underneath the semi-enclosed sliding doors.

Sulfur mass balance result shows varying percentages across various batches. Batches 2 and 9 mass balance results are close to the ideal condition (100%); while Batches 3, 4, 8 and 11 mass balance results deviate somewhat. Also, Batches 5, 10 and 12 results exhibit extremely diverging, while Batches 6, 7 and 13 results could not be calculated due to aforementioned errors. These results and laboratory analyses validate the decision to exclude Batches 5, 6 and 7 results from the final concentration and emission factor calculation (Section 5.2). In addition, laboratory results for non-conforming batches indicate an increase in the quantity of sulfur retained in fired bricks, when compared to the green bricks, implying retention of sulfur in the fired brick rather than anticipated

release of emissions. The following were identified as likely factors influencing the non-conformity of these batches' analyses to the ideal system:

- The complexity regarding oxidation and/or reduction reaction in the firing chamber. Generally, dominant oxidation conditions favour the release of sulfur as SO_2 emissions, while reduction conditions favour sulfur retention in brick as $CaSO_4$ and CaS (refer to Section 2.2).
- In order for mass balance analysis to be accurate, homogeneity during processing and mixing of clay bricks is required so as to ensure that the constituents of the clay and fuel material (including sulfur compounds) are evenly distributed across the whole batch. However, homogeneity may not be achieved since only two brick samples in 20000 – 35000 bricks were analysed per batch.

In order to calculate a useable average mass balance percentage, statistical analysis was performed to determine the batches whose mass balance result lie within 95% confidence interval of the assumed true mean i.e. 100%.

Assuming that Batch 2 to Batch 13 mass balance percentages represent samples of a population having a true mean of 100 % (the ideal mass balance percentage), a 95 percent confidence interval estimate of true mean is given by Ross (2014) as follows:

$$\boldsymbol{P\left\{\bar{X} - 1.96\,\frac{\sigma}{\sqrt{n}} < \mu < \bar{X} + 1.96\,\frac{\sigma}{\sqrt{n}}\right\} = .95} \qquad \text{Equation 17}$$

Where:

P = probability

$\bar{X}$ = sample mean

μ = true mean

σ = standard deviation

n = number of samples

The 95% confidence interval estimate of true mean falls within the range 40.9 < μ < 159.2. Therefore, all batches whose percentages fall within this range (shown by blue shading in Table 52) may be considered close to the true mean for which we have a 95% confidence level. The mean of the batches that are within the 95% confidence interval range of the assumed true mean (100%) yields 84.2%, which may be considered the statistical mean efficiency of capturing and channelling flue gas to the measuring point by the model kiln. Consequently, the statistical mean percentage of the emissions escaping underneath the semi-enclosed sliding doors will be equivalent to 15.8%. This average was taken as the overall indicator of the proportion of flue gas that escapes from underneath the semi-enclosed side boards, and will be utilized in correcting for final emission metrics.

Table 52: Sulfur mass balance analysis results

Batches	Percentage of output sulfur to input sulfur in the firing system	Deviation from assumed true mean – 100% (ideal mass balance condition)
2	98.4%	1.6%
3	72.8%	27.2%
4	65.0%	35.0%
5	222.2%	-122.2%
6	Not available	Not available
7	Not available	Not available
8	58.0%	42.0%
9	98.9%	1.1%
10	351.3%	-251.3%
11	112.3%	-12.3%
12	30.1%	69.9%
13	Not available	Not available
Mean [1]	84.2%	15.8%

NOTE:

[1] The mean is calculated from the mass balance result of the batches that lie within the 95% confidence interval of the assumed true mean – 100% (blue shading).

6.2 Final Emission Rates and Emission Factors

To account for emissions losses released underneath the semi-enclosed side boards, a statistical mean was calculated in Section 6.1 which is equal to 15.8% of the measured emissions. Therefore, each measurement was increased by 15.8%. Final adjusted emission rates and emission factors are provided in Table 53.

Final emissions factors (excluding hydrocarbon emissions) published in this study are assigned an emission factor rating of "A – excellent", based on description recommended by USEPA (1995). Emission factor for hydrocarbon emissions is assigned a rating of "D – below average". Emission factor rating is defined as "a general indication of reliability or robustness of the emission factors, and are assigned based on the projected reliability of the tests and techniques utilized in their development (USEPA, 1995).

Table 53: Final emission rates and emission factors corrected for occasional losses from underneath the sideboards

15.8 % correction	g/s		g/s brick		g/brick		g/kg of fired bricks	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
CO	7.99×10^{-1}	6.60×10^{-1}	2.78×10^{-5}	2.08×10^{-5}	22.5	18.8	7.83	6.65
NO_x/NO	4.52×10^{-3}	2.43×10^{-3}	1.62×10^{-7}	1.10×10^{-7}	0.14	0.10	0.05	0.03
NO_2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SO_2	4.17×10^{-2}	3.13×10^{-2}	1.51×10^{-6}	1.16×10^{-6}	1.07	0.66	0.38	0.25
CO_2	1.50×10^{1}	7.64×10^{0}	5.02×10^{-4}	3.12×10^{-4}	378	223	132	79.7
PM_{10}	3.24×10^{-2}	1.51×10^{-2}	1.27×10^{-6}	6.48×10^{-7}	0.96	0.47	0.34	0.17
PM_{15}	3.24×10^{-2}	ND	1.27×10^{-6}	ND	0.96	ND	0.34	ND
PM_4	3.24×10^{-2}	ND	1.27×10^{-6}	ND	0.96	ND	0.34	ND
$PM_{2.5}$	3.24×10^{-2}	ND	1.27×10^{-6}	ND	0.96	ND	0.34	ND
PM_1	3.23×10^{-2}	ND	1.27×10^{-6}	ND	0.96	ND	0.33	ND
HC	5.10×10^{-2}	ND	1.74×10^{-6}	ND	1.53	ND	0.45	ND

Based on a production rate of 3.4 billion bricks per annum for South Africa clamp kilns, estimated annual emissions for various pollutants, as well as potential emissions reduction based on 36% reduction in energy consumption (Section 5.3) are quantified in Table 54.

Table 54: Tons per annum of emissions based on 3.4 billion bricks produced per annum by SA clamp kilns

Emissions	Tons per annum of emissions	
	Total emissions from SA clamp kilns	Potential emissions reduction (36%)
CO	76 466	27 528
NO_x/NO	476	171
NO_2	0	0
SO_2	3 638	1 310
CO_2	1 286 594	463 174
PM_{10}	3 264	1 175
PM_{15}	3 264	1 175
PM_4	3 264	1 175
$PM_{2.5}$	3 264	1 175
PM_1	3 264	1 175
HC	5 202	1 873

6.3 COMPARISON WITH EMISSION FACTORS FROM LITERATURE

Final emission factors from this study were compared with applicable emission factors obtained from literature for different clay brick firing technologies, including BTK (Asia), DDK (Asia), Tunnel (Asia), VSBK (Asia), zig-zag (Asia), FCBTK (Asia), coal-fired (US) and Southeast Asia clamps (Table 55). A ranking of various firing technologies based on available emission metrics is presented in Table 56. CO emission factor for clamp kiln from the current study, although comparable to the DDK, is higher than emission factors obtained from literature for various firing technologies. Mean percentage fixed carbon content of coal samples from this study (45.6%) was compared with mean percentage fixed carbon of Indian coal samples (31.6%) obtained from Mishra (2009). Therefore, higher CO emissions from the study may be attributed to higher carbon content in South African coals used for clamp kiln firing (44% higher carbon content than Indian coal samples).

With respect to SO_2 emission factor, kiln technologies are ranked from lowest to highest potential for atmospheric pollution as follows: Zig-zag < SA clamps < Vertical shaft < US coal-fired < Fixed chimney Bull's trench < Tunnel. PM/PM_{10} emission factor from current study is less than those from the BTK, DDK, US coal fired, FCBTK, Asian clamps, but higher than the Zigzag, tunnel and VSBK. NO_x emission factor is lower than the USEPA coal fired kiln by a factor of six. Based on this analysis, it can be inferred that South African clamp kiln emissions are extremely high with respect to CO emissions (higher than all technology available for comparison); and moderate in terms of SO_2, CO_2 and PM/PM_{10} emissions. NO_x emissions are considered to be extremely low when compared to US coal fired kilns. Kiln technologies were ranked from lowest to highest potential for atmospheric pollution based on available emission metrics as follows: Zig-zag < Vertical shaft < South African Clamp < US coal-fired < Fixed chimney Bull's trench < Tunnel < Asian Clamps < Down draft < Bull's trench.

Table 55: Comparing emission factors from current study and from literature

Emission Factors (g/brick)									
Reference (Location)	**Kiln Type**	**SO_2**	**CO**	**NO_x**	**CO_2**	**PM**	**PM_{10}**	**$PM_{2.5}$**	**PM_4**
Current Study (SA)	Clamp	1.07	22.5	0.14	378	0.96	0.96	0.96	0.96
Maithel et al. 2012, Weyant et al. 2014 (Southeast Asia)	FCBTK	1.91	6.53	–	–	2.49	–	0.52	–
	Zig-zag	0.93	4.26	–	182	0.75	–	0.38	–
	VSBK	1.57	5.34	–	166	0.32	–	0.26	–
	DDK	–	16.8	–	–	4.52	–	2.81	–
	Tunnel	2.09	7.11	–	–	0.9	–	0.52	–
USEPA, 1997a (USA) [1]	Coal fired kiln	1.74	1.16	0.74	–	2.61	2.03	–	–
Baum, 2010, re-calculated in Lopez *et al,* 2012 (Southeast Asia)	Clamp	–	–	–	471	1.91	–	–	–
	BTK	–	–	–	249	8.06	–	–	–
	FCBTK	–	–	–	232	1.71	–	–	–
Emission Factors (g/kg)									
Reference (Location)	**Kiln Type**	**SO_2**	**CO**	**NO_x**	**CO_2**	**PM**	**PM_{10}**	**$PM_{2.5}$**	**PM_4**
Current Study (SA)	Clamp	0.38	7.83	0.05	132	0.34	0.34	0.34	0.34
Maithel *et al,* 2012 (Southeast Asia)	VSBK	0.54	1.84	–	70.0	0.11	–	0.09	–
	Tunnel	0.72	2.45	–	166	0.31	–	0.18	–
	FCBTK	0.66	2.25	–	115	0.86	–	0.18	–
	Zig-zag	0.32	1.47	–	103	0.26	–	0.13	–
	DDK	–	5.78	–	282	1.56	–	0.97	–
Maithel *et al,* 2014a, 2014b, 2014c, 2014d, 2014g, 2014h, 2014i (Southeast Asia)	VSBK	–	1.80	–	70.5	0.15	–	–	–
	Tunnel	–	3.31	–	166	0.24	–	–	–
	FCBTK	–	2.00	–	131	1.18	–	–	–
	Zig-zag	–	1.60	–	103	0.24	–	–	–
	DDK	–	5.78	–	–	1.56	–	–	–
Baum, 2015 (Southeast Asia)	VSBK	–	–	–	–	0.10	–	0.09	–
	Tunnel	–	–	–	–	0.26	–	0.18	–
	FCBTK	–	–	–	–	1.18	–	0.18	–
	Zig-zag	–	–	–	–	0.21	–	0.09	–
	DDK	–	–	–	–	1.55	–	0.95	–

NOTE: [1] Type of kiln not specified

Table 56: Ranking of various firing technologies based on available emission metrics

Kiln Type	SO_2	CO	NO_x	PM/PM_{10}	CO_2	Final Score	Final Rank
DDK (ASIA)	No data	6	No data	8	7	7.0	8
Coal fired (US)	4	1	2	7	No data	3.3	4
FCBTK (ASIA)	5	4	No data	6	3	4.5	5
Clamps (Asia)	No data	No data	No data	5	6	5.5	7
Clamps (SA)	2	7	1	4	3	3.1	3
Tunnel (ASIA)	6	5	No data	3	5	5.3	6
Zig-zag (ASIA)	1	1	No data	2	2	1.5	1
VSBK (ASIA)	3	2	No data	1	1	1.6	2
BTK (ASIA)	No data	No data	No data	9	No data	9.0	9
Lowest emissions						**Highest emissions**	
1	2	3	4	5	6	7	8	9

6.4 EMISSION CONTROL AND MANAGEMENT MEASURES

6.4.1 EMISSION CONTROL MEASURES

It has been established in previous studies (DEA, 2012; Akinshipe, 2013; Akinshipe & Kornelius 2017a; 2017b), as well as in this study, that the complex configuration of clamp kilns and the pseudo-enclosed nature of its firing chamber make it difficult for emissions to be controlled or captured into a stream where they can be fitted with emission control devices such as bag filters, scrubbers, flue gas desulfurization systems, electrostatic precipitators, etc. As a result, clamp kiln emission control efforts should be aimed at modifying the combustion and firing process to reduce the quantity of emissions, rather than efforts aimed at capturing and containing the release of emissions.

The model kiln design, which has proven to be an effective method for capturing and channelling emissions, whilst still maintaining the quality of fired bricks, cannot be economically scaled up to full size clamp kilns and may not be as efficient. The simple design utilized by the model kiln cannot be applied to a large scale kiln, thus, a complex and cumbersome design, as well as a huge financial commitment may be required. Further research may be conducted to attempt the application of the model kiln design to large-scale clamp kilns.

The following measures have been identified as effective means of modifying the combustion and firing process in order to reduce the quantity of emissions from a clamp kiln:

- Measures targeted at reducing the energy input in order to minimize release of atmospheric emissions. It was shown that the South African clamp kiln industry's SEC (3.4 MJ/kg) could be potentially reduced to 2.5 (MJ/kg) without compromising the firing process or quality of bricks fired (described in Section 5.2). This offers a 36% potential reduction in energy consumption for South African clamp kilns.
- Measures targeted at reducing the external energy consumption or modifying the ratio of the external energy to internal energy consumption during the firing process. It was also shown in Section 5.2 that emission and process metrics were most sensitive to the external fuel in the "scintle" of the kiln. Therefore, reducing the quantity of external energy consumed could potentially reduce emissions. The average ratio of external to internal energy calculated from field data in this study is 0.35.
- Measures aimed at regulating the complex oxidation and reduction reactions occurring in the firing chamber of the kiln. This involves promoting or favouring reducing conditions in the firing chamber of the kiln in order to minimize atmospheric emissions, while ensuring the retention of CaS and $CaSO_4$ within the bricks – refer to Section 2.2 (Akinshipe & Kornelius, 2017b).
- Measures aimed at regulating the complex thermodynamic processes in the firing chamber of the kiln. This involves regulating the firing chamber temperature at certain levels for a specific duration in order to regulate the exothermic and endothermic complexes in the kiln, which in turn controls the chemical processes and the release of pollutants associated with those processes. For instance, NO_x emissions are only given off at certain higher temperatures; while significant $CaSO_4$ retained within the clay brick material can only be decomposed to give off SO_2 at extreme temperatures (i.e. above 1200 ^oC). Hence,

maintaining peak temperatures below 1200 ^{o}C reduces the potential for SO_2 emissions (Akinshipe & Kornelius, 2017b).

6.4.2 Recommendations for Clamp Kiln Operation

The following recommendations are offered for clamp kiln operators:

- Clamp kiln operators should ensure that crushing, screening, milling and mixing of clay material and other additives is adequate to achieve homogeneity. Homogeneity during processing and mixing of material is required to ensure that the constituents of clay and fuel material are evenly distributed across the firing batch and therefore result in even firing of bricks as well as steady release of air emissions.
- Clamp kiln operators should monitor their kiln temperature by distributing thermocouples within the kiln in order to monitor and ensure a steady rise or fall in temperature. It has been established that a steadier temperature profile produces higher quality brick products and a steady release of air emissions than inconsistent temperature profile
- Clamp kiln operators should ensure that they utilize clay and coal materials that contain lower sulfur, carbon and metal contents available in their location and market. Periodic testing of clay and coal material constituents should be done to identify the most suitable for that period.
- Clamp kiln operators should reduce or attempt to reduce their coal use by reducing their current specific energy consumption as much as possible (closer to 2.5 MJ/kg) without compromising the firing process. Reduced energy consumption will result in reduced air emissions (refer to Section 5).
- Clamp kiln operators should ensure adequate sun drying of bricks prior to firing. Adequate drying will help reduce the energy consumption required for water-smoking or slow heating stage of the firing process where evaporation of "free or mechanical water" takes place (refer to Table 2).

6.4.3 Air Quality Management and Dispersion Modelling

Ambient air quality around a clamp kiln is most likely to be affected by air pollution. This is due to the localised effect of the emission on the immediate environment as a result of the low height of release and the limited buoyancy of the relatively cool emissions (compared to other industrial processes). It is therefore expedient to identify the area around clamp kiln operations which may potentially be affected by clamp kiln emissions.

A screening level dispersion simulation was conducted using Lakes' Screen View 3.5.0 model to simulate ground level concentration of pollutants within 5 km of a small clamp kiln (1 million bricks), medium clamp kiln (2.5 million bricks) and large clamp kiln (10 million bricks). The corrected final emission rates published in Section 6.2 were used to simulate ground level concentrations, assuming worst case meteorological conditions and a volume source configuration for the kiln. A release height of 4.2 m was used (Akinshipe, 2013), and the dimensions of bricks were taken as the standard South African brick i.e. 22.2 mm X 10.6 mm X 7.3 mm (CBA 2002; CBA, 2015b).

The result of the dispersion simulation is shown in Figure 83. Annual concentrations were extrapolated from hourly concentration by applying one of the methodologies described by Beychok (1994). Simulated annual ambient concentrations were then compared against their respective South African National Ambient Air Quality Standards (NAAQS), indicating that concentrations exceeded the limit from the kiln up to a distance of 600 m, 1100 m, 2100 m (for CO emissions); 800 m, 1400 m, 3100 m (for SO_2 emissions) and 1100 m, 2000 m, 4600 m (for PM_{10} emissions); for small, medium and large kilns respectively. It should be noted that, while worst case conditions have been simulated, this simulation does not account for cumulative impact (i.e. the effect of other sources in the vicinity of the kiln).

Consequently, it is recommended that an impact zone – an area where residential occupation should be restricted – be delineated around clamp kiln installations based on findings of site-specific air quality impact assessment studies. Where a site-specific air quality impact assessment study is not available, a suggested impact zone of 500 m, 1000 m and 2000 m from the clamp kiln area may be adopted for small, medium and large kilns respectively.

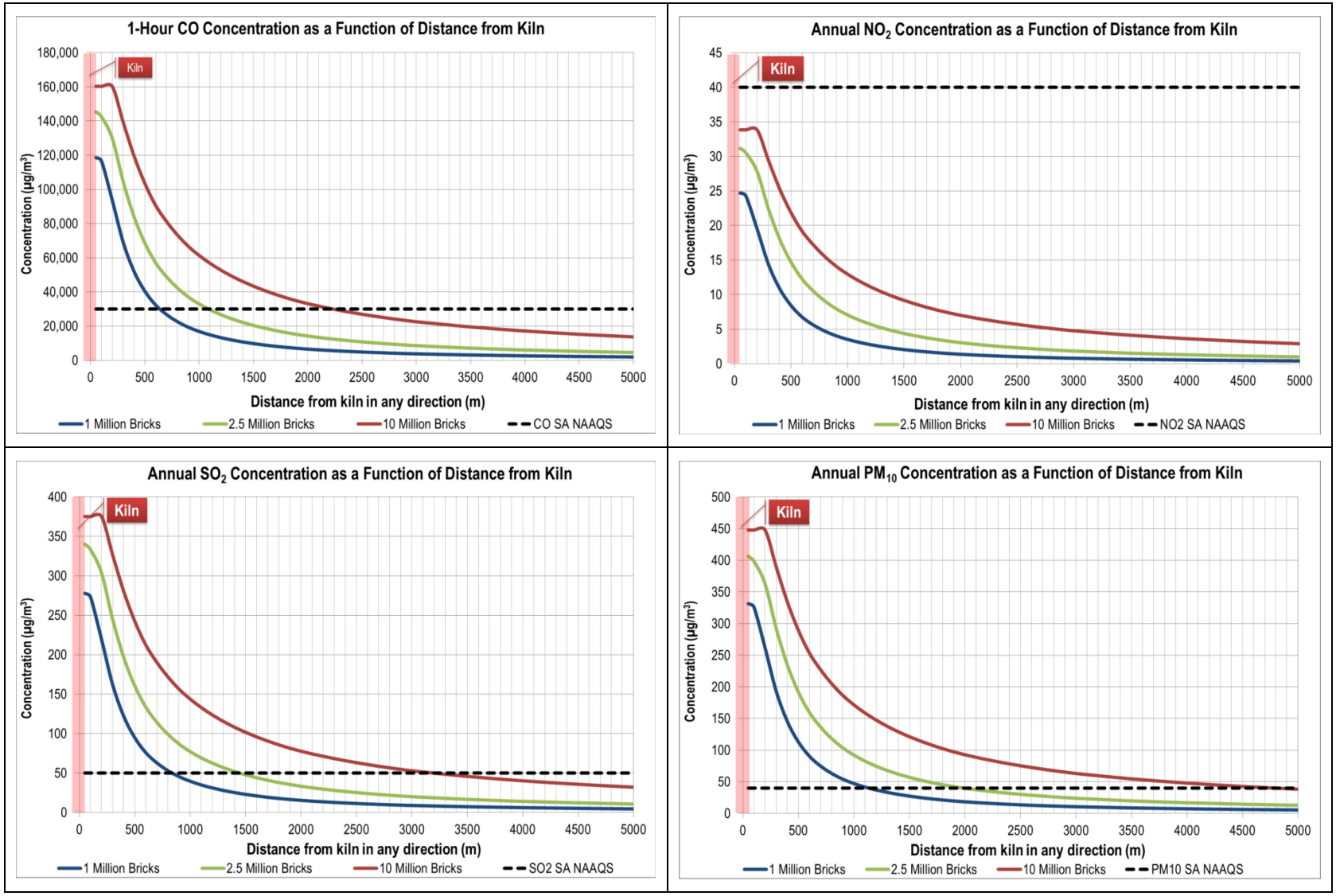


Figure 83: Screening level dispersion simulation results – worst case ground level concentration as a function of distance from clamp kiln

CHAPTER SEVEN

7 ALTERNATIVE ENERGY USE FOR CLAMP KILNS – PROPANE GAS AS EXTERNAL FUEL

7.1 BACKGROUND

It was established in Section 5 that the external energy component utilized in clamp kiln firing is most sensitive to release of atmospheric emissions. Hence, measures aimed at improving the energy efficiency of the kiln were targeted at reducing external energy consumption. In this section, a pilot study was conducted to substitute the external fuel (coal) with a locally available alternative, liquidified petroleum gas (LPG) or propane gas. The consideration for propane gas was based on its portability and accessibility to site, as well as cost effectiveness and suitability in being adapted for clamp kiln firing. It was anticipated that use of an energy alternative might improve clamp kiln firing efficiency and consequently result in reduction of atmospheric emissions.

7.2 METHODOLOGY FOR PACKING AND FIRING

The external fuel in the 'scintle' layer of the kiln was replaced with propane gas in this pilot test in order to determine the potential for emissions reduction. Green bricks for this firing were obtained from the same factory as Batch 2 firing run. Intrinsic properties of clay material, handling, processing, drying as well as internal energy input are expected to be similar to the Batch 2 firing run (refer to Section 3). The difference with this firing run is in the external energy use and brick packing methodology.

The setting and packing of bricks for the propane gas firing differs from the setting and packing for the coal-firing runs in the bottom three layers only. The approach to the propane gas firing is to pack the bottom layer in a honeycomb pattern and fire propane gas into that honeycomb at gradually increasing flow rate over the ignition period. In packing bricks for the propane gas firing, two flues or vents of about 20 cm width each, evenly spaced on the short side of the kiln, are formed at right angles to the sides of the model kiln at one end (northern end) using previously fired bricks (it should be recalled that the model kiln is 7.5 m long by 3 m wide). The vents run to the middle of the model kiln where a one-brick wall of previously fired bricks is used to partition the kiln, separating it from another set of flues on the other side of the kiln (southern side). Hence, four separate flues running outwards from the middle of the kiln are formed. The bottom course consist of previously fired bricks packed with their lengths at right angles to the vents, with spaces of one or two fingers wide between them to allow for free flow of hot gases within the bottom layers. The second course also consists of previously fired bricks set at an angle of 45 degrees to those in the first course (Figure 84).

Figure 84: First and second course of bricks packed from one end of the kiln to the middle (left); and from the other end to the middle of the kiln (right)

The third course consists of green bricks set at right angle to those in the second course below; with one or two finger size spaces between them to allow for free flow of hot gases within the layer (see top pictures in Figure 85). The fourth course of green bricks is packed parallel to the vents to seal in the flue gas, with bricks packed perpendicularly on top of the flue space to seal in the flue (see bottom pictures in Figure 85). Hence, there is no vertical continuation of the vent beyond the third course, but a few finger spaces are left between the bricks along the centre line of the kiln to make the setting permeable to hot gases within the firing chamber of the kiln. Subsequent course of green bricks are packed in similar fashion to the fourth course bricks, just like they are packed in traditional clamp kilns.

The model kiln is covered in the normal way with previously fired bricks, the vent space left opened to accommodate the gas burners blowing hot combustion gas into the vent.

Figure 85: Third course of bricks (top pictures) and fourth course of bricks (bottom pictures)

Kiln firing and concurrent stack monitoring was conducted for the pilot test in March 2017. The gas setup is shown in Figure 86. Propane gas is fed from storage vessels through evaporators to four individual burners that deliver a flame length of about 3 m reaching the centre of the kiln. The burners were not specially made up; the closest available size to that required was used. The amount of propane gas was calculated from typical 'scintle' total energy content, reduced by 25% to allow for better expected firing efficiency for gas when compared to coal firing. 766 kg of propane gas was supplied to the four burners at varying duration over 16 hours as follows:

- 1/8 of full burner capacity for 4 hours (1101 MJ/hour of energy used);
- 1/4 of full burner capacity for 4 hours (2202 MJ/hour of energy used);
- 3/8 of full burner capacity 4 hours (3303 MJ/hour of energy used); and
- 1/2 of full burner capacity for 4 hours (4404 MJ/hour of energy used).

Figure 86: Model kiln firing set up using propane gas as external fuel from the northern end (left) and southern end (right) of the model kiln – Propane gas is fed from storage vessels through evaporators to four individual burners that deliver a 3 m flame length into the vents (vent openings are sealed off with mineral wool)

Input and firing conditions, observations and parameters recorded during this monitoring campaign are presented in Table 57. These variables are compared with Batch 2 firing data since the bricks are obtained from the same factory.

Table 57: Input and observations during propane gas firing and monitoring

Input and Observation	Firing and Monitoring Batch	
	Batch 14 (Propane gas-fired)	Batch 2 (coal-fired)
Date and time of firing and monitoring (start)	1st March 09:00	26th November 12:00
Date and time of firing and monitoring (end)	12th March 16:00	5th December 17:00
Year of firing	2017	2014
Stack cross-sectional area (m^2)	0.13	0.13
Frequency of data logging (second)	1	1
Duration of data logging per hour (minutes)	5 – 6	5 – 6
Monitoring equipment used (PM)	A & C	A
Monitoring equipment used (Gases)	B	B
Total hours of firing	272	211
Total hours of monitoring	254	191
Total hours of missing data	18	20
Percentage data availability (%)	93.4%	90.5%
Number of hours of precipitation	4	8
Number of hours fan was off during monitoring	125	0
% of time fan was off during monitoring	46%	0%
Number of green bricks fired	25400	26000
Quantity of coal in bricks (kg)	5080	5933
Quantity of energy in bricks (MJ)	91 694	135 692
Quantity of coal as external fuel (kg)	NA	2543
Quantity of energy as external fuel (MJ)	NA	44 499
Quantity of propane gas as external fuel (kg)	766	NA
Quantity of energy in propane gas (MJ)	35 236	NA
Quantity of coal in fire box (kg)	NA	50
Total energy utilized in firing (MJ)	126 930	181 066
Specific energy consumption (MJ/kg)	1.65	2.30

NOTE:

"ND" implies "no data"
"NA" implies "not applicable"
A = Sidepak™ Personal Aerosol Monitor Model AM510
B = E INSTRUMENTS Model 5500
C = DustTrak™ DRX Handheld Aerosol Monitor Model 8534

7.3 Results and Discussion of Pilot Test Firing using Propane Gas

7.3.1 Firing Evaluation

It is essential to evaluate the performance of the pilot test firing using propane gas as external fuel in firing clay bricks that meets industry standards or requirement. The bricks can be categorized as under-fired, partially fired and evenly fired, based on their extent of firing (Figure 87).

Figure 87: Under-fired brick (left), partially fired brick (middle) and evenly fired brick (right) from the propane gas firing run

Physical evaluation was conducted during unpacking of the fired bricks, indicating different degree of firing within the firing chamber of the kiln. It can be observed that the bricks at the top section of the kiln were mostly evenly fired, while the bottom bricks were under-fired and partially fired (Figure 88). It was also observed that the bricks on top of the vent in a vertically pattern (and those close enough to the vent) were evenly fired, while the bricks further away from the vent were partially or under-fired.

Figure 88: Cross section of model kiln firing chamber showing under-fired, partially fired and evenly fired bricks during unpacking from the northern side of the kiln (left); and under-fired bricks from the south side during unpacking of the kiln (right)

The varying degree of firing identified at sections of the firing chamber of the kiln suggests inadequacies in the propane gas ignition process. These inadequacies may include:

- Insufficient number of vents to ensure uniform circulation of hot gases within each course of brick;
- Inadequate and/or inappropriate sizing of bottom burners;
- Inadequate spacing of the bricks in the bottom layers to allow for free flow of hot gases circulating uniformly across each layer or course of bricks; and
- The shutting down of the propane burners may have been too sudden. A more appropriate approach may be to consistently decrease the flow rate of the burners in similar fashion to the start-up process i.e. decrease from 1/2 flow rate to 3/8 flow rate to 1/4 flow rate to 1/8 flow rate and then final shutdown.

7.3.2 EMISSIONS RESULT – PILOT TEST FIRING USING PROPANE GAS

Emissions results obtained from stack monitoring for the propane gas firing run is presented in this section along with discussions. Pollutant concentrations are presented in mg/m^3 (refer to Section 1.3). It should be noted that this run was also characterized by malfunction of the bifurcated fan (refer to Table 57); though stack monitoring was conducted for the entire firing duration, with data availability above 93%. CO, NO_x/NO, SO_2 and PM_{10} concentration time series plot are presented in Figure 89, while temperature and velocity time series plots are presented in Figure 90. Histograms of emissions as well as flue gas temperature and velocity are also shown in Figure 91 for each firing batch. Polynomial curves are utilized in this section to better illustrate time trends over the firing period. The bifurcated fan was turned off for 125 hours (46%) of the entire firing cycle due to malfunction.

Measured CO concentration shows similar trend to the coal-fired runs, with concentration initiating at zero or low levels; gradually rising and reaching peak concentrations around 150 hours (i.e. third quarter of firing duration); and

gradually falling again to low levels towards the end of the firing cycle. CO emissions show a positively skewed histogram (leaning towards lower emissions), typical of kiln combustion process which gradually ignites fuel and carbonaceous compounds in the bricks; and burning out over time.

Measured NO_2 emission was not detected throughout the entire firing duration. Similar to the coal-fired runs, this is attributed to the high temperature occurring within the kiln, since it has been established that NO is preferentially formed from combustion of fossil fuels at high temperatures. In a typical combustion chamber, thermodynamic equilibrium is formed between nitrogen, oxygen, NO and NO_2 at temperatures in the combustion ranges. Hence, the higher the temperature, the more the equilibrium shifts to the production of NO rather than NO_2 (Bartok & Sarofim, 1991; Heywood, 1988; USEPA, 1999).

NO_x measurements for all batches recorded the same values as the NO, since NO_2 is not released from the kiln during propane gas firing. The measured NO_x /NO show concentration initiating at low levels, with a gradual rise in levels during the first and second quarter of the firing cycle; and reaching peak concentrations at about 140 hours (i.e. third quarter of firing), and gradually falling again to low levels towards the end of the firing cycle. NO_x emissions show a positively skewed histogram (leaning towards lower emissions), which is also typical of kiln combustion process.

Measured SO_2 concentration also showed similar trend to the coal-fired runs, with concentration initiating at low levels; and reaching peak concentrations within 160 hours (i.e. second and third quarter of firing duration), and gradually falling again to low levels towards the end of the firing cycle. SO_2 emissions show a positively skewed histogram (leaning towards lower emissions), which is also typical of kiln combustion process. A consistent low or zero emission is recorded for first 120 hours of the firing run, followed by a sudden spike in levels, peaking within 24 – 30 hours and dipping again to ambient levels towards the end of the firing cycle. The sudden spike in SO_2 levels is most likely due to the oxidation of the pyrite component (FeS_2) in the clay material, oxidation of the sulfur component of the internal fuel (coal that is mixed with the clay material during brick processing) and the dissociation of $CaSO_4$ in an oxidizing environment within the clay material to release SO_2 (refer to Section 2.2).

Measured PM_{10} concentration does not exhibit any consistent trend, with concentration initiating at mid to high levels, rising and falling over the firing period. PM_{10} emissions show a positively skewed histogram (leaning towards lower emissions), typical of kiln combustion process which gradually ignites fuel and release particulates as combustion proceeds; and burning out over time. In order to correct PM concentration obtained from the DustTrak monitor to gravimetric concentrations, the calibration factor of 0.61 described in Section 3.3.2.1 was utilized.

The temperature profile showed similar trend to the coal-fired runs, with temperature levels initiating at ambient levels; gradually rising and reaching the peak within 170 hours (i.e. third quarter of firing duration), and gradually falling again to ambient levels towards the end of the cycle. Temperature levels show a positively skewed histogram (leaning towards lower temperature levels), also typical of kiln combustion process. A slight rise and fall in temperature levels, following a diurnal and nocturnal temperature rise and dip is also observed.

Measured flue gas velocity does not exhibit any consistent trend, generally initiating at mid to high levels, rising and falling over the firing period. Velocity levels show negatively skewed histogram (leaning towards higher velocity levels). This is also a similar trend to the coal-fired runs, further affirming the notion that flue gas velocity at the stack may be controlled by the extraction fan and meteorological components such as wind speed and wind direction, rather than by convective processes inside the firing chamber of the kiln. Also, it was observed that at high wind speeds, visible smoke can be seen coming out from under the semi-enclosed air inlet at the opposing side to the direction of the wind. CO, NOx/NO, NO_2 and SO_2 emissions summary, as well as flue gas temperature and velocity summary are presented in Table 58. Size-segregated PM concentrations corresponding to PM_1, $PM_{2.5}$, respirable or PM_4, PM_{10}, and PM_{15} are presented in Table 59.

Table 58: CO, NOx/NO, NO_2 and SO_2 emission concentrations; temperature and velocity summary for propane gas firing run

	CO	NO_x/NO	NO_2	SO_2	CO_2	Temperature	Velocity
	mg/m³	mg/m³	mg/m³	mg/m³	mg/m³	°C	m/s
Max.	2778.0	26.0	0.0	178.0	36860	210.0	9.0
Mean	342.6	3.0	0.0	23.3	8536	72.4	4.9
SD	505.7	5.1	0.0	46.0	11 058	54.5	2.9
Median	39.0	1.0	0.0	0.0	1940	47.0	6.0
Min.	0.0	0.0	0.0	0.0	0.0	18.0	0.0

NOTE: "SD" implies "standard deviation"; "Max." implies "maximum"; while "Min." implies "minimum"
CO_2 emission is calculated from percentage measured by the gas sampler.

Table 59: Size-segregated PM concentrations during propane gas firing in mg/m³

Size-segregated PM Concentrations (mg/m³) – Propane Gas Firing					
	PM_1	$PM_{2.5}$	PM_4	PM_{10}	PM_{15}
Maximum	150	150	150	150	150
Mean	48.2	48.9	49.0	49.3	49.3
Mean as percentage of PM_{15}	97.7%	99.1%	99.4%	100%	100%
Standard Deviation	60.8	61.7	61.8	62.0	62.0
Median	4.07	4.07	4.07	4.07	4.08
Minimum	0	0	0	0	0
PM Concentrations correction to gravimetric concentration (calibration factor = 0.61)					
	PM_1	$PM_{2.5}$	PM_4	PM_{10}	PM_{15}
Mean	29.4	29.8	29.9	30.1	30.1
Standard Deviation	37.1	37.7	37.7	37.8	37.8

A variability plot is shown in Figure 92 for CO, NO_x/NO and SO_2 concentrations, as well as for flue gas temperature and velocity. The CO, NO_x/NO and SO_2 emission variability plot indicates skewed emissions (leaning towards lower concentrations); suggesting a high variability in data with little consistency over the firing period. Flue gas temperature and velocity showed less variability in data and steadier levels over the firing period.

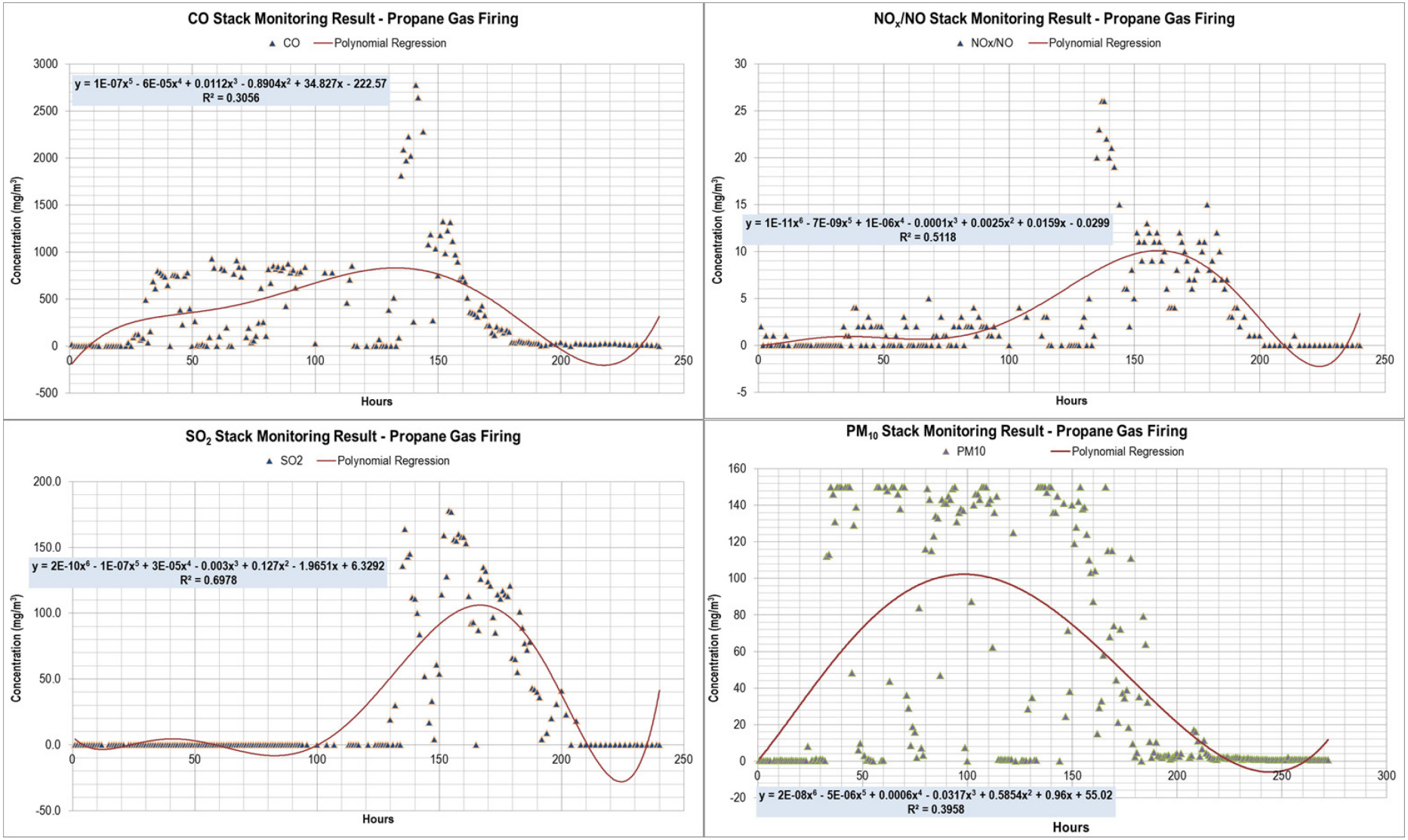


Figure 89: CO, NOx/NO, SO_2 and PM_{10} emissions concentrations in mg/m^3 during propane gas firing (hours 1 – 125 experienced malfunction of the bifurcated axial fan)

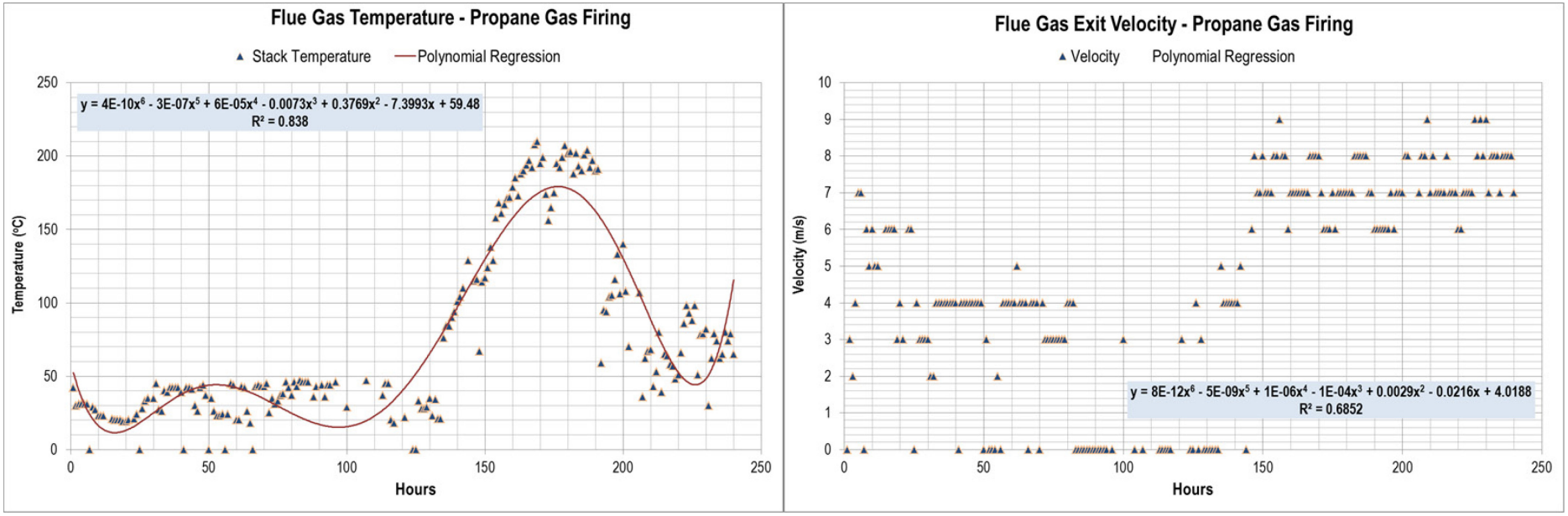


Figure 90: Flue gas temperature and exit velocity during propane gas firing (hours 1 – 125 experienced malfunction of the bifurcated axial fan)

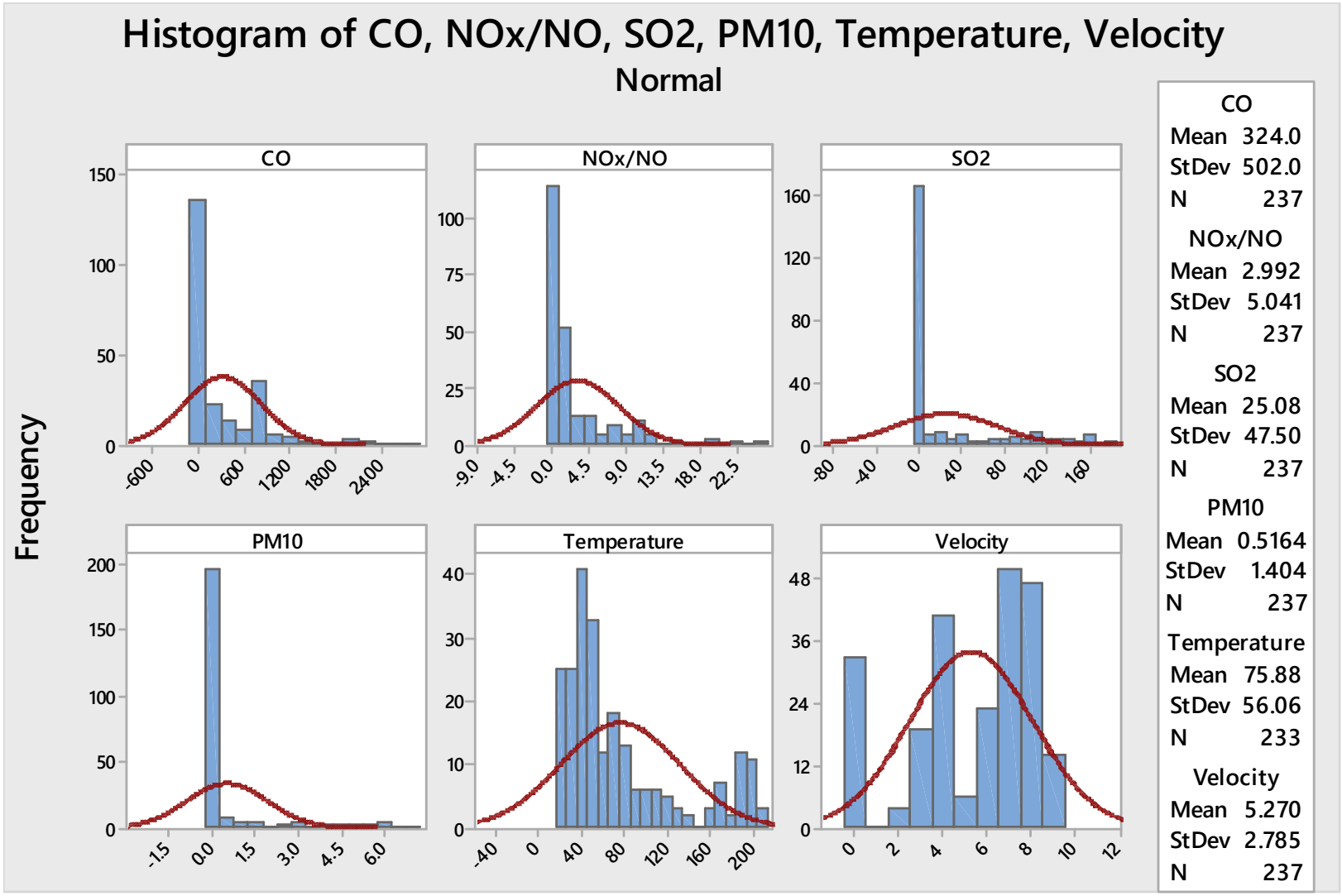


Figure 91: Histogram of emission concentrations and flue gas temperature and velocity across Batch 2 to Batch 13

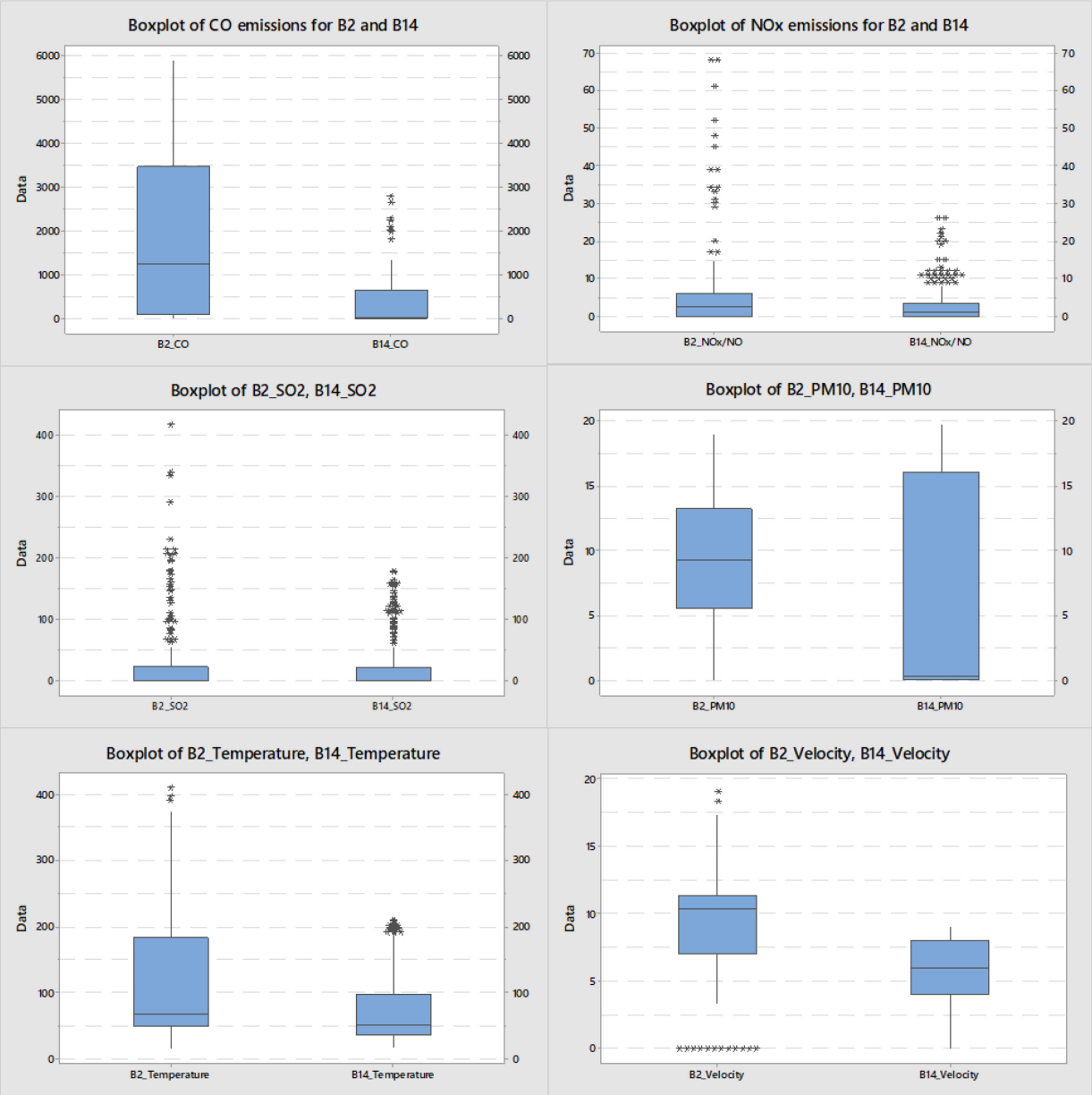


Figure 92: Emissions and process metrics variability plot – CO, NOx/NO and SO_2 emission variability plot indicates skewed emissions (leaning towards lower concentrations); suggesting a high variability in data with little consistency over the firing period. Flue gas temperature and velocity showed less variability in data and steadier levels over the firing period

7.3.3 Emission Rates and Emission Factors for Propane Gas Firing

Emission rates and emission factors were calculated from hourly emission concentration over the entire firing cycle, and are given in g/s, g/s brick, g/brick and kg/Mg or g/kg (Table 60). The mean concentration and standard deviation over the firing period was used in calculating the emission rates and emission factors, with standard deviation indicating high data variability across all batches. To account for emissions losses released underneath the semi-enclosed side boards, a statistical mean was calculated in Section 6.1 which is equal to 15.8% of the measured emissions. Therefore, each measurement was increased by 15.8%. Final adjusted emission rates and emission factors are provided in Table 61.

In order to account for the expected loss or reduction in extracted emission to the stack monitoring point during shut down of the bifurcated fan, velocity (and by extension, flow rate) readings during the hours when the bifurcated fan was off, were compared with velocity readings when the fan was on. This comparison was conducted for Batch 2 to Batch 13 firing cycle as well, using representative hours that the fan was off during Batch 14 run. The ratio obtained from the analysis was used to calculate backwards a 44% reduction in velocity and flowrate reading due to shut down of the fan. Applying this to emissions calculation, 46% (for CO), 23% (for NOx and NO), 0% (for NO_2), 10% (for SO_2) and 11% (for PM_{10}) increase in emission rate is quantified as losses due to fan shut down.

Table 60: Emission rates and emission factors during propane gas firing adjusted to account for emission loss due to shutdown of the bifurcated fan

	g/s		g/s brick		g/brick		kg/Mg or g/kg	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
CO	2.31×10^{-1}	5.27×10^{-1}	1.03×10^{-5}	2.03×10^{-5}	9.39	18.52	3.13	6.17
CO_2	1.12×10^{1}	5.33×10^{0}	5.09×10^{-4}	2.10×10^{-4}	465.03	191.84	155.01	63.95
NO_x/NO	2.41×10^{-3}	5.24×10^{-3}	1.08×10^{-7}	2.02×10^{-7}	0.10	0.18	0.03	0.06
NO_2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SO_2	2.51×10^{-2}	5.25×10^{-2}	9.66×10^{-7}	2.02×10^{-6}	0.88	1.85	0.29	0.62
PM_{10}	2.92×10^{-2}	4.85×10^{-2}	1.12×10^{-6}	1.86×10^{-6}	1.03	1.70	0.34	0.57
PM_{15}	2.92×10^{-2}	4.85×10^{-2}	1.12×10^{-6}	1.86×10^{-6}	1.03	1.70	0.34	0.57
PM_4	2.90×10^{-2}	4.84×10^{-2}	1.12×10^{-6}	1.86×10^{-6}	1.02	1.70	0.34	0.57
$PM_{2.5}$	2.89×10^{-2}	4.83×10^{-2}	1.11×10^{-6}	1.86×10^{-6}	1.02	1.70	0.34	0.57
PM_1	2.87×10^{-2}	4.81×10^{-2}	1.10×10^{-6}	1.85×10^{-6}	1.01	1.69	0.34	0.56

Table 61: Final emission rates and emission factors during propane gas firing corrected for occasional losses from underneath sideboards

15.8 % correction	g/s		g/s brick		g/brick		kg/Mg or g/kg	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
CO	2.67×10^{-1}	5.27×10^{-1}	7.06×10^{-6}	1.39×10^{-5}	9.39	18.5	3.13	6.17
CO_2	1.29×10^{1}	5.33×10^{1}	2.46×10^{-4}	3.17×10^{-4}	465	192	155	64.0
NO_x/NO	2.80×10^{-3}	4.27×10^{-3}	8.76×10^{-8}	1.64×10^{-7}	0.10	0.18	0.03	0.06
NO_2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SO_2	2.51×10^{-2}	4.78×10^{-2}	8.81×10^{-7}	1.84×10^{-6}	0.88	1.85	0.29	0.62
PM_{10}	1.92×10^{-2}	2.66×10^{-2}	6.16×10^{-6}	1.02×10^{-6}	1.03	1.70	0.34	0.57
PM_{15}	1.60×10^{-2}	2.66×10^{-2}	6.16×10^{-6}	1.02×10^{-6}	1.03	1.70	0.34	0.57
PM_4	1.59×10^{-2}	2.65×10^{-2}	6.12×10^{-6}	1.02×10^{-6}	1.02	1.70	0.34	0.57
$PM_{2.5}$	1.59×10^{-2}	2.65×10^{-2}	6.11×10^{-6}	1.02×10^{-6}	1.02	1.70	0.34	0.57
PM_1	1.58×10^{-2}	2.64×10^{-2}	6.06×10^{-6}	1.01×10^{-6}	1.01	1.69	0.34	0.56

7.3.4 COMPARING PROPANE GAS–FIRED WITH COAL–FIRED RESULTS

Results of propane gas firing (Batch 14) are compared with coal-fired run (Batch 2), since the green bricks for both runs were obtained from the same factory. Hence, intrinsic properties of clay material, handling, processing, drying as well as internal energy input are expected to be similar; and differing only in external energy use and brick packing methodology. An input and energy consumption comparison is presented in Table 62, indicating that Batch 2 energy consumption are higher than Batch 14 by 23% – 45%. Sulfur content of internal energy is also higher in Batch 2 firing by 18%. It can be inferred from the above, that the under-performance of the model kiln during the propane gas firing may also be due to lower energy input when compared to the similar coal-fired batch.

Table 62: Comparing coal-fired and propane gas-fired input and energy metrics

Input and Energy Metrics	Coal-fired run (Batch 2)	Gas-fired run (Batch 14)	Ratio of Batch 2 to Batch 14 energy input
Energy Consumption – total (MJ/kg)	2.30	1.65	1.39
Energy Consumption – internal (MJ/kg)	1.73	1.19	1.45
Energy Consumption – external (MJ/kg)	0.57	0.46	1.23
Percentage sulfur in body fuel (%)	0.65	0.55	1.18

A reduction in pollutant emissions (excluding SO_2 emissions) is observed between Batch 2 and Batch 14 monitoring results as presented in Table 63. CO emissions indicated 78% reduction, while CO_2, NO_x/NO and PM_{10} indicated 7%, 41% and 10% reduction in emissions respectively, during propane gas firing. This comparison should be interpreted with the understanding that the propane gas firing batch produced lesser quantity of evenly fired bricks (50% as against 80% – 90% for Batch 2 firing), less internal energy was used and consequently lower emissions resulted from the under-fired bricks. Inadequacies identified during the propane gas ignition process indicate that the brick packing methodology plays a vital role in the ignition of the kiln and circulation of heat in the kiln chamber. Hence, the brick packing methodology for propane gas ignition is a significant variable that requires further research, investigating on sub-variables such as adequate number of vents; adequate sizing of bottom burners; adequate spacing and brick packing technique; and effect of consistent reduction in propane supply, rather that sudden shutdown of propane burners.

SO_2 emission, on the other hand, shows a 19% increase in emissions during propane gas firing. This increase in SO_2 emission could not be verified quantitatively since sulfur content of body fuel is 18% higher in Batch 2 and the sulfur content of propane gas (external fuel for Batch 14) is negligible (Thermo Electron Corporation, 2004). The unprecedented increase may be attributed to lower energy consumption of Batch 14 firing which may alter the complex thermodynamic reactions in the model kiln, leading to release rather than retention of sulfur as CaS and $CaSO_4$.

In conclusion, only CO and NO_x/NO emissions provided significant reduction in emission rates to support the notion that substituting the external coal in the model kiln with locally available propane gas will result in significant reduction in atmospheric emissions. PM_{10} and CO_2 emission rate do not provide significant reduction, while SO_2

emission rate analysis indicates release, rather than retention of internal sulfur. The application of propane gas as external fuel should be further investigated on a model kiln and at industrial scale before adoption by industry is considered.

Table 63: Comparing coal-fired and propane gas-fired emissions (CO, CO_2, NO_x/NO and PM_{10} emission shows 87%, 7%, 41% and 10% reduction in emissions respectively, while SO_2 shows a 19% increase in emissions)

Pollutants	Coal-fired run – Batch 2 (g/brick)	Gas-fired run – Batch 14 (g/brick) [a]	Ratio of Batch 2 to Batch 14	Potential reduction in emission (%)
CO	73.6	9.39	7.83	87.2%
CO_2	502	465	1.08	7.4%
NO_x/NO	0.17	0.10	1.73	41.1%
NO_2	0.00	0.00	0.00	0.0%
SO_2	0.74	0.88	0.84	-18.9%
PM/PM_{10}	1.15	1.03	1.12	10.4%

NOTE: [a] The reader is reminded that the gas-fired run has been adjusted to account for emission loss during shutdown of the bifurcated fan (46% of the entire firing duration).

CHAPTER EIGHT

8 FINDINGS, CONCLUSIONS AND RECOMMENDATIONS

8.1 FINDINGS AND CONCLUSIONS

This study was carried out in order to design a scientifically acceptable technique for capturing and confining emissions from a simulated clamp kiln, so as to facilitate the comprehensive measurement and quantification of emission metrics, emission factors, energy efficiency, as well as to develop air quality management measures or practices for clamp kilns. This section summarizes the adopted methodology, findings and conclusions of the study and provides recommendations based on these outcomes.

To enable measurement and quantification of emission, process and energy metrics, a model kiln was designed to simulate operating conditions and configuration similar to a transverse slice of a typical full-scale clamp kiln, but with a lower capacity (20 000 to 35 000 bricks per firing cycle). The model kiln design ensures the adequate confinement and extraction of flue gases with the aid of a bifurcated fan forcing the draft through a horizontal extraction stack where monitoring occurs. The model kiln design, which comprises two adjacent sealed sides and two partially enclosing and sliding galvanized steel doors, provides adequate spacing for 'packing' and 'un-packing' of bricks and sufficient oxygen for combustion, while still ensuring minimum losses of emission via the semi-enclosed sides.

Concurrent firing and hourly monitoring of flue gases in the flue duct was conducted for fourteen batches of bricks over 8 – 14 days using varying brick products and energy inputs from eleven South African brick factories that utilize clamp kiln as firing technology. The model kiln was tested for its suitability in firing bricks that are similar to conventional South African clamp kilns, as well as its effectiveness in the capturing and channelling of flue gases through to the stack vent where monitoring of the flue gases took place.

The novelty of this research is in the design of the clamp kiln structure and simulation of the firing process which enables capture, confinement and channelling of flue gases to a point where representative measurement are obtained. In addition, computational analyses are utilized to generate representative emission rates and emission factors as well as energy metrics that have hitherto proven infeasible.

Significant findings and conclusions drawn from this study are:

- The model kiln has proven to be adequate in simulating full-size kilns. Physical examination of fired bricks (with respect to softness/hardness, strength, sound and core colour) from the model kiln showed similarities with bricks fired in conventional clamp kilns. Laboratory evaluation of fired bricks (in terms of compressive strength and water absorption test) indicated that the bricks fired in the model kiln achieved compressive strength and water absorption test values that are well within typical industry ranges, as well as compliant with SABS requirement and masonry brick dimensions. Approximately 70 – 90 % of the total brick fired in the model kiln across Batch 2 to Batch 13 were considered adequately fired.

- The model kiln has also proven to be effective in capturing and channelling emissions through an extraction stack for adequate monitoring, a quest which has met with limited success until now.
- From the 14 cycles or batches that were conducted, Batch 1 to Batch 13 utilized coal as external fuel for ignition; while Batch 14, a pilot test run for alternative energy analysis, utilized propane gas as ignition fuel. Batch 1 results could not be obtained due to equipment breakdown at the early stage of firing. Also, significant periods during Batches 5, 6, 7 and 13 firing campaigns were also characterized by equipment malfunction (gas samplers) and power failure, but measured data were considered adequate for analysis. Data availability is above 85% for all batches, with the exception of Batches 5 and 6 with less than 60% data availability.
- The pollutants investigated in this study are gases and particulates that have been identified as significant to air pollution studies in South Africa and globally. These include CO, NOx (comprising NO_2 and NO), SO_2, PM_{10}, PM_{15}, PM_4, $PM_{2.5}$ and PM_1. In addition, pollutant metrics applicable to this study include mg/m^3 or $\mu g/m^3$ (concentration); g/s or g/s brick (emission rates); and g/kg or g/brick (emission factors).
- The mean of the distribution of measured data for each firing cycle was taken as the most appropriate measure of central tendency, since various emission releasing reactions and processes occur within the firing chamber of the kiln at different periods during the firing cycle. These reactions and processes include the release of 'mechanical water' and 'combined water'; combustion of external fuel in the base layer and the internal fuel mixed into the bricks; oxidation of carbonates in the clay material; oxidation conditions leading to dissociation of $CaSO_4$ and release of CO_2 (and eventually SO_2); or retention of $CaSO_4$ in a reducing environment to give off CO and H_2; and destruction or development of lattice structure and change in crystal phase of the clay material.
- Model kiln emission concentrations and process metrics exhibit a wide range of variability during each firing cycle, indicating that they are sensitive to the various reactions and processes occurring within the kiln at a particular period. These concentrations and process metrics exhibit little or no similarity across firing campaigns; which may be attributed to the significantly varying input, packing and firing conditions applied to each batch. A high standard deviation, as well as a high range of data spread across the batches, indicates that emissions and process metrics from the kiln are sensitive to these input and firing variables.
- The mean of emissions concentration across firing cycles ranged from 113.3 – 1808.0 mg/m^3 for CO; 1.1 – 6.0 mg/m^3 for NOx; 0.0 mg/m^3 for NO_2; 0.0 – 6.0 mg/m^3 for NO; 0.0 – 91.5 mg/m^3 for PM_{10}, 7.8 – 75.6 mg/m^3 for SO_2; and 0.0 – 106.6 mg/m^3 for HC.
- The mean of flue gas process metrics across firing cycles ranged from 46.4 – 122.5 ^oC for temperature; 7.0 – 12.7 m/s for duct velocity; 19.8 – 20.9% for oxygen reference; 0.1 – 1.1% for percentage CO_2.
- A calibration factor of 0.61 was obtained from literature to correct PM concentration obtained from the DustTrak and SidePak monitors to gravimetric concentrations. This calibration factor was obtained by

McNamara et al (2011) from controlled laboratory wood stove emissions and is considered the most similar aerosol found in literature to the model kiln emissions.

- The mean concentration and standard deviation over each firing period was used in calculating the emission rates and emission factors. A sulfur mass balance analysis was conducted by quantifying the sulfur content of samples collected from the body fuel, green bricks, fired bricks and left over ash from each batch. A statistical mean efficiency for the model kiln emissions capturing and channelling capacity was calculated from the sulfur mass balance results of batches that lie within 95% confidence interval of the assumed true mean (100%) to give 84.2%. Therefore, 15.8% of emissions were considered to escape from underneath the semi-enclosed sides, and was utilized in correcting for final emission rates and factors.
- Energy performance analysis of each batch of firing indicated that output metrics were most sensitive to the external energy inputs (moderate to strong correlation observed); while output metrics were observed to be slightly sensitive to internal and total energy.
- Batch 3 external energy (0.40 MJ/kg SEC) produced the best performance in terms of sensitivity to output metrics, while Batch 2 firing (0.57 MJ/kg SEC) performed worst.
- Comparing the current South African industry SEC – 3.4 MJ/kg to batch 3 SEC – 2.5 MJ/kg and to the average SEC from this study – 2.6 MJ/kg; a significant reduction of 0.8 – 0.9 MJ/kg (32% – 36%) energy suggests that the industry could achieve significant reduction in energy use, thereby reducing cost of input, and more importantly, significantly reducing the quantity of atmospheric emissions.
- Final corrected emission factors (mean ± standard deviation) were quantified as 22.5 ± 18.8 g/brick for CO, 0.14 ± 0.1 g/brick for NO, 0.0 g/brick for NO_2, 0.14 ± 0.1 g/brick for NO_x, 1.07 ± 0.7 g/brick for SO_2, 378 ± 223 g/brick for CO_2, 0.96 ± 0.5 g/brick for PM_{10}. In addition, final corrected emission factors were quantified as 1.53 g/brick for hydrocarbons (calibrated to propane emissions) and 0.96 g/brick for PM_{15}, PM_4, $PM_{2.5}$ and PM_1, from one batch of firing. The similarity in PM_1, $PM_{2.5}$, PM_4, PM_{10} and PM_{15} emission factors indicate that the combustion PM is composed of extremely fine PM (since it is made up of nucleotides and particles that are yet to coagulate in the atmosphere).
- Final emissions factors (excluding hydrocarbon emissions) obtained in this study are assigned an emission factor rating of "A – excellent", based on description recommended by USEPA (1995). Emission factor for hydrocarbon emission is assigned a rating of "D – below average".
- It can be concluded that clamp kiln PM_{10} emissions are much lower (by a factor of 6) than the value obtained from previous literature (Burger & Breitenbach, 2008).
- Final corrected emission factors from this study were compared with applicable emission factors obtained from literature for different clay brick firing technologies, including BTK, DDK, Tunnel, VSBK, zig-zag, FCBTK, coal-fired and Southeast Asia clamps. It was established that the South African clamp kiln emissions are extremely high in terms of CO emissions (higher than all technology available for

comparison); and moderate in terms of CO_2, SO_2 and PM/PM_{10}. NO_x emissions are considered to be quite low in comparison to US coal fired kilns.

- Significant NO_2 is not emitted from a clamp kiln, contrary to assumptions from existing literature. All of the NO_x emitted is actually in the form of NO. This may be attributed to the high temperature occurring within the kiln, since it has been established that NO is formed from combustion of fossils at high temperatures, while NO_2 is formed at much lower temperatures in the atmosphere by the oxidation of NO, among other means (USEPA, 1999). It is adequate to conclude that NO_2 emissions from South African clamp kilns are insignificant.
- A pilot study was conducted during Batch 14 firing cycle to substitute the external fuel (coal) with a locally available alternative, liquidified petroleum gas (LPG) or propane gas. It was anticipated that use of an energy alternative might improve clamp kiln firing efficiency and consequently result in reduction of atmospheric emissions. Propane gas was successfully utilized as external fuel in igniting the firing process, with less percentage of adequately fired bricks (50%).
    - A reduction in pollutant emissions (excluding SO_2 emissions) was observed between Batch 2 and Batch 14 monitoring results (Batch 14 results are compared with Batch 2 results since processing methodology and green bricks for Batch 14 were obtained from the same factory as Batch 2). CO, CO_2, NO_x/NO and PM_{10} indicated 87%, 7%, 41% and 10% reduction in emissions respectively, during propane gas firing. SO_2 emission ratio, on the other hand, indicated a 19% increase in emissions during propane gas firing. This increase in SO_2 emission could not be verified quantitatively since sulfur content of body fuel is 18% higher in Batch 2 and the sulfur content of propane gas (external fuel for Batch 14) is negligible. The unexpected increase may be attributed to the lower energy consumption and/or lower firing temperature during Batch 14 firing which have been associated with retention of sulfur in the brick material as $CaSO_4$.
- Only CO and NO_x/NO emissions provided significant reduction in emission rates to support the notion that substituting the external coal in the model kiln with locally available propane gas will result in significant reduction in atmospheric emissions. PM_{10} and CO_2 emission rate do not provide significant reduction to support this notion, while SO_2 emission rate analysis indicate release, rather than retention of sulfur as CaS and $CaSO_4$.

8.2 Assumptions, Limitations and Gaps in Knowledge

Limitations, assumptions and knowledge gaps that are applicable to this study include the following:

- The Sidepak™ Personal Aerosol Monitor used for taking PM_{10} measurements in this study utilized a sampling range of 0.001 – 20 mg/m^3 which proved to be insufficient in capturing concentrations higher than

20 mg/m^3 during peak firing sessions. However, a correction factor was calibrated to remedy this limitation during the concluding batch of the study.

- In order to determine pollutant concentrations and emission metrics, hourly measurements (with data logged at every 1 second for a duration lasting 5 – 6 mins of every hour) were taken for gaseous pollutants, particulates and emission metrics. The average of each hourly measurement was taken and assumed to be the measurement value over each entire hour. This average value was considered representative of the entire hour since continuous monitoring was not feasible.
- The model kiln was presumed to have completed its firing cycle when stack measurements for pollutant concentration and temperature are comparable to ambient measurements and there is no visible release from the stack and kiln sides.
- The chemical and mineral composition of clay materials from each brick source could not be determined; hence chemical reactions during firing of each batch of bricks could not be evaluated. Evaluation of the chemical reactions and processes is essential in order to completely analyse and understand the firing process; as well as results of the emission monitoring.
- Low velocity and flow rate of flue gases can result in poor measurement and erroneous quantification of emissions. The levels of uncertainty in stack emission measurement are highest when velocity measurements are low and approach the lower detection limit of the Pitot tube used for measurement.
- Oxidation conditions in the firing chamber of the kiln favour the release of sulfur as SO_2 emissions, while reduction conditions favours sulfur retention in brick as CaS and $CaSO_4$. The complexity regarding oxidation and/or reduction reaction in the firing chamber of the kiln may result in retention rather than emission of sulfur compounds, rendering sulfur mass balance analysis uncertain.
- In order for mass balance analysis to be accurate, representative sampling during processing and mixing of clay bricks is required so as to ensure that the constituents of the clay and fuel material (including sulfur compounds) are evenly distributed across the whole batch. However, homogeneity may not be achieved since only two brick samples in 20 000 – 35 000 bricks were analysed per batch.

8.3 RECOMMENDATIONS

Clamp kiln emission control efforts should be aimed at modifying the combustion and firing process in order to reduce the quantity of emissions, rather than efforts aimed at capturing and containing the release of emissions. This is due to the difficulty in capturing emissions into a stream where they can be fitted with emission control devices.

The following measures (for which further research may be pursued) have been identified as effective means of modifying the combustion and firing process in order to reduce the quantity of emissions from a clamp kiln:

- Measures should be targeted at reducing the energy input in order to minimize release of atmospheric emissions. The South African clamp kiln industry's SEC (3.4 MJ/kg) could be potentially reduced to 2.5 (MJ/kg) without compromising the firing process or quality of bricks fired.
- Measures should be targeted at reducing the external energy consumption or modifying the ratio of the external energy to internal energy consumption during the firing process. Since emission and process metrics are most sensitive to the external fuel, reducing the quantity of external energy consumed could potentially reduce emissions.
- Measures should be aimed at regulating the complex oxidation and reduction reactions occurring in the firing chamber of the kiln. Reducing conditions should be promoted to retain $CaSO_4$ and CaS within the brick, consequently reducing atmospheric emissions.
- Measures should be aimed at regulating the complex thermodynamic processes in the firing chamber of the kiln. Maintaining the firing chamber temperature at certain levels for a specific duration helps regulate the exothermic and endothermic complexes in the kiln, which in turn controls the chemical processes and the release of pollutants associated with those processes.

The following measures are recommended for clamp kiln operators to reduce emissions from clamp kiln:

- Clamp kiln operators should ensure that crushing, screening, milling and mixing of clay material and other additives is adequate to achieve homogeneity. Homogeneity during processing and mixing of material is required to ensure that the constituents of clay and fuel material are evenly distributed across the firing batch and therefore result in even firing of bricks as well as steady release of air emissions.
- Clamp kiln operators should monitor their kiln temperature by distributing thermocouples within the kiln in order to monitor and ensure a steady rise or fall in temperature. It has been established that a steadier temperature profile produces higher quality brick products and a steady release of air emissions than an inconsistent temperature profile
- Clamp kiln operators should ensure that they utilize clay and coal materials that contain lower sulfur, carbon and metal contents available in their location and market. Periodic testing of clay and coal material constituents should be done to identify the most suitable material.
- Clamp kiln operators should reduce or attempt to reduce their coal use by reducing their current specific energy consumption as much as possible (closer to 2.5 MJ/kg) without compromising the firing process. Reduced energy consumption will result in reduced air emissions.
- Clamp kiln operators should ensure adequate sun drying of bricks prior to firing. Adequate drying will help reduce the energy consumption required for water-smoking or slow heating stage of the firing process where evaporation of "free and mechanical water" takes place.

Further research may be conducted to attempt the application of the model kiln design to large-scale clamp kilns, since the simple design utilized by the model kiln will not suffice for a large scale kiln; and a rather complex and cumbersome design and huge financial commitment may be required. Also, since all of the NO_x emitted from the

clamp kiln is in the form of NO, further research may also be undertaken to investigate the impact of NO release in atmospheric titration which governs the formation and destruction of stratospheric ozone.

Also, the comprehensive monitoring of actual temperature profile within the kiln (rather than monitoring of emission temperature conducted in this study) should be considered for future research work in order to further investigate the progression of brick firing and the direct impact of a steady temperature profile. This might help with reducing variation in clamp kiln performance and air emissions.

The lower PM_{10} result obtained from this study suggests extended implications for dust management around clamp kiln yards – i.e. good housekeeping, especially with regards to fugitive PM emissions (from roads, materials handling, crushing etc.), may have a much larger impact on mitigating PM emissions from a clamp kiln facility, than measures taken on the kiln only.

Findings in this study suggest South African clamp kilns emit lower quantities of emissions when compared to Asian clamp kilns due to the differences in energy use as well as brickmaking processing, packing and firing methodologies. Also, South African clamp kilns tend to be larger scale, and the technology better developed than Asian and Central American kilns.

In addition, due to the localization of clamp kiln emissions, it is recommended that an impact zone − an area where residential occupation should be restricted – be delineated around clamp kiln installations based on findings of site-specific air quality impact assessment studies. Where a site-specific air quality impact assessment study is not available, a suggested impact zone of 500 m, 1000 m and 2000 m from the clamp kiln area may be adopted for small, medium and large kilns respectively.

Furthermore, since the use of locally available alternative energy (propane) was partially successful in adoption as external fuel in igniting the firing process (50% as against 80% to 90% evenly-fired brick production for Batch 2 firing); further research is recommended to resolve inadequacies regarding propane gas ignition process. Inadequacies identified during the propane gas ignition process indicate that the brick packing methodology plays a vital role in the ignition of the kiln and circulation of heat in the kiln chamber. Hence, the brick packing methodology for propane gas ignition is a significant variable that requires further research, and sufficient investigation should be conducted on sub-variables such as adequate number of vents; adequate sizing of bottom burners; adequate spacing and brick packing technique; and effect of consistent reduction in propane supply, rather that sudden shutdown of propane burners.

Finally, the use of propane gas as alternative ignition fuel has shown potential effectiveness in lowering CO and NO_x/NO emissions, but not PM_{10}, CO_2 and SO_2 emission. The application of propane gas as external fuel should be further investigated on a model kiln and at industrial scale before adoption by industry is considered.

CHAPTER NINE

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CHAPTER TEN

10 APPENDIX

10.1 APPENDIX A – ADDITIONAL LITERATURE TABLES

Additional literature tables are provided in this section. Table 64 summarizes the specific energy consumption of brick kilns; Table 65 shows the geographical distribution of various brick kilns from around the world; Table 66 provides brick production by countries; Table 67 shows the firing capacities of various brick kilns; and Table 68 captures the duration of firing for different types of kiln.

Table 64: Specific energy consumption of brick kilns (as obtained from literature)

Reference	Clamp (Informal/ Traditional)	Clamp (Formal/ Industrial)	VSBK	Tunnel	Hoffmann /TVA	BTK / MCBTK	FCBTK	Zigzag /HDK	DDK	Scotch	Scove	Hybrid Hoffman	Improved FCBTK	UDK
RSPCB (2011) [a]	5 - 6				1.0 - 2	1.2 - 1.7	1.0 - 1.3	0.85 - 0.9	3 - 4					
Maithel *et al* (2014f)					1.36		1.3							
Maithel *et al* (2014h)				1.4 (1.3 - 1.5)										
Maithel *et al* (2014i)			0.8 (0.5 - 1.1)											
CSE (2015)	1.7 - 4.2		0.8 - 1.1	1.65 - 2.1										
Müller (2015)			0.83				1.16							
Maithel *et al* (2014a)	2.1 (2 - 4) [d]													
ILO (1984) [b]	2.3			1.3	1.7	1.5		1.0	5.2	5.3	5.3			
Maithel *et al* (2014b)									3 (2.8 - 3.1)					
Maithel *et al* (2012)			0.5 – 1.0	1.47			1.22	1.12	2.9					
Maithel *et al* (2014c)							1.3 (1.1 - 1.5)							
Maithel *et al* (2014d)								1.0 (0.9 - 1.1)						
Schilderman (1999b)	3.0 - 8.0		0.8 - 1.4	1.5. - 2	1.5 - 4.3	1.1 - 4.0				1.5				
Erbe (2011)	3.0 - 8.0		0.7 - 1.0	1.5 - 2.0	1.5 - 4.3	1.1 - 4.0		0.8 - 1.1		1.5 - 7				
Baum (2010)	1.9 - 3		0.7 - 0.9			1.25 - 1.5	1 - 1.3							
Croitoru & Sarraf (2012)			1.2				1.9					0.9	1.3	
Bellprat (2009)			0.7 - 1.0			1.2 - 1.75	1.1 - 1.4							
Klimont (2012)	5		0.8	1.8			1.4	1.1						
Calculated from Akinshipe (2013)		2.9 (1.4 - 4.5)												
Calculated from Lordan (2011) [c]		2.67												
Houben & Guillaud (1994)	2.8 - 3.5		1.0 - 1.3			2.5 - 2.8								
UNIDO (2010)	2 - 4.5		0.7 - 1		1.2 - 1.5	1.8 - 4.5	1.8							
Maithel (2003)	2 - 8		0.8 - 1.1	1.2 - 2.5		1.1 - 1.6								
Hibberd (1996)		3.97												
TARA (2014e)			0.7 - 0.8											
Oral & Mıstıkoglu (2007); FAO	2.0 - 8.0		0.8 - 0.9	1.2 - 2.5	1.5 - 2.8	2.5 - 2.8		1.2 - 1.8	2 - 8	2 - 8	2 - 8			

Reference	Clamp (Informal/ Traditional)	Clamp (Formal/ Industrial)	VSBK	Tunnel	Hoffmann /TVA	BTK / MCBTK	FCBTK	Zigzag /HDK	DDK	Scotch	Scove	Hybrid Hoffman	Improved FCBTK	UDK
(1990)														
Rajarathnam *et al* (2012); Maithel *et al* (2002a)	1.2 - 2.5		0.7 - 1.0			1.2 - 1.75	1.1 - 1.4	0.8 - 1.1						
Praseeda *et al* (2015)	1.67 - 2.9		1.2		2.94	1.27 - 4.05	1.51		1.9 - 3.5					
Maithel *et al* (2002b), APEIS (2003)	2.25		0.9			1.5	1.3	1.0						
BEE (2010)	1.2 - 1.9		0.7 - 1.0			1.2 - 1.75	1.1 - 1.4	1.1 - 1.5						
Manandhar & Dangol (2013)	2.36		0.72		1.25	1.5	1.25							
FAO (1993)	2.0 - 8.0			1.2 - 2.5	1.5 - 2.8	1.5 - 2.8					2 - 8			2 - 8
Sharma & Prasad (1988)					0.8	1.2								
World Bank (1989)	3.8										3.8			3.8
Sannen (1981)	4.0 - 7.0			1.7 - 2.5	2.2 - 3.5						4 - 7			4 - 7
Carey (1984)		3.7		3.51	2.94				8.5					
Schilderman (1999b); CSE (2015); Hamner, 2006; Heierli & Maithel, 2008, Erbe (2011)	10 - 28		60 - 100	45 - 56	20 - 56	21 - 77		75		12 - 59				
Baum (2010), re-calculated in Lopez *et al* (2012)	32 - 71		11 - 16	17.5 - 40		19 - 28	17.5 - 24							
Colour Legend	MJ/kg fired Bricks					% efficiency					Coal consumption (tons/100,000 bricks)			

NOTE:

[a] Calorific value of the coal has been assumed to be 5000 k. cal/kg for the purpose of calculations

[b] Average weight of bricks assumed to be 3 kg

[c] Calorific value of the coal has been assumed to be 22 MJ/kg of coal and average weight of bricks assumed to be 3 kg

[d] Ranges are in brackets

Table 65: Geographical distribution of brick kilns (as obtained from literature)

Reference	Clamp (Informal/ Traditional)	Clamp (Formal/ Industrial)	VSBK	Tunnel	Hoffmann /TVA	BTK/ MCBTK	FCBTK	Zigzag /HDK	DDK	Scotch	Round/ Annular	Scove	Shuttle	UDK
RSPCB (2011); Pradhan (2015); Cole & Lorch (2003); Subrahmanya (2006b); Kumbhar *et al* (2014); Subrahmanya (2006a); Praseeda *et al* (2015)	India,			India	India	India	India	India	India					
Akinshipe (2013)		South Africa												
Maithel *et al* (2014h); Weyant (2014)				India, Vietnam, USA, Europe										
Maithel *et al* (2014f)					India, Germany									
CBA 2002, CSE (2015); BIA (2006)		South Africa		South Africa	South Africa			South Africa	South Africa					
Maithel *et al* (2012)			China, India, Nepal, Afghanistan, Vietnam, Pakistan, Sudan, and South Africa					Germany, Australia, India						
Maithel *et al* (2014i)			India, Nepal, Vietnam,											
Müller (2015)			Nepal											
Punmia *et al* (2003)						India								
Maithel *et al* (2012)									India					
ILO (1984)	Lesotho, Turkey				Honduras, Madagascar	India		India	Ghana, West Africa	Madagascar, Ghana		Sudan, Madagascar, Tanzania, Lesotho and Ghana		
Maithel *et al* (2014d)								India, Bangladesh, Nepal						
Maithel *et al* (2014c)							India, Pakistan, Bangladesh, Nepal							
Erbe (2011)	Mexico													

Reference	Clamp (Informal/ Traditional)	Clamp (Formal/ Industrial)	VSBK	Tunnel	Hoffmann /TVA	BTK/ MCBTK	FCBTK	Zigzag /HDK	DDK	Scotch	Round/ Annular	Scove	Shuttle	UDK
Schilderman (1999b)	Zimbabwe													
Schilderman (2001)	Sudan													
EcoSur (2006)			Nicaragua			India								
Goyer (2006)														
Umlauf *et al* (2011)	Kenya, Mexico													
Baum (2010)					China	India, Pakistan, Nepal, Bangladesh								
Bellprat (2009)					Mexico									
Pokhre & Lee (2014); MinErgy (2015); Pokhrel & Lee (2014); Raut (2003); Haack & Khatiwada (2007); Shrestha & Rajbhandari (2010), Carvalho & Nogueiraf (1997),	Nepal		Nepal		Nepal	Nepal	Nepal	Nepal						
Sarraf *et al* (2011), Gomes & Hossain (2003), Guttikunda & Khaliquzzaman (2014)			Bangladesh		Bangladesh	Bangladesh	Bangladesh	Bangladesh						
Goyer (2006)	Mexico, Honduras, Philippines, Ghana,		India,	Italy								Mexico, Uganda		
Heeney (2003); Jefremovas (2002)	Rwanda													
Hashemi & Cruickshank (2015b); MRHP (2002); Hashemi & Cruickshank (2015a)	Uganda, Tanzania													
CBA (2015b)		South Africa												
Cole & Lorch (2003)	Sudan													
Pool & Maithel (2012)	India		India, China			India	India		India					
Rexford (2011)	Ghana								Ghana					
Hibberd (1996)	UK			Australia, UK	Australia, UK				Australia, UK					
Clough (1989)	New Zealand									New Zealand				
Khurana (2014); TARA (2014e); TARA (2014c); TARA (2014b); TARA (2014d); TARA (2014a)	Malawi		Malawi, India, Nepal											
Ranta & Makunka (1986)	Zambia													

Reference	Clamp (Informal/ Traditional)	Clamp (Formal/ Industrial)	VSBK	Tunnel	Hoffmann /TVA	BTK/ MCBTK	FCBTK	Zigzag /HDK	DDK	Scotch	Round/ Annular	Scove	Shuttle	UDK
Koroneos & Dompros (2007), Mancuhan & Kucukada (2006), Carvalho & Nogueiraf (1997)				Portugal									Spain, France, Turkey, Portugal, Greece, Cyprus	
Lalchandani (2012)				China	China						China			
Baily (1981)				Colombia	Colombia				Colombia					Colombia
Maithel *et al* (2003), Narasimhal & Nagesha (2013), APEIS (2003), Maithel *et al* (2002a)	India		India	India	India	India	India	India	India	India		India		
Van de Ven (1996)	Tanzania, East Africa											Zimbabwe, Tanzania, East Africa		Tanzania East Africa
Køster (2014)				Denmark	Denmark									

Table 66: Brick production by countries (as obtained from literature)

Reference	Total	Clamp (Informal/ Traditional)	Clamp (Formal/ Industrial)	VSBK	Tunnel	Hoffmann /TVA	BTK/ MCBTK	FCBTK	Zigzag/HDK
China [7, 8]	700 - 1 000								
India [13, 1, 7, 8, 13, 15, 5, 19]	140 - 250	60 - 62.5		0.015 - 0.12			16 - 64	175-250	0.06 - 0.1
Nepal [7, 8, 1]	5.4								
South Africa [2, 17, 16, 10, 3, 18]	3.5 - 4.0		2.4 - 3.4	0.07	0.7	0.3			0.07
Pakistan [7, 8, 1]	47.3 - 100								
Bangladesh [6, 7, 8, 11, 12, 14, 1]	18 - 50					2.4%	16%	75%	5%
Vietnam [7, 8, 17, 4, 18]	17 - 25.7								
USA [9, 20]	3 - 9								
UK [17]	1.5								
Argentina [6]	1.44 x10^{-4}								
Bolivia [6]	8.4 x10^{-5}								
Brazil [6]	5.38x10^{-3}								
Columbia [6]	1.1 x10^{-2}								
Ecuador [6]	2.08 x10^{-4}								
Honduras [6]	2.42 x10^{-4}								
Mexico [6]	7.5 x10^{-3}								
Nicaragua [6]	3.11 x10^{-4}								
Peru [6]	1.12 x10^{-3}								
Colour Legend	Number of bricks X **1 000 000 000** per year					% of total			

Reference List: Maithel *et al* (2012) [1], Akinshipe (2013) [2], CBA 2002 [3], CDM (2006) [5], CCAC (2015) [6], Baum (2010) [7], CCAC (2015) [8], Kornmann *et al,* (2007) [9], Mienie *et al* (2015) [10], Sarraf *et al* (2011) [11], Hossain (2008) [12], Pool & Maithel (2012) [13], Gomes & Hossain (2003) [14], Rajarathnam *et al* (2012) [15], Lordan (2011) [16], Wienerberger (2015) [17], Smith (2013) [18], Kumbhar *et al* (2014) [19], Ahmari & Zhang (2012) [20]

Table 67: Firing capacities of brick kilns (as obtained from literature)

Reference	Clamp (Informal/clusters)	Clamp (Formal/Industrial)	VSBK	Tunnel	Hoffmann /TVA	BTK / MCBTK	FCBTK	Zigzag /HDK	DDK	Scotch	Round	Annular	Scove	Beehive
RSPCB (2011)	25 000 – 500 000					500 000 – 600 000			10 000 – 100 000					
Maithel *et al* (2012)				60 000 – 200 000										
Maithel *et al* (2014f)					10 000 – 20 000									
Maithel *et al* (2014h)				50 000										
CBA 2002									40 000 – 100 000					
Akinshipe (2013)		1 000 000 – > 7 000 000												
Maithel *et al* (2014i)														
Maithel *et al* (2014b)									20 000 – 40 000					
Maithel *et al* (2014a)														
Maithel *et al* (2014c)							20 000 – 50 000							
CDM (2006)	5 000 – 50 000						25 000 – 50 000							
Maithel *et al* (2014d)								15 000 – 40 000	10 000 – 100 000					
ILO (1984)					2 000 – 24 000	14 000 – 28 000		15 000 – 30 000	10 000 – 50 000	15 000 – 25 000			5 000 – 100 000	
Erbe (2011)	5 000 – 100 000													
Cermalab (2014)		500 000 – 14 000 000												
Pokhre & Lee (2014)			3 000 – 8 000			10 000 – 28 000								
Heeney (2003)														13 000 – 40 000
Hull (2008)	20 000 – 30 000													
Maithel (2003)			2 000 – 5			15 000 –								

Reference	Clamp (Informal/clusters)	Clamp (Formal/Industrial)	VSBK	Tunnel	Hoffmann /TVA	BTK / MCBTK	FCBTK	Zigzag /HDK	DDK	Scotch	Round	Annular	Scove	Beehive
			000			60 000								
TIDE (2003)									20 000 – 40 000					
Oral & Mıstıkoglu (2007); FAO, 1990	5 000 – 1 000 000		4 000 – 30 000	50 000 – 150 000	2 000 – 24 000	10 000 – 48 000			10 000 – 40 000	5 000 – 40 000			5 000 – 100 000	
Colour Legend	bricks per batch							bricks per day						

Table 68: Duration of firing per technology (as obtained from literature)

Reference	Clamp (Informal/ Traditional)	Clamp (Formal/ Industrial)	VSBK	Tunnel	Hoffmann/TVA	BTK / MCBTK	FCBTK	Zigzag/HDK	Down-Draught
	Number of days per batch								
RSPCB (2011)						25 - 30			
Maithel *et al* (2012)			1 - 1.5						
Akinshipe (2013)		14 - 28		3 - 5					
Maithel *et al* (2014h)				1.5 - 3					
CBA 2002		21			10 - 14				
Maithel *et al* (2014i)			1 - 1.5						
Maithel *et al* (2014b)									7 - 10
Maithel *et al* (2014c)							1 - 2		
Maithel *et al* (2014d)								1 - 2	
Pokhre & Lee (2014)	12 - 21		1		10	18 - 21			
Maithel (2003)			0.75 - 1.67			12 - 15			

10.2 APPENDIX B – ADDITIONAL EMISSION RESULTS

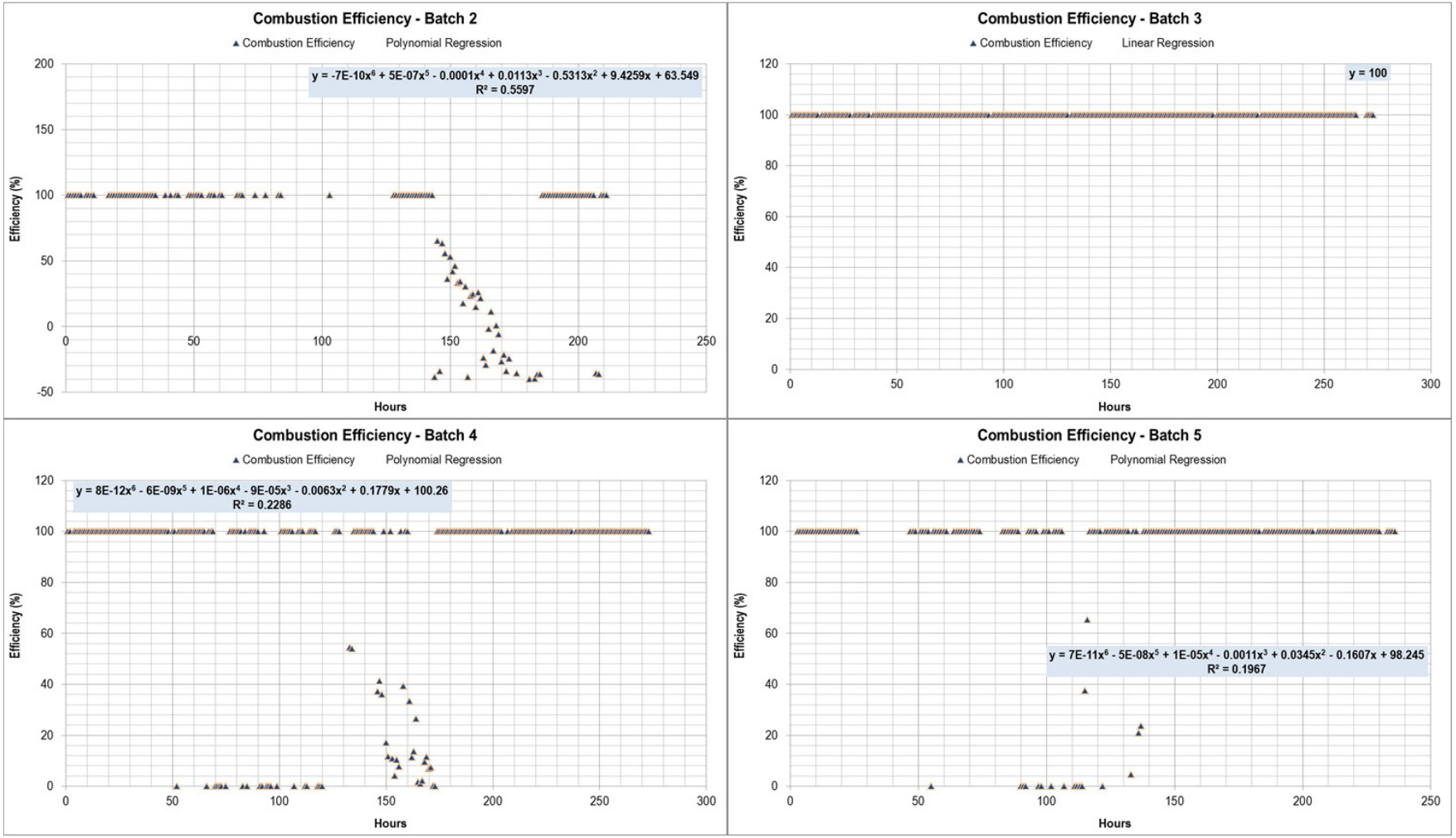


Figure 93: Model kiln combustion efficiency in % (Batches 2, 3, 4 and 5)

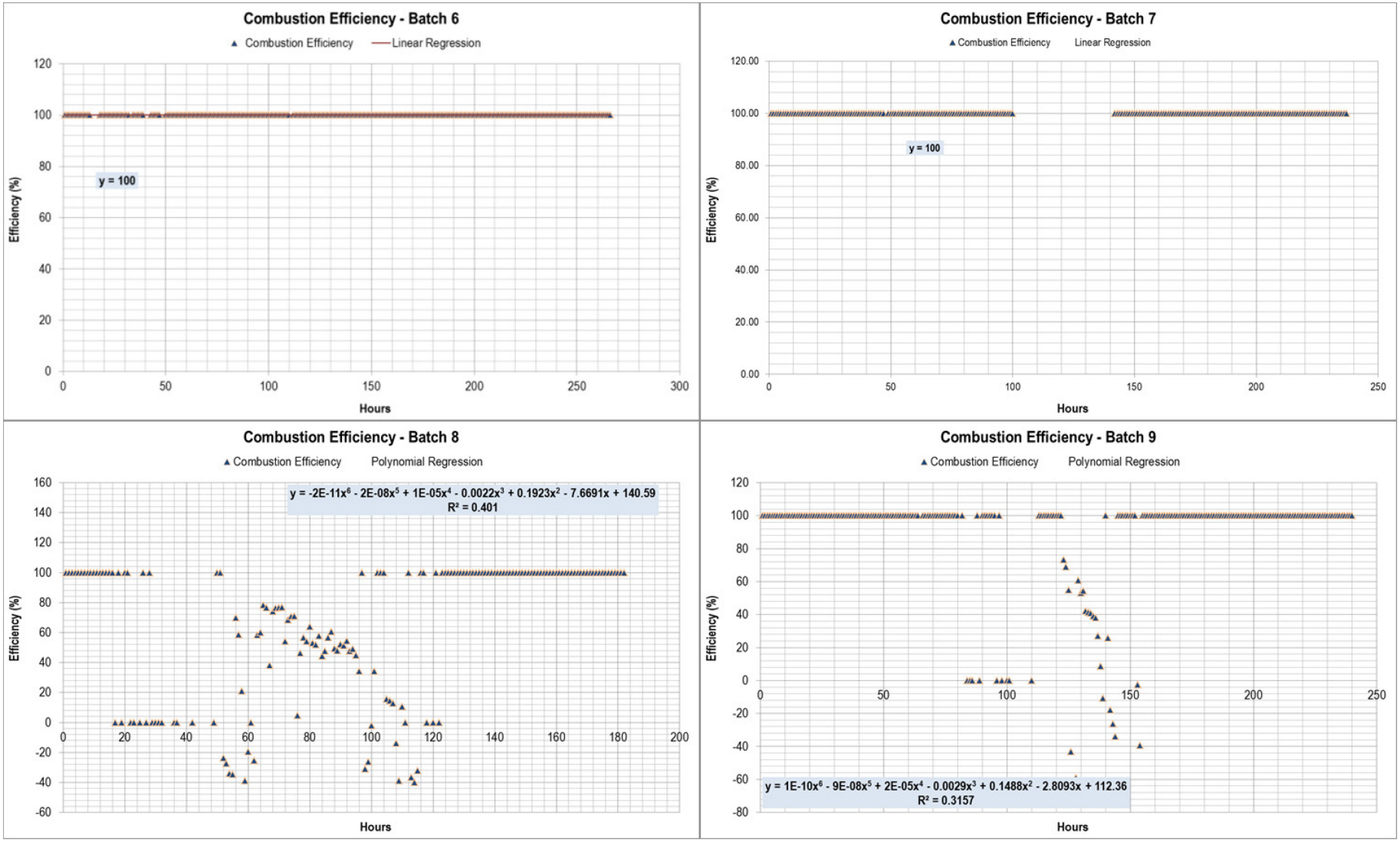
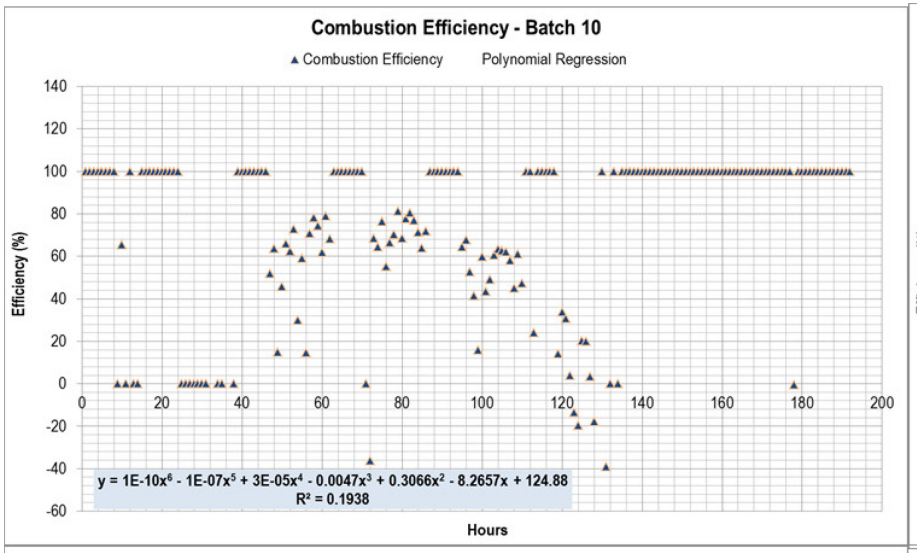
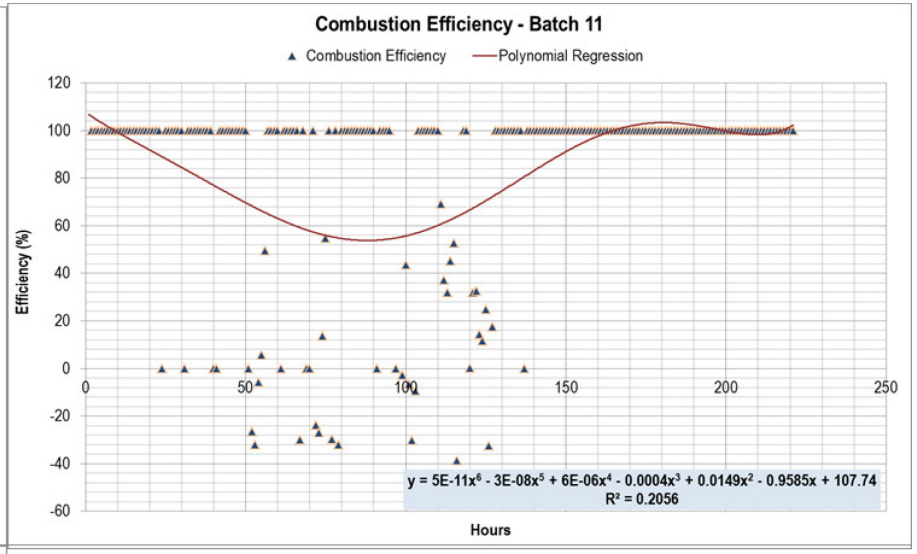


Figure 94: Model kiln combustion efficiency in % (Batches 6, 7, 8 and 9)





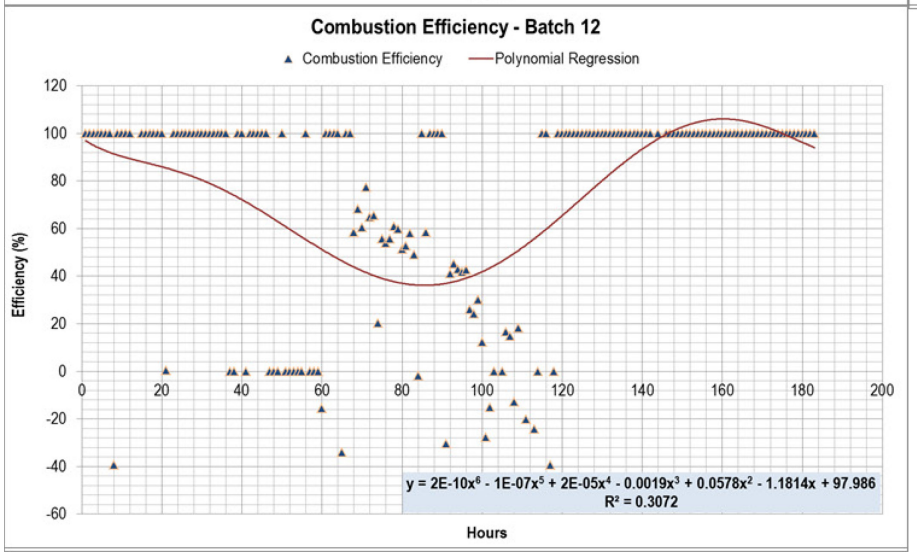


Figure 95: Model kiln combustion efficiency in % (Batches 10, 11 and 12)

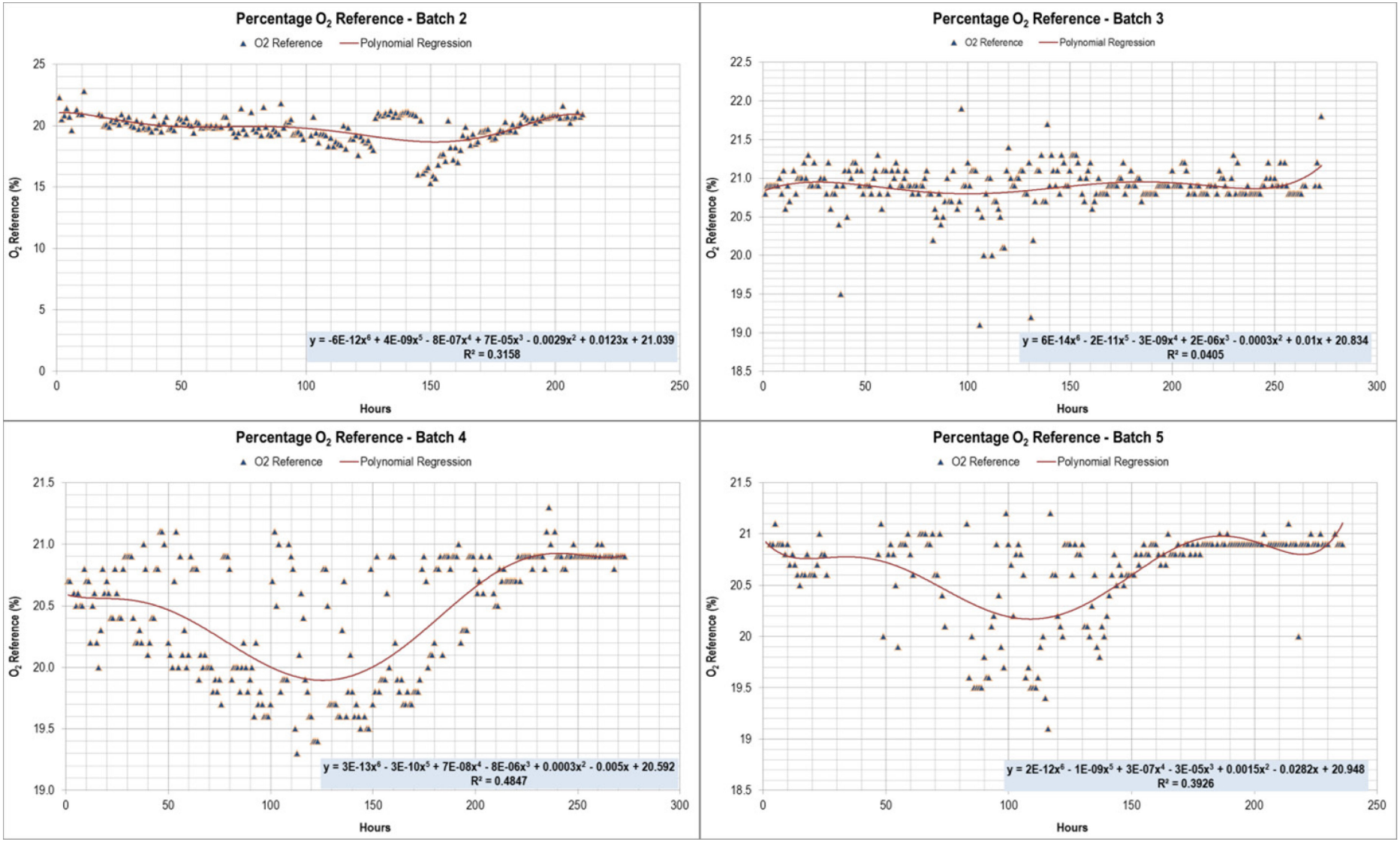


Figure 96: Model kiln percentage oxygen reference (Batches 2, 3, 4 and 5)

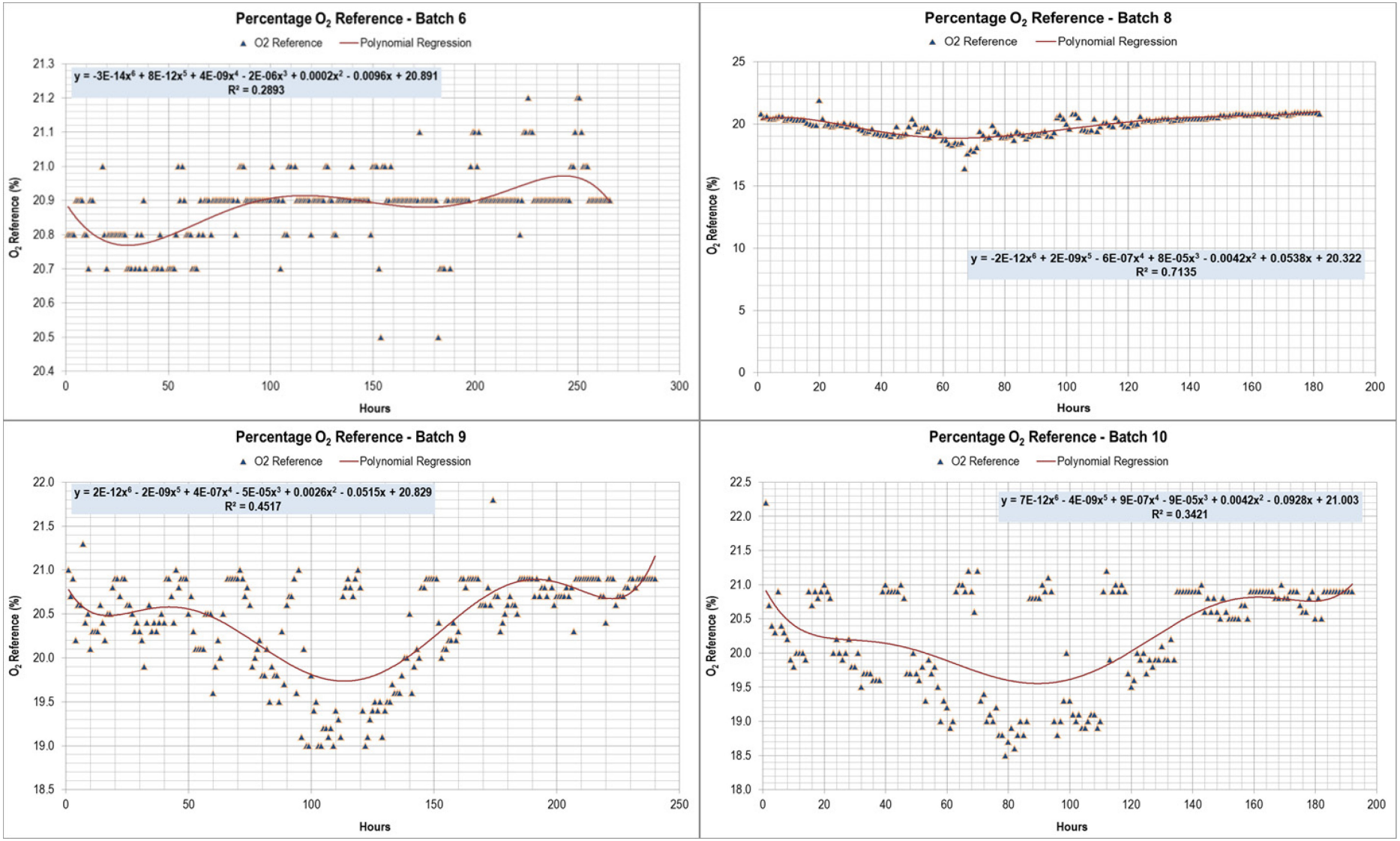


Figure 97: Model kiln percentage oxygen reference (Batches 6, 8, 9 and 10)

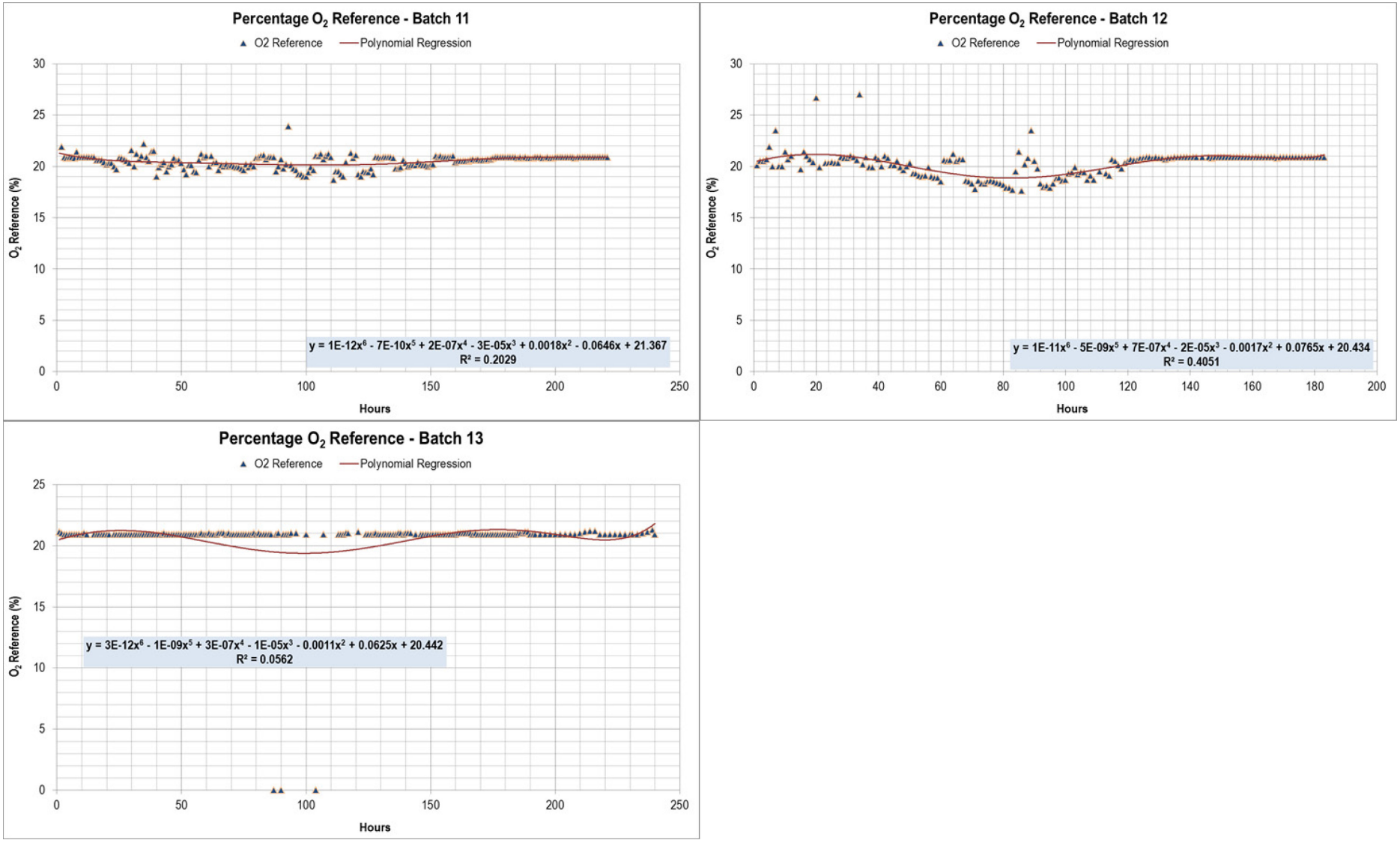


Figure 98: Model kiln percentage oxygen reference (Batches 11, 12 and 13)

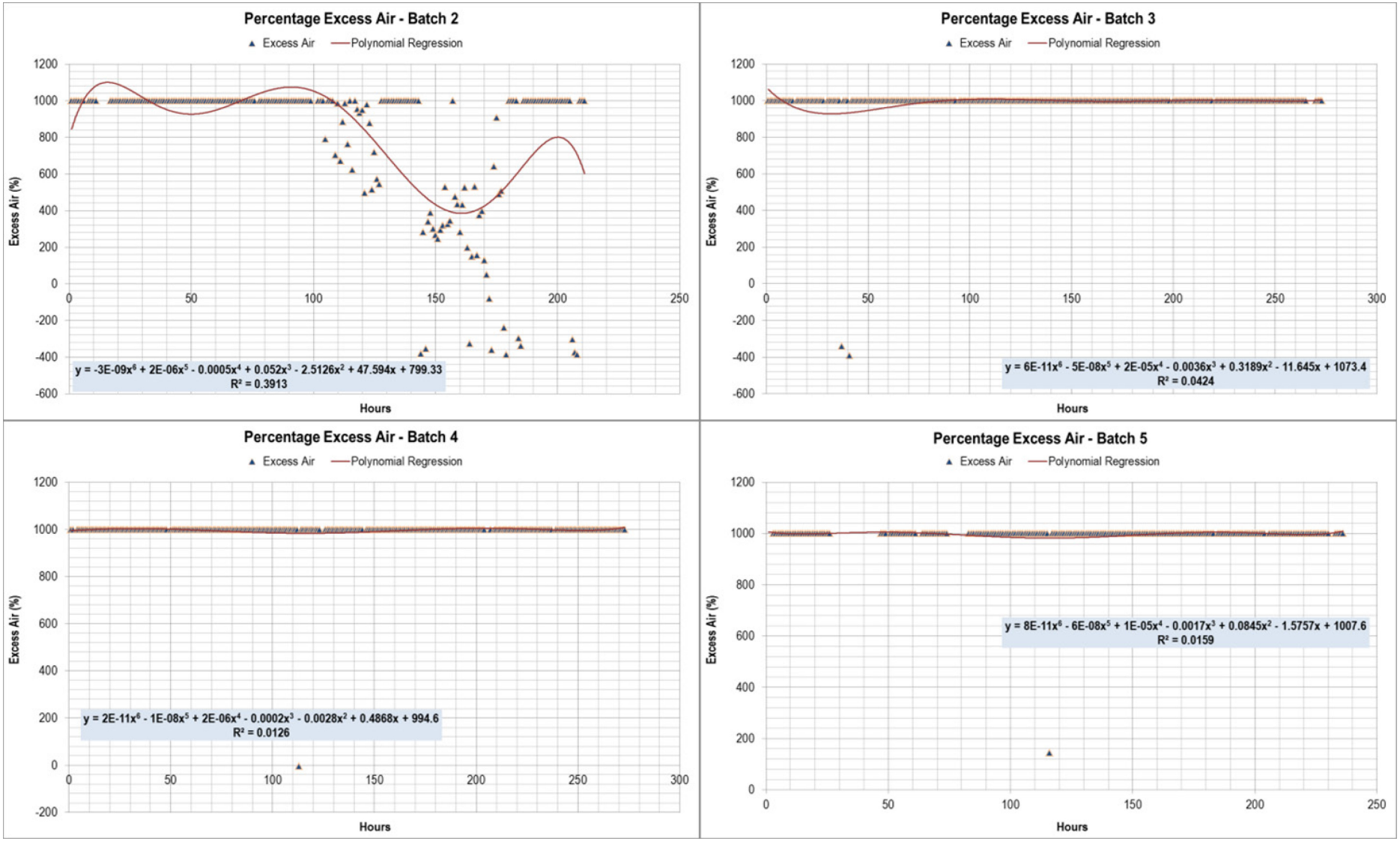


Figure 99: Model kiln percentage excess air (Batches 2, 3, 4 and 5)

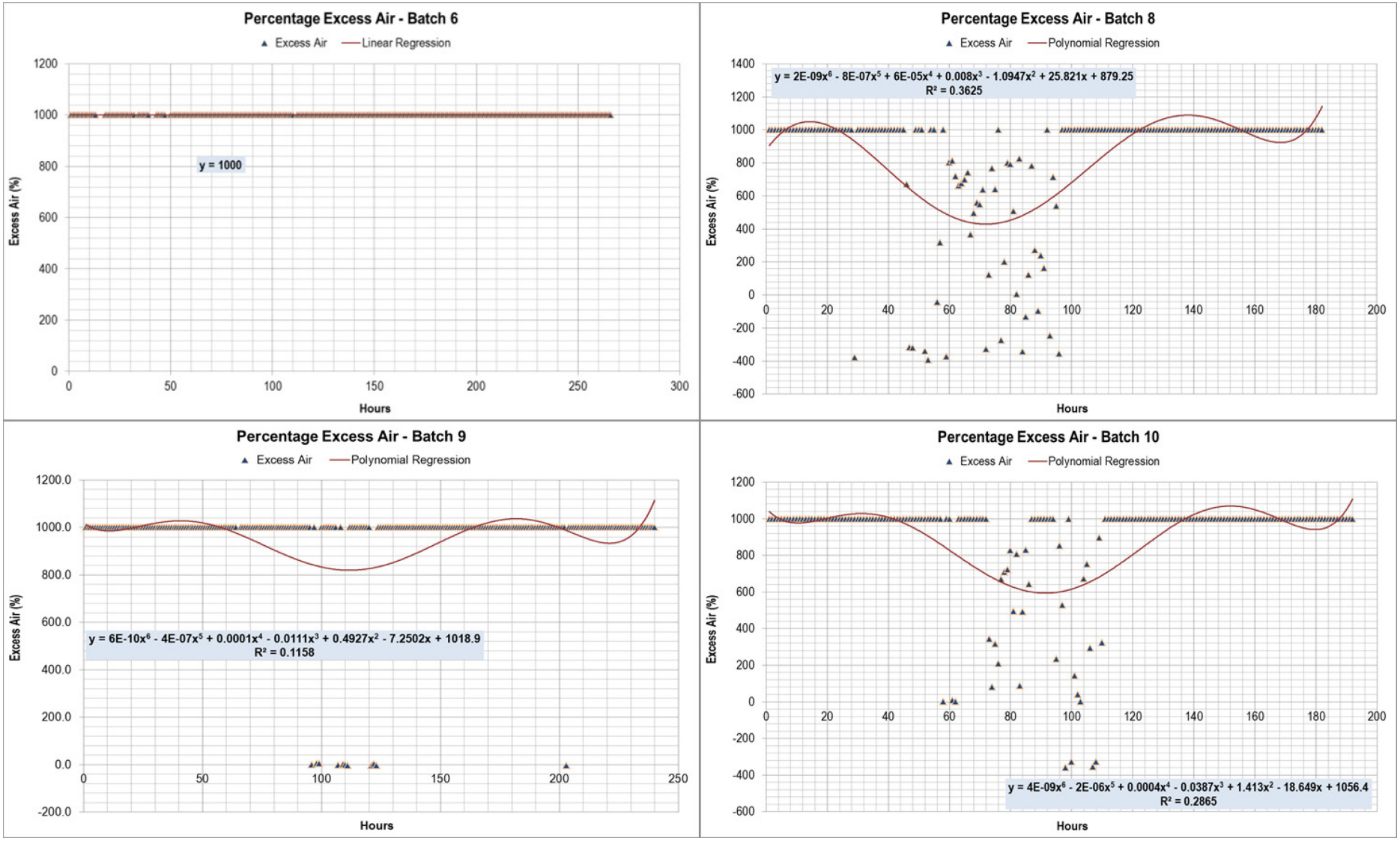


Figure 100: Model kiln percentage excess air (Batches 6, 8, 9 and 10)

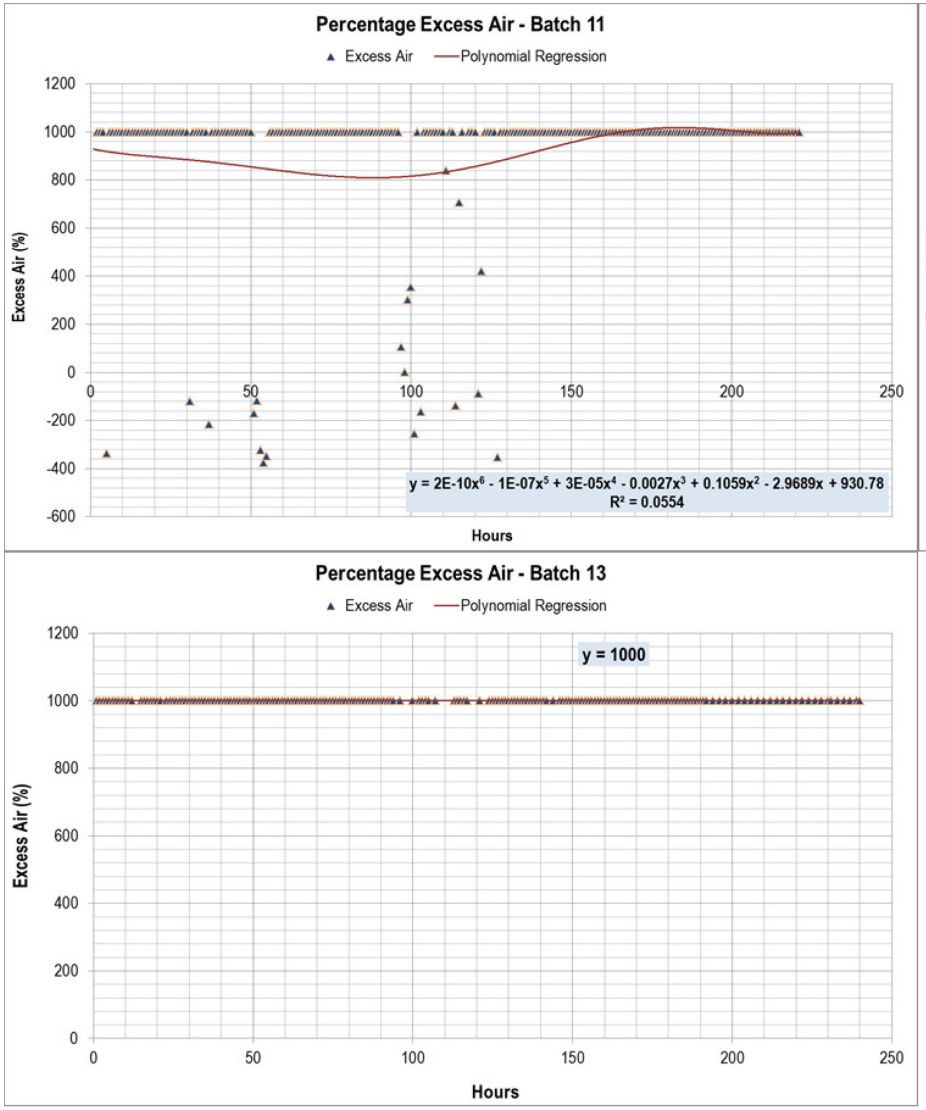


Figure 101: Model kiln percentage excess air (Batches 11, 12 and 13)

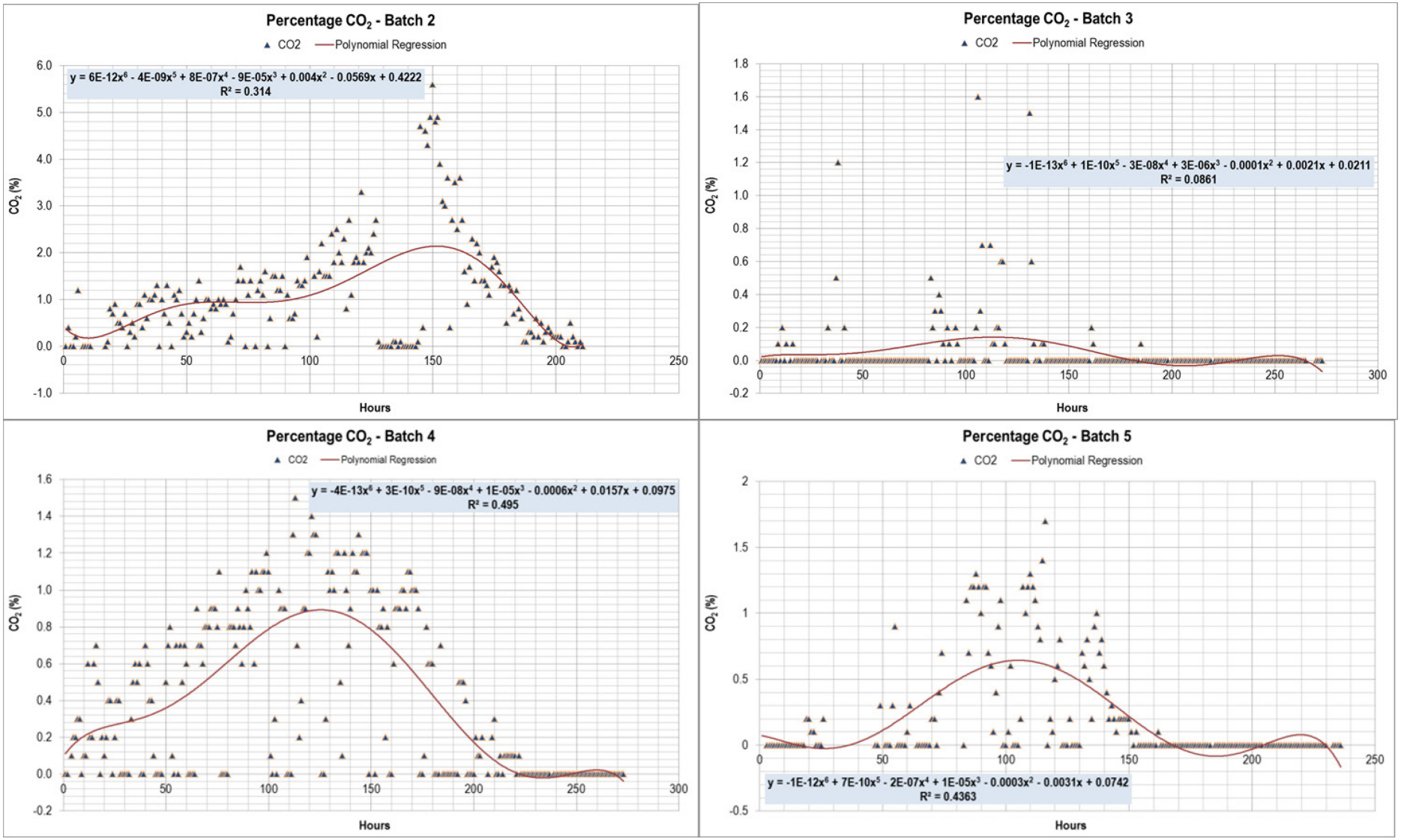


Figure 102: Model kiln percentage CO_2 levels (Batches 2, 3, 4 and 5)

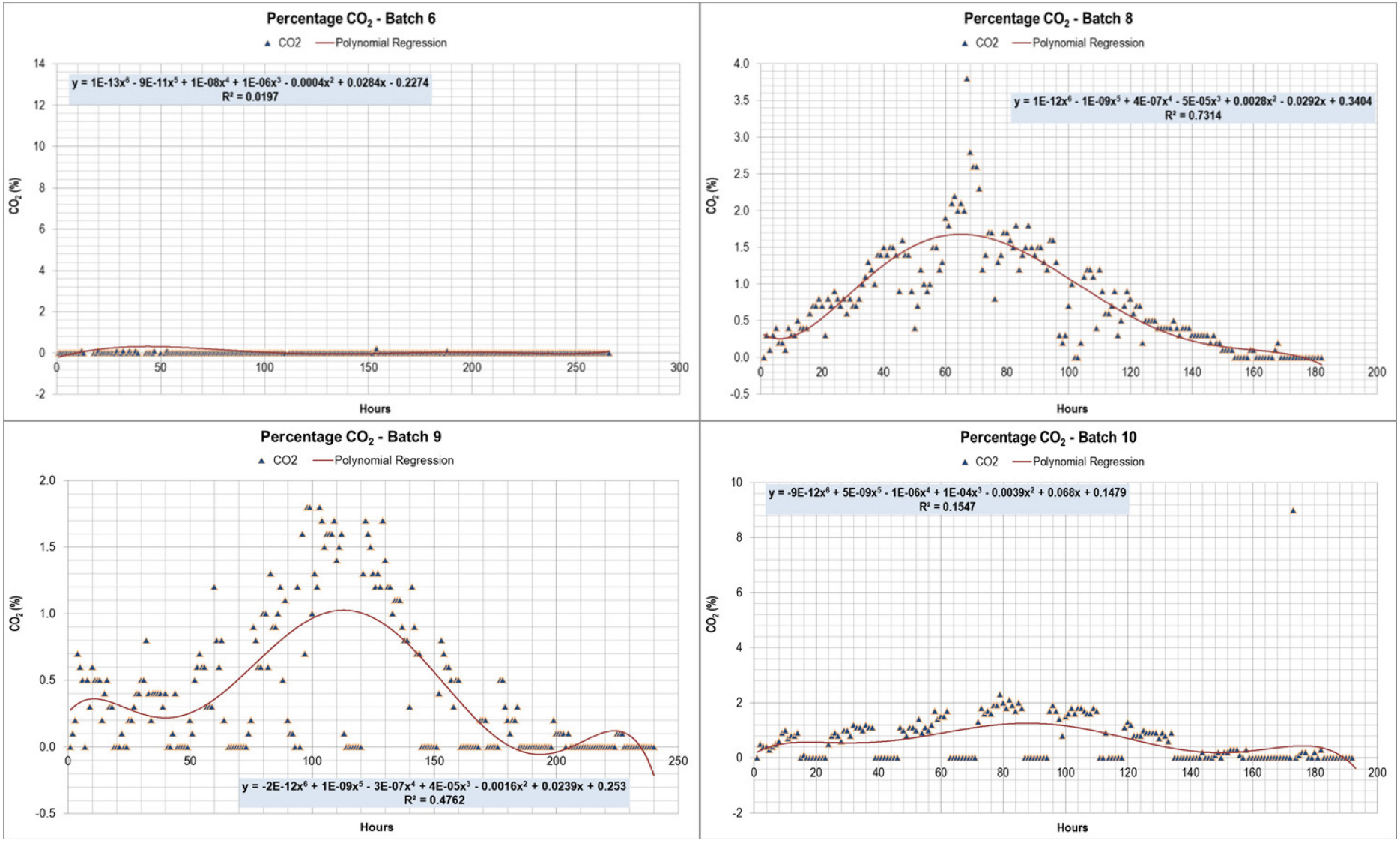


Figure 103: Model kiln percentage CO_2 levels (Batches 6, 8, 9 and 10)

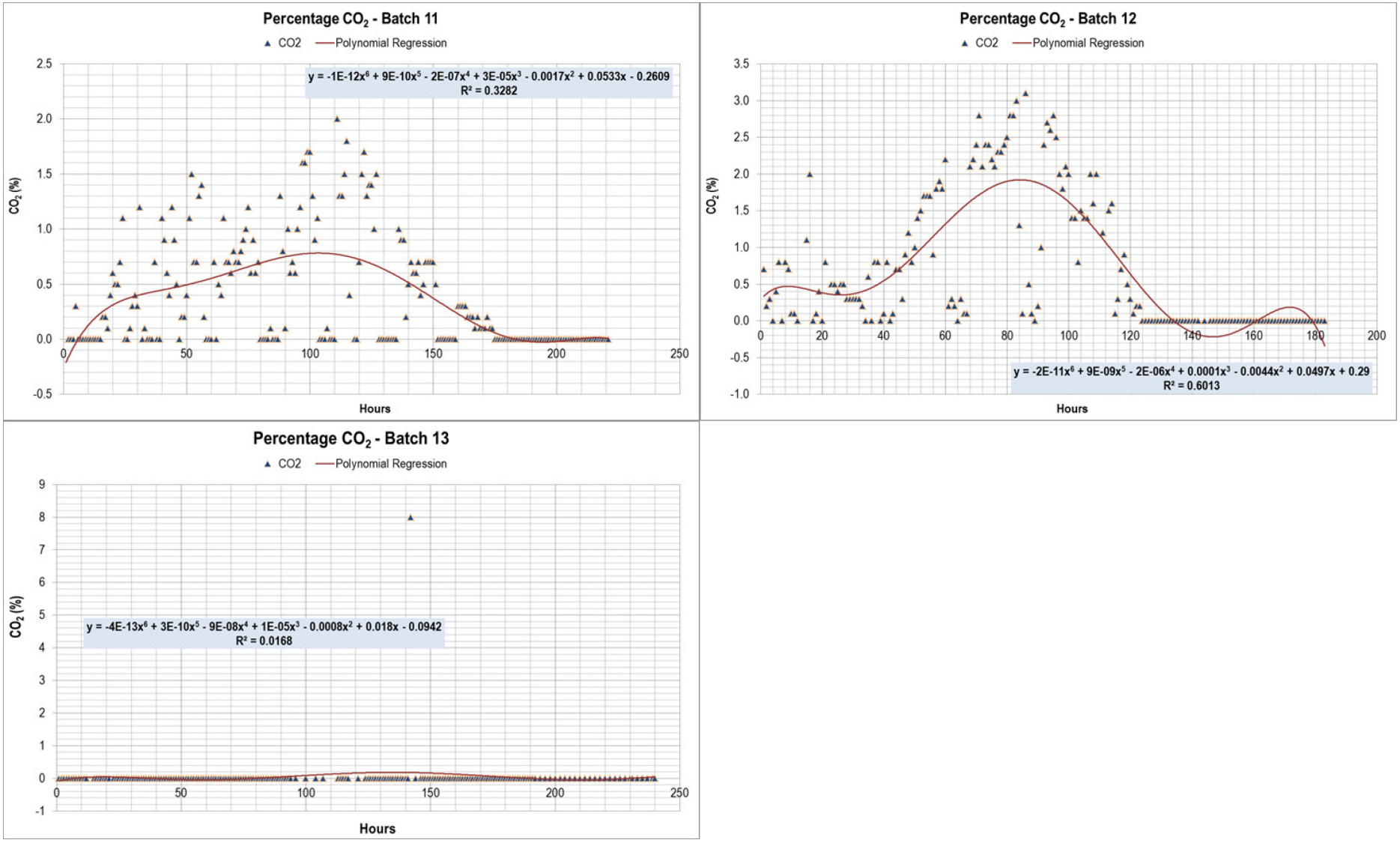


Figure 104: Model kiln percentage CO_2 levels (Batches 11, 12 and 13)

10.3 APPENDIX C – SULFUR MASS BALANCE ANALYSIS RESULTS

ENERGY AND MASS BALANCE INPUT

Input and Firing Metrics	2	3	4	5	6	7	8	9	10	11	12	13
Percentage sulfur in body fuel (%)	0.65	0.65	0.37	0.45	0.65	0.51	0.51	0.65	0.28	0.66	0.28	0.51
Percentage sulfur in external fuel (%)	0.19	0.19	1.13	1.37	0.62	0.48	0.48	0.19	0.62	0.19	0.84	0.48
Percentage fixed carbon in body fuel (%)	48.7	48.7	39.5	42.65	48.7	43.2	43.2	48.7	49.7	44.60	49.7	43.2
Percentage fixed carbon in external fuel (%)	41.4	41.4	46.4	42.86	59.3	45.6	45.6	41.4	49.1	38.97	49.1	45.6
% Ash in internal fuel	31.4	24.6	59.2	31.56	24.6	36	36	24.6	28.9	31.4	56.9	36
% Ash in external fuel	32.6	32.6	22.5	31.56	13.1	31.3	31.3	32.60	27	32.6	11.3	31.3
% volatile matter (internal fuel)	21.5	23.6	0.3	23.04	23.6	20.8	20.8	23.6	18.9	21.5	2.4	20.8
% volatile matter (external fuel)	20.3	20.3	25.6	22.71	24.8	23.1	23.1	20.30	20.9	20.3	36.3	23.1
Total Sulfur - internal fuel (kg)	5933	7886	19800	10720	7632	6000	6000	5800	14504	3000	8529	5000
Total Sulfur - external fuel (kg)	2543	1980	3000	1650	1663	1800	1800	2100	2500	6230	3600	1300
Total carbon - internal fuel (kg)	50	70	0	60	200	200	200	500	0	200	0	200
Total carbon external fuel (kg)	22.87	22.87	12.36	22.87	22.87	19.00	19.00	22.87	21.89	18.23	11.76	19.00
Total volatile - internal fuel (kg)	17.50	17.50	22.60	17.50	28.45	20.00	20.00	17.50	22.15	17.50	28.76	20.00
Total volatile - external fuel (kg)	21.5	23.6	0.3	23.04	23.6	20.8	20.8	23.6	18.9	21.5	2.4	20.8
Total ash - internal fuel (kg)	20.3	20.3	25.6	22.71	24.8	23.1	23.1	20.30	20.9	20.3	36.3	23.1
Total ash - external fuel (kg)	135.7	180.3	244.7	245.2	174.5	114.0	114.0	132.6	317.5	54.7	100.3	95.0

BATCH 2

Internal Fuel (Bricks)		Green (%)	Fired (%)	Mass in Green (g)	Mass in Fired (g)	Mass emitted (g)	% emitted	Mass emitted as SO2 (g per brick)	% mass of SO2 emitted per brick	Mass emitted as SO2 (g/s/brick)	Mass emitted as CO2/SO2 (g/s)	Kg SO2 per Mg of bricks fired
Sample 1	Sulfur	0.07	0.07	2.3294	1.9858	0.3436	14.75%	0.6872	0.0201%	9.05E-07	0.0235	2.01E-01
	Mass	100	100	3426	2878							
Sample 2	Sulfur	0.08	0.07	2.6720	2.0146	0.6574	24.60%	1.3147	0.0384%	1.73E-06	0.0450	3.84E-01
	Mass	100	100	3426	2878							
					Average	**Sulfur**	**19.68%**	**1.00**	**0.0292%**	**1.32E-06**	**0.0343**	**0.2922**
External fuel (coal/ash)		Coal (%)	Ash (%)	Mass S emitted (tons)	Mass emitted as SO2 (tons)	% of SO2 emitted per ton of coal used	Mass of SO2 emitted per ton of coal used (tons)	Mass emitted as SO2 (g/s)	Mass of SO2 emitted (g/s/brick)	Mass emitted as SO2 (g per brick)	Kg SO2 per Mg of bricks fired	
Sample 1	Sulfur	0.30	0.90	-0.0050	-0.0100	-0.0039	-0.0039	-0.0102	0.0000	-0.2969	-0.0867	
	Mass (ton)	2.543	1.41	Coal	Ash							
				0.2944	0.4865							
Sample 2	Sulfur	0.29	0.90	-0.0053	-0.0107	-0.0042	-0.0042	-0.0109	0.0000	-0.3172	-0.0926	
	Mass (ton)	2.543	1.41	Coal	Ash							
				0.2807	0.4859							
				Sulfur	**-0.01**	**-0.41%**	**-0.0041**	**-0.0105**	**-4.04E-07**	**-0.3071**	**-0.0896**	
	Internal	**External**	**Total**	**Ratio (internal/External)**	**Stack monitoring result**	**Mass balance result**	**Ratios (Stack/Mass bal)**					
g/s	0.0343	-0.0105	0.0238	-3.26	0.0218	0.0238	0.92	**Final Results**				
g/brick	1.0010	-0.3071	0.6939	-3.26	0.5167	0.6939	0.74	2.745	Out			
kg/mg	2.9220E-01	-0.0896	0.2026	-3.26	0.1845	0.2026	0.91	2.788	in			
g/s/br	1.3177E-06	-4.043E-07	9.13E-07	-3.26	6.80E-07	9.135E-07	0.74	98.44%	%			

BATCH 3

Internal Fuel (Bricks)		Green (%)	Fired (%)	Mass in Green (g)	Mass in Fired (g)	Mass emitted (g)	% emitted	Mass emitted as SO2 (g per brick)	% mass of SO2 emitted per brick	Mass emitted as SO2 (g/s/brick)	Mass emitted as SO2 (g/s)	Kg SO2 per Mg of bricks fired
Sample 1	Sulfur	0.07	0.04	2.1213	1.1562	0.9651	45.50%	1.9301	0.0628%	2.08E-06	0.0592	6.28E-01
	Mass	100	100	3074	2964.6							
Sample 2	Sulfur	0.06	0.04	1.8753	1.2155	0.6598	35.19%	1.3197	0.0429%	1.42E-06	0.0405	4.29E-01
	Mass	100	100	3074	2964.6							
Quantity in body fuel		5.5575	tons		**Average**	**Sulfur**	**40.34%**	**1.62**	**0.05%**	**1.75E-06**	**0.0499**	**0.5285**
External fuel (coal/ash)		Coal (%)	Ash (%)	Mass S emitted (tons)	Mass emitted as SO2 (tons)	% of SO2 emitted per ton of coal used	Mass of SO2 emitted per ton of coal used (tons)	Mass emitted as SO2 (g/s)	Mass of CO2/SO2 emitted (g/s/brick)	Mass emitted as SO2 (g per brick)	Kg SO2 per Mg of bricks fired	
Sample 1	Sulfur	0.5	0.90	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0034	0.0011	
	Mass (ton)	1.98	1.10	Coal	Ash							
				0.3474	0.3456							
Sample 2	Sulfur	0.5	0.90	6.24E-05	1.25E-04	0.0063%	6.308E-05	0.0001	4.46E-09	0.00	1.35E-03	
	Mass (ton)	1.98	1.10	Coal	Ash							
				0.3474	0.3452							
			Average	**Sulfur**	**0.00**	**0.01%**	**0.0001**	**0.0001**	**4.07E-09**	**0.0038**	**0.0012**	
	Internal + External Fuel	**Internal**	**External**	**Total**	**Ratio (internal/External)**	**Stack monitoring result**	**Mass balance result**	**Ratios (Stack/ Mass bal)**				
	g/s	0.0499	0.0001	0.0500	430.10	0.0111	0.0500	0.22	**Final Results**			
	g/brick	1.6249	0.0038	1.6287	430.10	0.3512	1.6287	0.22	1.707	Out		
	kg/mg	5.2855E-01	0.0012	0.5298	430.10	0.1185	0.5298	0.22	2.346	in		
	g/s/br	1.7495E-06	4.068E-09	1.75E-06	430.10	3.88638E-07	1.754E-06	0.22	72.76%	%		

BATCH 4

Internal Fuel (Bricks)		Green (%)	Fired (%)	Mass in Green (g)	Mass in Fired (g)	Mass emitted (g)	% emitted	Mass emitted as SO_2 (g per brick)	% mass of SO_2 emitted per brick	Mass emitted as SO_2 (g/s/brick)	Mass emitted as SO_2 (g/s)	Kg SO_2 per Mg of bricks fired
Sample 1	Sulfur	0.04	0.04	1.2645	0.9608	0.3037	24.02%	0.6074	0.0197%	6.18E-07	0.0185	1.97E-01
	Mass	100	100	3084.2	2668.9							
Sample 2	Sulfur	0.04	0.04	1.2191	1.0934	0.1257	10.31%	0.2513	0.0080%	2.56E-07	0.0077	8.04E-02
	Mass	100	100	3125.9	2666.9							
Quantity in body fuel		3.6	tons		**Average**	**Sulfur**	**17.16%**	**0.43**	**0.01%**	**4.37E-07**	**0.0131**	**0.1387**
External fuel (coal/ash)		Coal (%)	Ash (%)	Mass C/S emitted (tons)	Mass emitted as CO2/SO2 (tons)	% of SO_2 mitted per ton of coal used	Mass of SO_2 emitted per ton of coal used (tons)	Mass emitted as SO_2 (g/s)	Mass of SO_2 emitted (g/s/brick)	Mass emitted as SO_2 (g per brick)	Kg SO_2 per Mg of bricks fired	
Sample 1	Sulfur	1.13	0.41	0.027103678	0.054207357	1.8069%	0.018069119	0.055156041	1.84E-06	1.81	5.86E-01	
	Mass (ton)	3	1.66	Coal	Ash							
				1.13	0.226544051							
Sample 2	Sulfur	1.13	0.77	0.021188054	0.042376108	1.4125%	0.01413	0.04312	1.44E-06	1.41	4.52E-01	
	Mass (ton)	3	1.66	Coal	Ash							
				1.13	0.423731538							
			Average	**Sulfur**	**0.05**	**1.61%**	**0.0161**	**0.0491**	**1.64E-06**	**1.6097**	**0.5189**	
		Internal	**External**	**Total**	**Ratio (Int/Ext)**	**Stack monitoring result**	**Stack monitoring result**	**Mass balance result**	**Ratios (Stack/Mass bal)**			
	g/s	0.0131	0.0491	0.0622	0.27	0.0116	0.0622	0.19	**Final Results**			
	g/brick	0.4294	1.6097	2.0391	0.27	0.3801	2.0391	0.19	1.542	Out		
	kg/mg	1.3868E-01	0.5189	0.6576	0.27	0.1425	0.6576	0.22	2.372	in		
	g/s/br	4.3690E-07	1.638E-06	2.07E-06	0.27	3.867E-07	2.075E-06	0.19	65.03%	%		

BATCH 5

Internal Fuel (Bricks)		Green (%)	Fired (%)	Mass in Green (g)	Mass in Fired (g)	Mass emitted (g)	% emitted	Mass emitted as SO_2 (g per brick)	% mass of SO_2 emitted per brick	Mass emitted as SO_2 (g/s/brick)	Mass emitted as SO_2 (g/s)	Kg SO_2 per Mg of bricks fired
Sample 1	Sulfur	0.09	0.17	2.7606	4.3844	-1.6238	-58.82%	-3.2476	-0.1059%	-3.82E-06	-0.1237	-1.06E+00
	Mass	100	100	3067	2594.3							
Sample 2	Sulfur	0.05	0.17	1.4030	4.3439	-2.9409	-209.62%	-5.8819	-0.1929%	-6.92E-06	-0.2240	-1.93E+00
	Mass	100	100	3050	2616.8							
Quantity in body fuel		6.600624	tons			**Sulfur**	**-134.22%**	**-4.56**	**-0.15%**	**-5.37E-06**	**-0.1738**	**-1.4937**
External fuel (coal/ash)		Coal (%)	Ash (%)	Mass C/S emitted (tons)	Mass emitted as CO2/SO2 (tons)	% of SO_2 mitted per ton of coal used	Mass of SO_2 emitted per ton of coal used (tons)	Mass emitted as SO_2 (g/s)	Mass of SO_2 emitted (g/s/brick)	Mass emitted as SO_2 (g per brick)	Kg SO_2 per Mg of bricks fired	
Sample 1	Sulfur	0.30	1.38	-0.0113	-0.0225	-0.9290%	-0.0093	-0.0229	-7.09E-07	-0.60	-1.96E-01	
	Mass (ton)	2.4267	1.34	Coal	Ash							
				0.22575	0.5741							
Sample 2	Sulfur	0.29	1.36	-0.01136948	-0.0227	-0.9370%	-0.0094	-0.0231	-7.15E-07	-0.61	-1.99E-01	
	Mass (ton)	2.4267	1.34	Coal	Ash							
				0.21525	0.5666							
% int:ext	272%			**Sulfur**	**-0.02**	**-0.93%**	**-0.0093**	**-0.0230**	**-7.12E-07**	**-0.6049**	**-0.1978**	
		Internal	**External**	**Total**	**Ratio (Int/Ext)**	**Stack monitoring result**	**Stack monitoring result**	**Mass balance result**	**Ratios (Stack/Mass bal)**			
	g/s	-0.1738	-0.0230	-0.1969	7.55	0.0137	-0.1969	0.07	Final Results			
	g/brick	-4.5647	-0.6049	-5.1696	7.55	0.3609	-5.1696	0.07	5.115		Out	
	kg/mg	-1.4937E+00	-0.1978	-1.6914	7.55	0.1180	-1.6914	-0.07	2.302		in	
	g/s/br	-5.3728E-06	-7.120E-07	-6.08E-06	7.55	4.25E-07	-6.085E-06	-0.07	222.17%		%	

BATCH 6

Internal Fuel (Bricks)		Green (%)	Fired (%)	Mass in Green (g)	Mass in Fired (g)	Mass emitted (g)	% emitted	Mass emitted as SO_2 (g per brick)	% mass of SO_2 emitted per brick	Mass emitted as SO_2 (g/s/brick)	Mass emitted as SO_2 (g/s)	Kg SO_2 per Mg of bricks fired
Sample 1	Sulfur	0.07	0.11	2.4930	3.3482	0.8553	34.31%	1.7105	0.0501%	1.79E-06	0.0370	5.01E-01
	Mass	100	100	3415	3016.4							
Sample 2	Sulfur	0.06	0.07	2.0990	2.1131	0.0141	0.67%	0.0282	0.0008%	2.95E-08	0.0006	8.34E-03
	Mass	100	100	3386	3062.5							
Quantity in body fuel		4.19175	tons		**Average**	**Sulfur**	**17.49%**	**0.87**	**0.03%**	**9.08E-07**	**0.0188**	**0.2546**
External fuel (coal/ash)		Coal (%)	Ash (%)	Mass C/S emitted (tons)	Mass emitted as CO2/SO2 (tons)	% of SO_2 mitted per ton of coal used	Mass of SO_2 emitted per ton of coal used (tons)	Mass emitted as SO_2 (g/s)	Mass of SO_2 emitted (g/s/brick)	Mass emitted as SO_2 (g per brick)	Kg SO_2 per Mg of bricks fired	
Sample 1	Sulfur	0.62	0.19	0.00856045	0.017120901	1.0295%	0.0103	0.0174	8.42E-07	0.81	2.36E-01	
	Mass (ton)	1.663	0.92	Coal	Ash							
				0.4981	0.0845							
Sample 2	Sulfur	0.62	0.19	0.0086	0.0172	1.0340%	0.0103	0.0175	8.45E-07	0.81	2.39E-01	
	Mass (ton)	1.663	0.92	Coal	Ash							
				0.4981	0.0828							
				Sulfur	**0.02**	**1.03%**	**0.0103**	**0.0175**	**8.43E-07**	**0.8076**	**0.2375**	
		Internal	**External**	**Total**	**Ratio (Int/Ext)**	**Stack monitoring result**	**Stack monitoring result**	**Mass balance result**	**Ratios (Stack/Mass bal)**			
	g/s	0.0188	0.0175	0.0363	1.08	0.0000	0.0363	0.00	Final Results			
	g/brick	0.8694	0.8076	1.6770	1.08	0.0005	1.6770	0.00	2.815		Out	
	kg/mg	2.5461E-01	0.2375	0.4921	1.07	0.0001	0.4921	0.00	2.794		in	
	g/s/br	9.0786E-07	8.434E-07	1.75E-06	1.08	0.0000	1.751E-06	0.00	100.73%		%	

BATCH 7

Internal Fuel (Bricks)		Green (%)	Fired (%)	Mass in Green (g)	Mass in Fired (g)	Mass emitted (g)	% emitted	Mass emitted as SO_2 (g per brick)	% mass of SO_2 emitted per brick	Mass emitted as SO_2 (g/s/brick)	Mass emitted as SO_2 (g/s)	Kg SO_2 per Mg of bricks fired
Sample 1	Sulfur	0.12	0.07	3.8212	1.9858	1.8353	48.03%	3.6707	0.1114%	4.30E-06	0.0000	1.11E+00
	Mass	100	100	3294	2878							
Sample 2	Sulfur	0.12	0.07	4.2254	2.0038	2.2217	52.58%	4.4433	0.1304%	5.21E-06	0.0000	1.30E+00
	Mass	100	100	3408	2862.5							
					Average	**Sulfur**	**50.30%**	**4.06**	**0.12%**	**4.76E-06**	**0.0000**	**1.2091**
External fuel (coal/ash)		Coal (%)	Ash (%)	Mass C/S emitted (tons)	Mass emitted as CO2/SO2 (tons)	% of SO_2 mitted per ton of coal used	Mass of SO_2 emitted per ton of coal used (tons)	Mass emitted as SO_2 (g/s)	Mass of SO_2 emitted (g/s/brick)	Mass emitted as SO_2 (g per brick)	Kg SO_2 per Mg of bricks fired	
Sample 1	Sulfur		0.88	-0.0092856	-0.0185712	-1.0317%	-0.0103	-0.0189	#DIV/0!	#DIV/0!	#DIV/0!	
	Mass (ton)	1.8	1.06	Coal	Ash							
				#DIV/0!	#DIV/0!							
Sample 2	Sulfur		0.90	-0.00954	-0.01908	-1.0600%	-0.0106	-0.0194	#DIV/0!	#DIV/0!	#DIV/0!	
	Mass (ton)	1.8	1.06	Coal	Ash							
				#DIV/0!	#DIV/0!							
% int:ext	#REF!		**Average**	**Carbon**	**#REF!**	**#REF!**	**#REF!**	**#REF!**	**#REF!**	**#REF!**	**#REF!**	
				Sulfur	**-0.02**	**-1.05%**	**-0.0105**	**-0.0192**	**#DIV/0!**	**#DIV/0!**	**#DIV/0!**	
		Internal	**External**	**Total**	**Ratio (Int/Ext)**	**Stack monitoring result**	**Stack monitoring result**	**Mass balance result**	**Ratios (Stack/Mass bal)**			
	g/s	0.0000	-0.0192	-0.0192	0.00	0.0000	-0.0192	0.00	Final Results			
	g/brick	4.0570	#DIV/0!	#DIV/0!	#DIV/0!	0.0000	#DIV/0!	#DIV/0!	#DIV/0!	Out		
	kg/mg	1.2091E+00	#DIV/0!	#DIV/0!	#DIV/0!	0.0000	#DIV/0!	#DIV/0!	#DIV/0!	in		
	g/s/br	4.7551E-06	#DIV/0!	#DIV/0!	#DIV/0!	0.0000	#DIV/0!	#DIV/0!	#DIV/0!	%		

BATCH 8

Internal Fuel (Bricks)		Green (%)	Fired (%)	Mass in Green (g)	Mass in Fired (g)	Mass emitted (g)	% emitted	Mass emitted as SO_2 (g per brick)	% mass of SO_2 emitted per brick	Mass emitted as SO_2 (g/s/brick)	Mass emitted as SO_2 (g/s)	Kg SO_2 per Mg of bricks fired
Sample 1	Sulfur	0.03	0.01	0.0010	0.2925	-0.2915	-29716.51%	-0.5830	-17.8299%	-8.90E-07	-0.0214	-1.78E+02
	Mass	100	100	3.27	2925.00							
Sample 2	Sulfur	0.03	0.01	0.0010	0.2925	-0.2915	-29716.51%	-0.5830	-17.8299%	-8.90E-07	-0.0214	-1.78E+02
	Mass	100	100	3.27	2925.00							
Quantity in body fuel		2.16	tons		**Average**	**Sulfur**	**-29716.51%**	**-0.58**	**-17.83%**	**-8.90E-07**	**-0.0214**	**-178.2991**
External fuel (coal/ash)		Coal (%)	Ash (%)	Mass C/S emitted (tons)	Mass emitted as CO2/SO2 (tons)	% of SO_2 mitted per ton of coal used	Mass of SO_2 emitted per ton of coal used (tons)	Mass emitted as SO_2 (g/s)	Mass of SO_2 emitted (g/s/brick)	Mass emitted as SO_2 (g per brick)	Kg SO_2 per Mg of bricks fired	
Sample 1	Sulfur	2.11	0.37	0.03517	0.07034	3.9076%	0.0391	0.0716	2.98E-06	1.95	5.97E+02	
	Mass (ton)	1.8	0.76	Coal	Ash							
				1.5825	0.1172							
Sample 2	Sulfur	2.11	0.37	0.03517	0.07034	3.9076%	0.0391	0.0716	2.98E-06	1.95	5.97E+02	
	Mass (ton)	1.8	0.76	Coal	Ash							
				1.5825	0.1172							
% int:ext	120%		**Average**	**Sulfur**	**0.07**	**3.91%**	**0.0391**	**0.0716**	**2.98E-06**	**1.9538**	**597.4856**	
		Internal	**External**	**Total**	**Ratio (Int/Ext)**	**Stack monitoring result**	**Stack monitoring result**	**Mass balance result**	**Ratios (Stack/ Mass bal)**			
	g/s	-0.0214	0.0716	0.0502	-0.30	0.0443	0.0502	0.88	Final Results			
	g/brick	-0.5830	1.9538	1.3707	-0.30	1.0177	1.3707	0.74	0.919	Out		
	kg/mg	-1.7830E+02	597.4856	419.1865	-0.30	0.2993	419.1865	0.00	1.583	in		
	g/s/br	-8.8986E-07	2.982E-06	2.09E-06	-0.30	0.0000	2.092E-06	0.74	58.01%	%		

BATCH 9

Internal Fuel (Bricks)		Green (%)	Fired (%)	Mass in Green (g)	Mass in Fired (g)	Mass emitted (g)	% emitted	Mass emitted as SO_2 (g per brick)	% mass of SO_2 emitted per brick	Mass emitted as SO_2 (g/s/brick)	Mass emitted as SO_2 (g/s)	Kg SO_2 per Mg of bricks fired
Sample 1	Sulfur	0.03	0.03	0.9072	0.8611	0.0461	5.08%	0.0922	0.0031%	1.07E-07	0.0031	3.05E-02
	Mass	100	100	3024	2870							
Sample 2	Sulfur	0.03	0.03	0.9072	0.8611	0.0461	5.08%	0.0922	0.0031%	1.07E-07	0.0031	3.05E-02
	Mass	100	100	3024	2870							
Quantity in body fuel		2.61	tons		**Average**	**Sulfur**	**5.08%**	**0.09**	**0.00%**	**1.07E-07**	**0.0031**	**0.0305**
External fuel (coal/ash)		Coal (%)	Ash (%)	Mass S emitted (tons)	Mass emitted as SO2 (tons)	% of SO_2 mitted per ton of coal used	Mass of SO_2 emitted per ton of coal used (tons)	Mass emitted as SO_2 (g/s)	Mass of SO_2 emitted (g/s/brick)	Mass emitted as SO_2 (g per brick)	Kg SO_2 per Mg of bricks fired	
Sample 1	Sulfur	0.50	0.10	0.00896	0.01792	0.8533%	0.0085	0.0182	6.29E-07	0.54	1.80E-01	
	Mass (ton)	2.1	1.54	Coal	Ash							
				0.3621	0.0531							
Sample 2	Sulfur	0.50	0.10	0.0090	0.0179	0.8533%	0.0085	0.0182	6.29E-07	0.54	1.80E-01	
	Mass (ton)	2.1	1.54	Coal	Ash							
				0.3621	0.0531							
% int:ext	124%		**Average**	**Sulfur**	**0.02**	**0.85%**	**0.0085**	**0.0182**	**6.29E-07**	**0.5432**	**0.1796**	
		Internal	**External**	**Total**	**Ratio (Int/Ext)**	**Stack monitoring result**	**Stack monitoring result**	**Mass balance result**	**Ratios (Stack/Mass bal)**			
	g/s	0.0031	0.0182	0.0213	0.17	0.0229	0.0213	1.07	Final Results			
	g/brick	0.0922	0.5432	0.6355	0.17	0.6831	0.6355	1.07	1.256	Out		
	kg/mg	3.0506E-02	0.1796	0.2101	0.17	0.2439	0.2101	1.16	1.269	in		
	g/s/br	1.0677E-07	6.287E-07	7.36E-07	0.17	0.0000	7.355E-07	1.07	98.93%	%		

BATCH 10

Internal Fuel (Bricks)		Green (%)	Fired (%)	Mass in Green (g)	Mass in Fired (g)	Mass emitted (g)	% emitted	Mass emitted as SO_2 (g per brick)	% mass of SO_2 emitted per brick	Mass emitted as SO_2 (g/s/brick)	Mass emitted as SO_2 (g/s)	Kg SO_2 per Mg of bricks fired
Sample 1	Sulfur	0.01	0.10	0.3074	2.9646	-2.6572	-864.32%	-5.3143	-0.1729%	-7.65E-06	-0.2256	-1.73E+00
	Mass	100	100	3074	2965							
Sample 2	Sulfur	0.01	0.10	0.3074	2.9646	-2.6572	-864.32%	-5.3143	-0.1729%	-7.65E-06	-0.2256	-1.73E+00
	Mass	100	100	3074	2965							
Quantity in body fuel		8.85	tons		**Average**	**Sulfur**	**-864.32%**	**-5.31**	**-0.17%**	**-7.65E-06**	**-0.2256**	**-1.7286**
External fuel (coal/ash)		Coal (%)	Ash (%)	Mass C/S emitted (tons)	Mass emitted as CO2/SO2 (tons)	% of SO_2 mitted per ton of coal used	Mass of SO_2 emitted per ton of coal used (tons)	Mass emitted as SO_2 (g/s)	Mass of SO_2 emitted (g/s/brick)	Mass emitted as SO_2 (g per brick)	Kg SO_2 per Mg of bricks fired	
Sample 1	Sulfur	0.95	0.13	0.0218	0.04354	1.7419%	0.0174	0.04431	1.50E-06	1.04	3.39E-01	
	Mass (ton)	2.5	1.52	Coal	Ash							
				0.8050	0.0669							
Sample 2	Sulfur	0.95	0.13	0.0217	0.0435	1.7419%	0.0174	0.04431	1.50E-06	1.04	3.39E-01	
	Mass (ton)	2.5	1.52	Coal	Ash							
				0.805084746	0.066983051							
% int:ext	354%		**Average**	**Sulfur**	**0.04**	**1.74%**	**0.0174**	**0.0443**	**1.50E-06**	**1.0436**	**0.3395**	
		Internal	**External**	**Total**	**Ratio (Int/Ext)**	**Stack monitoring result**	**Stack monitoring result**	**Mass balance result**	**Ratios (Stack/Mass bal)**			
	g/s	-0.2256	0.0443	-0.1813	-5.09	0.0744	-0.1813	0.41	Final Results			
	g/brick	-5.3143	1.0436	-6.3580	-5.09	1.7530	-6.3580	0.28	3.908	Out		
	kg/mg	-1.7286E+00	0.3395	-1.3892	-5.09	0.6261	-1.3892	0.45	1.113	in		
	g/s/br	-7.6487E-06	1.502E-06	-6.15E-06	-5.09	0.0000	-6.147E-06	0.41	351.28%	%		

BATCH 11

Internal Fuel (Bricks)		Green (%)	Fired (%)	Mass in Green (g)	Mass in Fired (g)	Mass emitted (g)	% emitted	Mass emitted as SO_2 (g per brick)	% mass of SO_2 emitted per brick	Mass emitted as SO_2 (g/s/brick)	Mass emitted as SO_2 (g/s)	Kg SO_2 per Mg of bricks fired
Sample 1	Sulfur	0.03	0.04	1.0440	1.1440	-0.1000	-9.58%	-0.2000	-0.0057%	-2.55E-07	-0.0054	-5.75E-02
	Mass	100	100	3480	2860							
Sample 2	Sulfur	0.03	0.04	1.0440	1.1440	-0.1000	-9.58%	-0.2000	-0.0057%	-2.55E-07	-0.0054	-5.75E-02
	Mass	100	100	3480	2860							
Quantity in body fuel		1.89	tons		**Average**	**Sulfur**	**-9.58%**	**-0.20**	**-0.01%**	**-2.55E-07**	**-0.0054**	**-0.0575**
	External fuel (coal/ash)											
External fuel (coal/ash)		Coal (%)	Ash (%)	Mass S emitted (tons)	Mass emitted as SO2 (tons)	% of SO_2 mitted per ton of coal used	Mass of SO_2 emitted per ton of coal used (tons)	Mass emitted as SO_2 (g/s)	Mass of SO_2 emitted (g/s/brick)	Mass emitted as SO_2 (g per brick)	Kg SO_2 per Mg of bricks fired	
Sample 1	Sulfur	0.19	0.06	0.0098	0.0195	0.3135%	0.003135323	0.019874911	9.46E-07	0.74	2.13E-01	
	Mass (ton)	6.23	3.450781026	Coal	Ash							
				0.5637	0.0986							
Sample 2	Sulfur	0.19	0.06	0.0098	0.0195	0.3135%	0.003135323	0.019874911	9.46E-07	0.74	2.13E-01	
	Mass (ton)	6.23	3.450781026	Coal	Ash							
				0.56367	0.09859							
% int:ext	30%		**Average**	**Sulfur**	**0.02**	**0.31%**	**0.0031**	**0.0199**	**9.46E-07**	**0.7428**	**0.2134**	
		Internal	**External**	**Total**	**Ratio (Int/Ext)**	**Stack monitoring result**	**Stack monitoring result**	**Mass balance result**	**Ratios (Stack/Mass bal)**			
	g/s	-0.0054	0.0199	-0.0252	-0.27	0.0372	-0.0252	1.48	Final Results			
	g/brick	-0.2000	0.7428	-0.9428	-0.27	1.3919	-0.9428	1.48	1.939	Out		
	kg/mg	-5.7471E-02	0.2134	-0.2709	-0.27	0.4867	-0.2709	1.80	1.608	in		
	g/s/br	-2.5484E-07	9.464E-07	0.0000	-0.27	0.0000	-1.201E-06	1.48	120.58%	%		

BATCH 12

Internal Fuel (Bricks)		Green (%)	Fired (%)	Mass in Green (g)	Mass in Fired (g)	Mass emitted (g)	% emitted	Mass emitted as SO_2 (g per brick)	% mass of SO_2 emitted per brick	Mass emitted as SO_2 (g/s/brick)	Mass emitted as SO_2 (g/s)	Kg SO_2 per Mg of bricks fired
Sample 1	Sulfur	0.13	0.01	3.8588	0.2578	3.6011	93.32%	7.2022	0.2426%	1.23E-05	0.3273	2.43E+00
	Mass	100	100	2968	2578							
Sample 2	Sulfur	0.13	0.01	3.8588	0.2578	3.6011	93.32%	7.2022	0.2426%	1.23E-05	0.3273	2.43E+00
	Mass	100	100	2968	2578							
Quantity in body fuel		10.335	tons		**Average**	**Sulfur**	**93.32%**	**7.20**	**0.24%**	**1.23E-05**	**0.3273**	**2.4263**
External fuel (coal/ash)		Coal (%)	Ash (%)	Mass S emitted (tons)	Mass emitted as SO2 (tons)	% of SO_2 mitted per ton of coal used	Mass of SO_2 emitted per ton of coal used (tons)	Mass emitted as SO_2 (g/s)	Mass of SO_2 emitted (g/s/brick)	Mass emitted as SO_2 (g per brick)	Kg SO_2 per Mg of bricks fired	
Sample 1	Sulfur	0.44	0.21	0.013152	0.026304	0.7307%	0.007306667	0.026764347	1.01E-06	0.59	1.98E-01	
	Mass (ton)	3.6	1.28	Coal	Ash							
				0.597735849	0.101433962							
Sample 2	Sulfur	0.44	0.21	0.013152	0.026304	0.7307%	0.007306667	0.026764347	1.01E-06	0.59	1.98E-01	
	Mass (ton)	3.6	1.28	Coal	Ash							
				0.597735849	0.101433962							
% int:ext	287%		**Average**	**Sulfur**	**0.03**	**0.73%**	**0.0073**	**0.0268**	**1.01E-06**	**0.5890**	**0.1984**	
		Internal	**External**	**Total**	**Ratio (Int/Ext)**	**Stack monitoring result**	**Stack monitoring result**	**Mass balance result**	**Ratios (Stack/Mass bal)**			
	g/s	0.3273	0.0268	0.3540	12.23	0.0894	0.3540	0.25	Final Results			
	g/brick	7.2022	0.5890	7.7912	12.23	1.9684	7.7912	0.25	1.343	Out		
	kg/mg	2.4263E+00	0.1984	2.6248	12.23	0.7637	2.6248	0.29	4.457	in		
	g/s/br	1.2349E-05	1.010E-06	1.34E-05	12.23	0.0000	1.336E-05	0.25	30.14%	%		

BATCH 13

Internal Fuel (Bricks)		Green (%)	Fired (%)	Mass in Green (g)	Mass in Fired (g)	Mass emitted (g)	% emitted	Mass emitted as SO_2 (g per brick)	% mass of SO_2 emitted per brick	Mass emitted as SO_2 (g/s/brick)	Mass emitted as SO_2 (g/s)	Kg SO_2 per Mg of bricks fired
Sample 1	Sulfur	0.03	0.03	1.0201	0.9118	0.1082	10.61%	0.2165	0.0064%	2.51E-07	0.0050	6.37E-02
	Mass	100	100	3400	3039							
Sample 2	Sulfur	0.03	0.03	1.0201	0.9118	0.1082	10.61%	0.2165	0.0064%	2.51E-07	0.0050	6.37E-02
	Mass	100	100	3400	3039							
Quantity in body fuel		1.8	tons		**Average**	**Sulfur**	**10.61%**	**0.22**	**0.01%**	**2.51E-07**	**0.0050**	**0.0637**
External fuel (coal/ash)		Coal (%)	Ash (%)	Mass S emitted (tons)	Mass emitted as SO2 (tons)	% of SO_2 mitted per ton of coal used	Mass of SO_2 emitted per ton of coal used (tons)	Mass emitted as SO_2 (g/s)	Mass of SO_2 emitted (g/s/brick)	Mass emitted as SO_2 (g per brick)	Kg SO_2 per Mg of bricks fired	
Sample 1	Sulfur	0.48	1.20	-0.00336	-0.00672	-0.5169%	-0.005169231	-0.006837607	-3.42E-07	-0.30	-8.69E-02	
	Mass (ton)	1.3	0.8	Coal	Ash							
				0.312	0.48							
Sample 2	Sulfur	0.48	1.20	-0.00336	-0.00672	-0.5169%	-0.005169231	-0.006837607	-3.42E-07	-0.30	-8.69E-02	
	Mass (ton)	1.3	0.8	Coal	Ash							
				0.312	0.48							
% int:ext	138%		**Average**	**Sulfur**	**-0.01**	**-0.52%**	**-0.0052**	**-0.0068**	**-3.42E-07**	**-0.2954**	**-0.0869**	
		Internal	**External**	**Total**	**Ratio (Int/Ext)**	**Stack monitoring result**	**Stack monitoring result**	**Mass balance result**	**Ratios (Stack/Mass bal)**			
	g/s	0.0050	-0.0068	-0.0018	-0.73	#DIV/0!	-0.0018	#DIV/0!	Final Results			
	g/brick	0.2165	-0.2954	-0.0789	-0.73	#DIV/0!	-0.0789	#DIV/0!	#DIV/0!	Out		
	kg/mg	6.3666E-02	-0.0869	-0.0232	-0.73	#DIV/0!	-0.0232	#DIV/0!	0.725	in		
	g/s/br	2.5056E-07	-3.419E-07	-9.13E-08	-0.73	#DIV/0!	-9.132E-08	#DIV/0!	#DIV/0!	%		

10.4 APPENDIX D – SAMPLE OF LAKES' SCREEN VIEW DISPERSION MODEL OUTPUT

08/09/16

14:30:17

*** SCREEN3 MODEL RUN ***

*** VERSION DATED 96043 ***

C:\Users\oladapo.OLA\Dropbox\PHD 2016\DATA\Analysis\Modelling\test.scr

SIMPLE TERRAIN INPUTS:

SOURCE TYPE = VOLUME

EMISSION RATE (G/S) = 12.7000

SOURCE HEIGHT (M) = 4.2000

INIT. LATERAL DIMEN (M) = 85.6100

INIT. VERTICAL DIMEN (M) = 0.9800

RECEPTOR HEIGHT (M) = 1.5000

URBAN/RURAL OPTION = RURAL

THE REGULATORY (DEFAULT) MIXING HEIGHT OPTION WAS SELECTED.

THE REGULATORY (DEFAULT) ANEMOMETER HEIGHT OF 10.0 METERS WAS ENTERED.

BUOY. FLUX = 0.000 M**4/S**3; MOM. FLUX = 0.000 M**4/S**2.

*** FULL METEOROLOGY ***

****

*** SCREEN AUTOMATED DISTANCES ***

****

*** TERRAIN HEIGHT OF 0. M ABOVE STACK BASE USED FOR FOLLOWING DISTANCES ***

DIST (M)	CONC (UG/M**3)	STAB	U10M (M/S)	USTK (M/S)	MIX HT (M)	PLUME HT (M)	SIGMA Y (M)	SIGMA Z (M)	DWASH
50.	0.000	0	0.0	0.0	0.0	0.00	0.00	0.00	
100.	0.000	0	0.0	0.0	0.0	0.00	0.00	0.00	
200.	6359.	6	1.0	1.0	10000.0	4.20	90.22	4.60	NO
300.	5536.	6	1.0	1.0	10000.0	4.20	92.99	6.09	NO
400.	4751.	6	1.0	1.0	10000.0	4.20	95.75	7.49	NO
500.	4109.	6	1.0	1.0	10000.0	4.20	98.50	8.82	NO
600.	3595.	6	1.0	1.0	10000.0	4.20	101.24	10.09	NO
700.	3223.	6	1.0	1.0	10000.0	4.20	103.97	11.15	NO
800.	2910.	6	1.0	1.0	10000.0	4.20	106.70	12.19	NO
900.	2648.	6	1.0	1.0	10000.0	4.20	109.42	13.19	NO
1000.	2436.	6	1.0	1.0	10000.0	4.20	112.12	14.08	NO
1100.	2254.	6	1.0	1.0	10000.0	4.20	114.82	14.95	NO

1200.	2095.	6	1.0	1.0	10000.0	4.20	117.52	15.78	NO
1300.	1956.	6	1.0	1.0	10000.0	4.20	120.20	16.59	NO
1400.	1832.	6	1.0	1.0	10000.0	4.20	122.88	17.38	NO
1500.	1722.	6	1.0	1.0	10000.0	4.20	125.55	18.14	NO
1600.	1623.	6	1.0	1.0	10000.0	4.20	128.21	18.89	NO
1700.	1534.	6	1.0	1.0	10000.0	4.20	130.87	19.62	NO
1800.	1453.	6	1.0	1.0	10000.0	4.20	133.52	20.34	NO
1900.	1380.	6	1.0	1.0	10000.0	4.20	136.16	21.04	NO
2000.	1316.	6	1.0	1.0	10000.0	4.20	138.80	21.67	NO
2100.	1259.	6	1.0	1.0	10000.0	4.20	141.43	22.25	NO
2200.	1207.	6	1.0	1.0	10000.0	4.20	144.06	22.82	NO
2300.	1158.	6	1.0	1.0	10000.0	4.20	146.68	23.38	NO
2400.	1112.	6	1.0	1.0	10000.0	4.20	149.29	23.92	NO
2500.	1070.	6	1.0	1.0	10000.0	4.20	151.90	24.46	NO
2600.	1031.	6	1.0	1.0	10000.0	4.20	154.50	24.99	NO
2700.	993.6	6	1.0	1.0	10000.0	4.20	157.10	25.51	NO
2800.	958.9	6	1.0	1.0	10000.0	4.20	159.69	26.02	NO
2900.	926.3	6	1.0	1.0	10000.0	4.20	162.27	26.52	NO
3000.	896.4	6	1.0	1.0	10000.0	4.20	164.85	26.99	NO
3500.	775.6	6	1.0	1.0	10000.0	4.20	177.68	28.99	NO
4000.	681.2	6	1.0	1.0	10000.0	4.20	190.39	30.85	NO
4500.	605.6	6	1.0	1.0	10000.0	4.20	202.99	32.58	NO
5000.	543.7	6	1.0	1.0	10000.0	4.20	215.49	34.21	NO

MAXIMUM 1-HR CONCENTRATION AT OR BEYOND 50. M:

186.	6450.	6	1.0	1.0	10000.0	4.20	89.86	4.40	NO

DWASH= MEANS NO CALC MADE (CONC = 0.0)

DWASH=NO MEANS NO BUILDING DOWNWASH USED

DWASH=HS MEANS HUBER-SNYDER DOWNWASH USED

DWASH=SS MEANS SCHULMAN-SCIRE DOWNWASH USED

DWASH=NA MEANS DOWNWASH NOT APPLICABLE, X<3*LB **********

*** SUMMARY OF SCREEN MODEL RESULTS *** **********

CALCULATION PROCEDURE	MAX CONC (UG/M**3)	DIST TO MAX (M)	TERRAIN HT (M)
SIMPLE TERRAIN	6450.	186.	0.

****

** REMEMBER TO INCLUDE BACKGROUND CONCENTRATIONS ** **********

GLOSSARY OF TERMS

Body or internal fuel	In the South African clay brick Industry, body fuel refers to the fuel (mostly duff coal or carbon fly ash) that is mixed with the clay material during processing. This allows for uniform firing or burning of the bricks.
Duff coal	Duff is a local South African coal product with a size range of 0 – 9 mm.
External fuel	The external fuel refers to fuel (mostly peas, small nuts or large nuts coal) placed in the base layer (scintle) and is ignited at the start of the firing. The external fuel keeps the kiln ablaze until the body fuel is ignited.
Fire-box	The fire-box is a made of previously fired bricks, enclosing a small quantity of coal (peas or small nuts) from where the ignition process is started, before it is transferred to the kiln. This is an optional step in the firing process that is commonly used in South Africa.
Green brick	Green brick is a term used to describe a brick that has been processed, dried and is ready to be fired.
Large nuts	Large nuts are local South African coal products with a size range of 50 – 70 mm.
Peas	Peas are local South African coal products with a size range of 10 – 25 mm.
PM_1	Particles which pass through a size-selective inlet with a 50% efficiency cut-off at 1 µm aerodynamic diameter.
PM_{10}	Particles which pass through a size-selective inlet with a 50% efficiency cut-off at 10 µm aerodynamic diameter. PM_{10} corresponds to the "thoracic convention" as defined in ISO 7708:1995, Clause 6.
PM_{15}	Particles which pass through a size-selective inlet with a 50% efficiency cut-off at 15 µm aerodynamic diameter.
$PM_{2.5}$	Particles which pass through a size-selective inlet with a 50% efficiency cut-off at 2.5 µm aerodynamic diameter. $PM_{2.5}$ corresponds to the "high-risk respirable convention" as defined in ISO 7708:1995, 7.1.
PM_4	Particles which pass through a size-selective inlet with a 50% efficiency cut-off at 4 µm aerodynamic diameter.
Scintle	The scintle is a term used in the South African clay brick industry to refer to the base layer of the clamp kiln that holds the external fuel.
Small nuts	Small nuts are local coal products with a size range of 25 – 50 mm.