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THERMAL RADIATION ANALYSIS OF AN OIL WELL GAS FLARE

Richard Fagbenle* and Olawale S. Ismail+
University of Ibadan, Mechanical Engineering Department, Faculty of
Technology, University of Ibadan, Ibadan, Oyo State, Nigeria
*Corresponding author, +Presenting author
E-mail: ro.fagbenle@yahoo.com, osismail@yahoo.com

ABSTRACT

Gas flaring, a long-established but unacceptable practice in the Nigerian Petroleum industry, has deleterious effects on the environment. Generally, empirical formulae are employed to estimate thermal radiation fluxes around a gas flare. Thermal radiation field data on Nigerian oil field associated gas flares are rare to come by, thus restricting information on such fields to what can be obtained from existing empirical formulae which are based on data from foreign oil fields. Even then such methods are unable to provide local information on a point-by-point basis. In this work, the governing equations have been solved numerically yielding local information on the thermal radiation field. The gas flare was considered as a three dimensional turbulent jet issuing into a continuous cross flow of air. The momentum and scalar fluxes were approximated by the k-ɛ turbulence model and the resultant conservation equations were solved using the finite volume technique. The laminar flamelet concept was used to characterize the local thermochemical state of the combusting mixture, while the discrete transfer method was used to compute the radiative heat flux. A model for an accurate prediction of the heat flux at any point in the thermal radiation field around a gas flare was developed. This model has superior prediction capabilities to existing empirical formulae. Safe distances could be deduced from thr heat flux field around the flare for both humans and habitat using the model.

NOMENCLATURE

C_1	[-]	Constant in turbulence model
C_2	[-]	Constant in turbulence model
C_D	[-]	Constant in turbulence model
C_μ	[-]	Constant in turbulence model
f	[-]	Mixture fraction
f''^2	[-]	mixture fraction variance
g	[m/s^2]	Acceleration due to gravity
N	[-]	Soot particle mass fraction
P	[N/m^2]	Pressure
S	[-]	Source term
T	[K]	Temperature
U	[m/s]	Velocity
x	[m]	Cartesian axis direction
y	[m]	Cartesian axis direction
$Y_{C(s)}$	[-]	Soot mass fraction
Z	[m]	Cartesian axis direction

Special characters

$\mathcal{P}$	[kg/m^3]	Density
φ	[-]	Variable
ε	[ ]	dissipation rate of turbulence kinetic energy
k	[-]	kinetic energy of turbulence
μ	[ ]	turbulent viscosity

Subscripts

$i,,j,k$	Direction i,j,k
p	Point p
k	Turbulence kinetic energy term
ε	dissipation rate of turbulence kinetic energy
nb	neighbours of point p

INTRODUCTION

Nigeria, Africa's most populous country has significant oil, and even more gas reserves, but most of this oil and gas (in the form of liquefied natural gas, LNG) are exported. Oil production began in the Niger Delta about 45 years ago and so did the practice of flaring associated gas. The waste involved in the practice, and the expected controversy arising from the consequent environmental and ecological degradation, was recognized earlier on.

The development of the oil industry continued during the 16 years (1983 – 1999) Nigeria spent under military rule, and oil in Nigeria has relegated agriculture as the prime source of foreign exchange and export commodity for the past several decades. Nevertheless Nigeria still ranks as one of the poorest countries in the world, with more than half of her population estimated to be living below the poverty line. As at 2004, Nigeria had about 1088 gas flares [1] where about 25838.35m^3 of natural gas was flared annually [2] all of which are located in the Niger Delta areas of the country.

The gas flare shown in Fig 1 is a common sight in the oil fields of the Nigerian petroleum industry. The hazards associated with this type of fire occur mainly in two ways. Near the fire, the radiant energy flux can be sufficiently high to threaten both the structural integrity of neighboring buildings and physical safety of plant personnel. It also affects nearby vegetation and habitat which may be unable to withstand the sustained radiant energy flux. At much greater distances, the smoke and gaseous combustion products generated by the fire can reach the ground in concentrations that may be unacceptable from environmental considerations. These products eventually contribute to local and trans_border environmental pollution through smog, acid rain, carbon dioxide and other Greenhouse Gases (GHGs) migration.

Figure 1. Gas Flaring

Nigeria is still identified as flaring more gas than most other oil producing countries in the world (figs. 2 & 3). According to satellite research, worldwide [3] 168 billion cubic meters of natural gas is flared yearly. Nigeria accounted for 23 billion cubic meters, biggest after Russia..Thus, about 13 per cent of global flaring originates from Nigeria.

In monetary terms, according to World Bank estimates, Nigeria is currently losing on the average more than $ 2.5 bn (N 332.5 bn) annually to gas flaring [4]. At about 57 % of the daily production of over 2 billion SCF the volume of flared gas is capable of generating up to 6 GW of electric power annually.

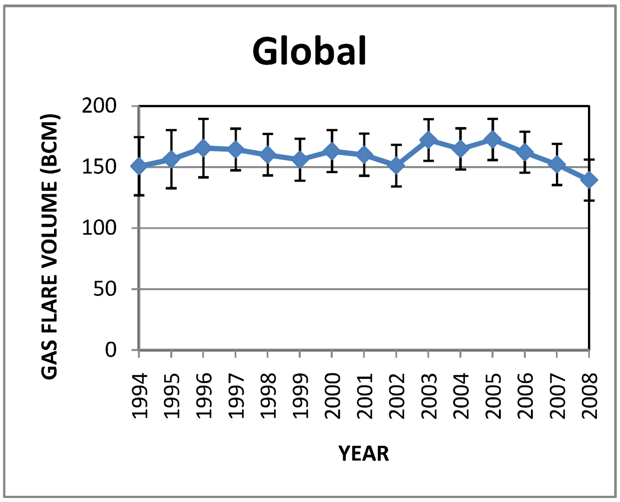

Fig. 2. Global gas flaring by National Geophysical Data Centre,

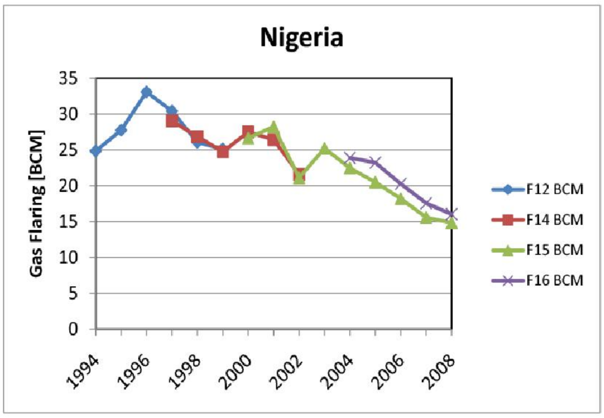

Figure 3. Gas flaring in Nigeria by National Geophysical Data Centre.

It is this large volume of gas being flared that makes the process of solution gas flaring an environmental, ecological, economic and social concern for the public, oil and gas producers, and regulatory agencies.

The economic problem is simply the loss of valuable materials. Process flaring leads to a loss of an average of about 0.15 – 0.5% of feedstock in refineries and petrochemical plants [5], also according to Chamberlain [6] a release rate of 100kg/s over a few seconds would produce a flame about 65m long in moderate winds and release some 5000MW of combustive power, which is very close to Nigeria's total installed capacity of about 6000MW out of which only 2000 to 3000MW is currently (2009) operational.

The environmental and ecological problems associated with flaring are principally those of air pollution, greenhouse-gases (GHGs) released thus contributing to global warming problem (locally and trans_border globally) and noise. Environmental issue of gas flaring are generally described in terms of efficiency and emission, since the goal of a flare is to consume the gases safely, reliably, and efficiently, and through oxidation produce a more desirable emission to the atmosphere than simply venting the gases. When inefficiencies occur, unburned fuel, carbon monoxide and other products of incomplete combustion are emitted into the atmosphere. Air pollution is primarily in the form of visible smoke. However, unburned hydrocarbon, SO_2 and NO_x are possible pollutants whose appearance is far less conspicuous. To suppress smoke formation in process flaring, it is customary to inject steam into the flared gas. The amount of steam per unit mass of hydrocarbon depends both on the type of hydrocarbon and on the design of the flare tips. This process of steam addition is the principal source of noise in process flaring.

Incomplete combustion of natural gas, as witnessed by visible smoke from a flare stack, contributes to increased hazardous chemicals being released into the environment including volatile organic compounds (VOCs). Among toxins released from flaring including carcinogens such as benzopyrene, benzene, carbon di-sulphide (CS_2), carbonyl sulphide (COS) and toluene; metals such as mercury, arsenic and chromium; sour gas with H_2S and SO_2; nitrogen oxides (NO_x); carbon dioxide (CO_2); and methane (CH_4) many of which are greenhouse gases.

The medical effect of prolonged inhalation and ingestion of these compounds includes chills, fever, myalgia, respiratory irritation, nausea, vomiting, headaches, renal failure, central nervous system depression, cardio-vascular failure and altered neuro-behavioural function in addition to multiple airway and lung injury such as cancer, alveolar damage, emphysema and chronic bronchitis. Environmental contaminants have also been related to endocrine dysfunction, immune dysfunction, reproductive disorders and autoimmune rheumatic diseases [7].

The principal problem in flaring is one of safety. Personnel and sensitive structures must be protected from the intense thermal radiation emitted by the flare. There is a limit to which fluxes released can be tolerated. Typical levels by Bjorge and Bratseth, [8] are 1.6kW/m^2 for continuous exposure, 4.7kW/m^2 for exposure of limited duration and 6.3kW/m^2 for short time (less than a minute) exposure. Brzustowski and Sommer [9] and Schwartz [10] all reported personal experiences with flare radiant heat intensity. All suggest that people with appropriate clothing can tolerate a radiant heat intensity of about 4.73kW/m^2 for several minutes. The several minute time spans is satisfactory for situations where a worker is infrequently in the flare area or must go into the flare area briefly to take some action. Oenbring and Sifferman [11] recommended allowable fluxes of 600 Btu/hr sq ft (1.89 kW/m^2) for continuous exposure time, 750 Btu/hr sq ft (2.37 kW/m^2) for to 2 hours, 900 Btu/hr sq ft (2.84 kW/m^2) for half to 1 hour, 1,100 Btu/hr sq ft (3.47 kW/m^2) for 5 to 10 minutes, 1,400 Btu/hr sq ft (4.42 kW/m^2) for 2 to 5 minutes and 2,000 Btu/hr sq ft (6.31 kW/m^2) for 15 seconds (escape only). The Nigerian Department of Petroleum Resources (DPR) has set a maximum limit of 6.31kW/m^2 for a limited duration.

General flaring was made illegal under regulations in 1984, and only allowed in specific circumstances on a field-by-field basis pursuant to a ministerial certificate. The Nigerian government has not enforced environmental regulations effectively because of the overlapping and conflicting jurisdiction of separate governmental agencies governing petroleum and the environment as well as because of non-transparent governance mechanisms [12]. Neither the Federal Environmental Protection Agency (FEPA) nor the Department of Petroleum Resources (DPR) has implemented antiflaring policies for natural gas waste from oil production, nor have they monitored the emissions to ensure compliance with the regulation.

Since 1988, the Federal Environmental Protection Agency (FEPA) has had the authority to issue standards for water, air and land pollution and to make regulations for oil industry. However, in some cases their regulations conflict with the Department of Petroleum Resources (DPR)'s regulations started in 1991 for oil exploration and their own regulations [13]. Oil companies find it more economically expedient to flare the natural gas and pay the insignificant fine than to re-inject the gas back into the oil wells. Additionally, because there is an insufficient energy market especially in rural areas [14], oil companies do not see an economic incentive to collect the gas.

In 1979 the Nigerian Government passed the so-called Associated Gas Re-injection Decree, under which oil producing companies were expected to develop projects aiming at utilizing associated gas. The companies were given four years to reach compliance, and gas flaring was to cease by January 1 1984. Lack of economic incentives and regulations, however, deterred investments in associated gas utilization projects, and the companies within this time span, except for some re-injection projects, undertook no project of any substantive size.

Failing to comply, the companies were instead fined a penalty for flaring. In 1985 a new Decree permitted companies to continue flaring if issued a Certificate by the Minister stating that gas utilization or re-injection was inappropriate for the field in question. The issuing of such certificates was subject to payments by the companies. In 1995 this penalty was increased 20-fold from 0.50 Naira to 10 Naira (about 0.12 USD) for every 1,000 cubic feet (28.32 standard cubic meters) of natural gas. At present (2009) a fine of 413 Naira (3.50 USD) is now charged per million standard cubic meter of gas flared. It is not quite clear whether the government's motive was to end flaring or to raise revenue. A new Petroleum Industry Bill recently approved by the National Assembly aims to develop strategies for optimal gas utilization and hence stoppage of flaring in the near future.

This study is aimed at developing a gas flare model for prediction and mapping of the ground level thermal radiation field around the flare. This allows the determination of the safe distance where a worker could be during flaring or how long he can stay at a particular place during flaring considering the maximum allowable heat fluxes to which the human body may be exposed for prolonged periods. The resulting temperature field can also be predicted from the program with given necessary boundary conditions.

THE FLARE MODEL AND SOLUTION METHOD

Computer simulation and prediction of turbulent, chemically reacting flows is an extremely difficult problem, owing to the complex interactions of many reacting chemical species with continuously changing temperature and velocity fields.

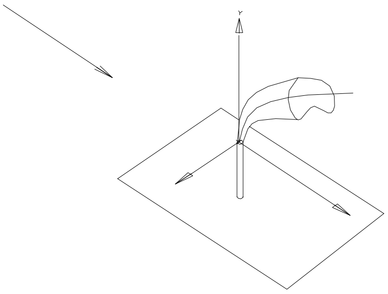

Figure 3 Turbulent jet in a cross flow

The flare is modelled as a turbulent jet (Fig 3) issuing from a circular orifice. The flow field is usually axisymmetrical, but since the flare is affected by wind, the jet will be deflected as a result of the stream normal to the axis of the jet resulting into a three dimensional flow. The flare was therefore considered as a three-dimensional turbulent jet issuing into a continuous cross flow of air. The momentum and scalar fluxes were approximated by the k-ε turbulence model and the resultant conservation equations were solved using the finite volume technique. The laminar flamelet concept was used to characterize the local thermochemical state of the combusting mixture, while the discrete transfer method was used to compute the radiative heat flux. Prediction of the radiative flux around the flare was obtained from the converged flow field calculations using a finite-volume scheme for solving the fluid dynamic equations.

With the density-weighted averaging, the equations of the continuity, momentum and scalar transport may be written, for high-turbulence Reynolds numbers, as

$$\frac{\partial(\bar{\rho}\tilde{U}_j)}{\partial x_j}=0 \qquad 1$$

$$\frac{\partial(\bar{\rho}\tilde{U}_i\tilde{U}_j)}{\partial x_j} = -\frac{\partial \bar{P}}{\partial x_i} + \frac{\partial \tilde{\tau}_{ij}}{\partial x_j} + \bar{\rho} g_i \qquad 2$$

and

$$\frac{\partial(\bar{\rho}\tilde{U}_j\tilde{\phi})}{\partial x_j} = -\frac{\partial(\bar{\rho}u''\phi'')}{\partial x_j} + \bar{\rho}\tilde{S}(\phi) \qquad 3$$

respectively

where the turbulent scalar flux is

$$\bar{\rho} u''\phi'' = -\frac{\mu_t}{\sigma_t}\frac{\partial\tilde{\phi}}{\partial x_j} \qquad 4$$

where

$$\tilde{\tau}_{ij} = -\rho\tilde{u}_i\tilde{u}_j = \mu_t\left(\frac{\partial\tilde{U}_i}{\partial x_j}+\frac{\partial\tilde{U}_j}{\partial x_i}\right)-\frac{2}{3}\delta_{ij}\left(\bar{\rho}k+\mu_t\frac{\partial\tilde{U}_k}{\partial x_k}\right)$$

5

where $\mu_t = C_\mu\bar{\rho}\frac{k^2}{\varepsilon}$

The respective transport equations for the turbulence kinetic energy, k and the rate of dissipation of the turbulent kinetic energy, ε, are based upon the transport equation

$$\frac{\partial}{\partial x_j}(\bar{\rho}\tilde{U}_j k) = \frac{\partial}{\partial x_j}\left(\frac{\mu_t}{\sigma_k}\frac{\partial k}{\partial x_j}\right) - \bar{\rho}u''_i u''_j\frac{\partial\tilde{U}_i}{\partial x_j} - \bar{\rho}\varepsilon$$
$$\frac{\partial}{\partial x_j}(\bar{\rho}\tilde{U}_j \varepsilon) = \frac{\partial}{\partial x_j}\left(\frac{\mu_t}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial x_j}\right) - C_1\frac{\varepsilon}{k}\bar{\rho}u''_i u''_j\frac{\partial\tilde{U}_i}{dx_j} - C_2\bar{\rho}\frac{\varepsilon^2}{k} \qquad 6$$

For non-premixed turbulent reacting flows most of the fluctuation in scalar quantities and chemical reaction rates can be associated with the fluctuation in a conserved scalar such as the mixture fraction. The conservation equation is

$$\frac{\partial}{\partial x_j}(\bar{\rho}\tilde{U}_j\tilde{f}) = \frac{\partial}{\partial x_j}\left(\frac{\mu_t}{\sigma_t}\frac{\partial\tilde{f}}{\partial x_j}\right) \qquad 7$$

and for turbulent flow this can be modeled in the same way as other scalars.

The mixture fraction variance $\tilde{f}''^2$ quantifies the magnitude of the fluctuations of the scalar. It is governed by the following conservation equation

$$\frac{\partial}{\partial x_j}(\bar{\rho}\tilde{U}_j\tilde{f}''^2) = \frac{\partial}{\partial x_j}\left(\frac{\mu_f}{\sigma_t}\frac{\partial\tilde{f}''^2}{\partial x_j}\right) + 2\frac{\mu_t}{\sigma_t}\left(\frac{\partial\tilde{f}}{\partial x_j}\right)^2 - C_D\bar{\rho}\frac{\varepsilon}{k}\tilde{f}''^2 \qquad 8$$

Fluctuations of the mixture fraction are taken into account by introducing a presumed probability density function (pdf). A generally accepted form for the mixture fraction pdf is the beta function pdf

$$\tilde{P}(f) = \frac{f^{\alpha-1}(1-f)^{\beta-1}}{\int_0^1 f^{\alpha-1}(1-f)^{\beta-1}df} \qquad 9$$

where the parameters α and β are defined in terms of the mean mixture fraction and variance,

$$\alpha = \tilde{f}\left[\tilde{f}(1-\tilde{f})/\tilde{f}''^2-1\right] \qquad 10$$

$$\beta = (1-\tilde{f})\left[\tilde{f}(1-\tilde{f})/\tilde{f}''^2-1\right] \qquad 11$$

and the mean density ρ obtained from

$$\bar{\rho} = \left[\int_0^1 \frac{P(f,x_i)}{\rho(f)}df\right]^{-1} \qquad 12$$

Predictions of soot level within the flame were incorporated in the model through the solution of balance equations for soot mass fraction, $Y_{c(s)}$ and soot particle number density, N, using the following transport equations.

$$\frac{\partial}{\partial x_j}(\bar{\rho}\tilde{U}_j\tilde{Y}_{C(S)}) = \frac{\partial}{\partial x_j}\left(\frac{\mu_t}{\sigma_t}\frac{\partial\tilde{Y}_{C(S)}}{\partial x_j}\right) + \bar{\rho}\tilde{S}(Y_{C(S)}) \qquad 13$$

$$\frac{\partial}{\partial x_j}(\bar{\rho}\tilde{U}_j\tilde{N}) = \frac{\partial}{\partial x_j}\left(\frac{\mu_t}{\sigma_t}\frac{\partial\tilde{N}}{\partial x_j}\right) + \bar{\rho}\tilde{S}(N) \qquad 14$$

where the last terms in both Equations 13 and 14 are the instantaneous rates of formation of the soot mass fraction and soot particle number density which are given as

$$\bar{\rho}\tilde{S}(Y_{C(S)}) = \tilde{r}_i M_{C(S)} + \tilde{r}_{ii}\bar{\rho}Mc_{(s)}{}^{1/3}\tilde{Y}_{C(S)}{}^{2/3}\tilde{N}^{1/3} - \tilde{r}_{iii}\bar{\rho}M_{C(S)}{}^{1/3}{}_{(s)}\tilde{Y}_{C(S)}{}^{2/3}\tilde{N}^{1/3}$$

15

where the terms on the right-hand side represent the processes of nucleation, surface growth and oxidation respectively, and

$$\bar{\rho}\tilde{S}(N) = \tilde{r}_{iv} - r_v\bar{\rho}^2 M_{C(S)}{}^{-1/6}\tilde{Y}_{C(S)}{}^{1/6}\tilde{N}^{11/6} \qquad 16$$

where also the terms on the right-hand side represent nucleation and coagulation respectively ,and

$$r_i = k_i[C_2H_2]$$
$$r_{ii} = k_{ii}f(p)[C_2H_2]$$
$$r_{iii} = k_{iii}f'(p)[O_2]$$
$$r_{iv} = \frac{2}{C_{\min}}N_A r_i$$
$$r_v = 2C_a\left(\frac{6M_{C(S)}}{\pi\rho_{C(S)}}\right)^{1/6}\left(\frac{6kT}{\rho_{C(S)}}\right)^{1/2}$$
$$f(p) = \pi\left(\frac{6M_{C(S)}}{\pi\rho_{C(S)}}\right)^{2/3}$$
$$f'(p) = \frac{f(p)}{M_{C(S)}}$$

Thermal radiation received at ground level around the flare was computed from converged flow field calculations using the discrete transfer radiation model (DTRM).

The governing partial differential equations for the conservation of mass (Equation 1), momentum (Equation 2), and scalar quantities (Equation 3) under steady-state conditions can be rearranged into a general form that can be written as

$$\frac{\partial(\rho u\phi)}{\partial x}+\frac{\partial(\rho v\phi)}{\partial y}+\frac{\partial(\rho w\phi)}{\partial z}=\frac{\partial}{\partial x}\left[\Gamma\frac{\partial\phi}{\partial x}\right]+\frac{\partial}{\partial y}\left[\Gamma\frac{\partial\phi}{\partial y}\right]+\frac{\partial}{\partial z}\left[\Gamma\frac{\partial\phi}{\partial z}\right]+S_{\phi}$$

17

In tensor notation form, Equation 3.14a can be written as

$$\frac{\partial(\rho u_j\phi)}{\partial x_j}=\frac{\partial}{\partial x_j}\left[\Gamma\frac{\partial\phi}{\partial x_j}\right]+S_{\phi} \qquad 18$$

The transport Equations are reduced to their finite-difference form by integrating over the computational cells into which the domain is divided. The resulting algebraic equations can be written in the following form:

$$a_P\phi_P=\sum_{nb}a_{nb}\phi_{nb}+S_{\phi} \qquad 19$$

RESULTS AND DISCUSSION

An important application of the model is its ability to predict accurately the heat flux received by field personnel during gas flaring. The model equations were simulated using FORTRAN 95 programme. The heat flux obtained by the model was validated using results obtained from experiment performed and also compared with other empirical formulae.

The model was validated using data from the experimental work of Birch *et al.* [15]. The predicted and experimental heat flux results for the symmetry and cross-stream plane are shown in Fig 4 and 5 respectively. The predicted heat fluxes are similar to the results obtained from experiment. Downwind of the maximum heat flux, it falls off more slowly because of the influence of the wind, since the wind is in that direction and the place is largely filled with either visible flame or hot combustion products dispersed in the direction of the wind.

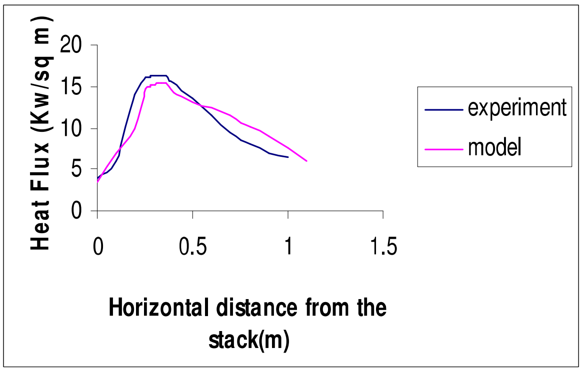

Fig **4 Variation of radiative heat flux on the symmetry plane (i.e on the ground).**

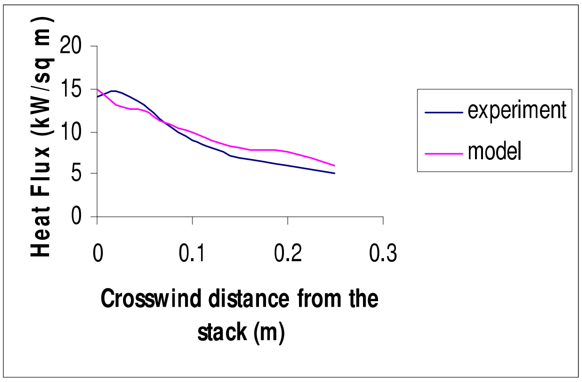

Fig **5 Variation of radiative heat flux on cross-stream plane (i.e on the ground)**

The model was compared with four different existing empirical formulae obtained from the literature. The results (Fig. 6) show similar Gaussian thermal radiation profiles at the ground level for all the models, but different value for the maximum and for distances downwind from the source.

For this comparison, the heat flux predicted and that from empirical formulae were plotted against the distance from the base of the flare stack. The differences in the value of heat flux at the near field (that is close to the flare stack base) vary largely from each other and have nearly close values at the far field (at some distance away from the flare stack base).

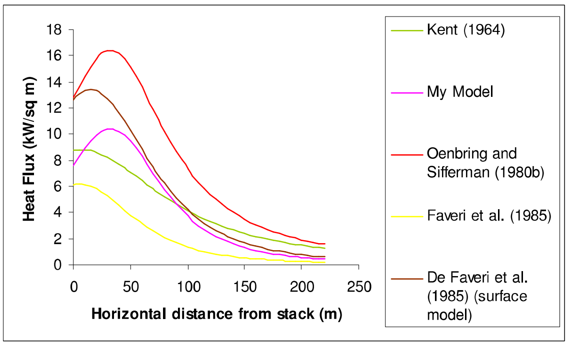

Fig **6. Comparison of the model with four empirical formulae.**

At the near field, the maximum value predicted by the model is 15.5% higher than that of Kent [16], 36.5% lower than that of Oenbring ans Sifferman [17], 41.9% higher than that of De Faveri *et al.* [18] and 22.5% lower than that of De Faveri *et al.*[18] (surface mode).

At the maximum limit of 6.31kW/m^2 for a limited duration set by the Nigerian Department of Petroleum Resources (DPR), the model predicted a safe distance of above 75m from the flare stack base while Kent predicted a distance of above 60m, and that of Oenbring ans Sifferman and De Faveri *et al* (surface model) a safe distance of above 105 and

80m respectively while the whole area is safe as for De Faveri *et al*.

The correct value of the heat flux is very important because in many cases, it forms the basis for determining the flare stack height and location. If underestimated it puts the workers at great risk of exposure to dangerous heat fluxes and if overestimated result to taller-than-required stack which results in waste of resources.

Another important application of the model is its ability to accurately predict the heat flux and temperature at any point in the vicinity of a flare. Such information is also useful in siting and determining the height of a flare stack.

At the maximum heat flux limit of 6.31kW/m^2 for a limited duration set by the Nigerian Department of Petroleum Resources (DPR), the model predicted a safe distance of above 75m from the flare stack base while Kent predicted a distance of above 60m, and that of Oenbring and Sifferman and De Faveri *et al.* (surface model) a safe distance of above 105 and 80m respectively while the whole area is considered safe using the equation from De Faveri *et al*.

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APPENDIX

Below are Environmntal Rights Action/Friends of the Earth Nigeria Factsheet:, *Harmful Gas Flaring in Nigeria*. November 2008. From which the following pictures are taken:

Gas flares near the communities of Ebocha and Mgbede.
© Friends of the Earth, April 2005.

A woman from Iwhrekan drying cassava near the gas flare.
© Kadir van Lohuizen I NOOR, January 2008.