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MODELLING AND EXPERIMENTAL RESULTS OF A BIOMASS PYROLYSIS PILOT PLANT

Mohamed Ammar Abbassi[1], Kamel Guedri [*2], Hamza Ahmed Ghulman[2], and Abdulmajeed Saeed Al-Ghamdi[2]

[1] Unité de Recherche Matériaux, Energie et Energies Renouvelables (MEER) Faculté des Sciences de Gafsa, B.P.19, Zarroug, Gafsa, 2112, Tunisia.
[2]Mechanical Engineering Department, Faculty of Engineering and Islamic Architecture, Umm Al-Qura University, B. Po. 5555, Makkah, 21955, Kingdom of Saudi Arabia,
E-mails: kmguedri@uqu.edu.sa; kamel.guedri@enim.rnu.tn

ABSTRACT

Fire Dynamics Simulator (FDS) and global modelling are used to solve numerically pyrolysis, combustion and heat recuperation in a pilot plant of biomass pyrolysis using pyrolysis products as fuel. Obtained results are validated with experimental measurements. In the case of FDS modelling three different treatments of radiation are considered: without radiation, with gray gas radiation and with non gray gas radiation. The results of numerical simulations are compared with the global model results and with the experimental results. It was shown that the FDS results are in good qualitative and quantitative agreement with the experimental results. The global model gives qualitative results in agreement with experimental results with less CPU time compared with FDS results. Whereas FDS results are more accurate than those of the global model. At the end of the process FDS results are better than global model results this is due to the fact that global model doesn't take into account the thermal inertia of the pilot plant. The global model is used to study the racing reaction in the pilot plant and to study the case with and without catalyser. FDS is used to predict CO and CO2 emissions. The effect of the non gray gas behaviour is emphasised and demonstrated to affect pollutant emissions.

INTRODUCTION

Renewable energy sources like wind, solar, geothermal, hydrogen, and biomass play an important role in the future of our energy demand. In Tunisia, the biomass energy significantly contributes to the total energy balance. Wood is the principal consumed biomass to produce energy with 2.65 million tons/year. This consumption is largely dominated by the firewood which accounts for 72% of the primary wood demand, against 28% for the charcoal production. Unfortunately the production of charcoal in Tunisia is currently made by traditional methods which generate a very significant atmospheric pollution, leading to poor conversion efficiency and the degradation of biomass potential. The consequence is dramatic on the environment and wood resources. Tunisia ratified the Kyoto protocol in 2006 aiming the diminution of green house gas emissions. Consequently, traditional charcoal devices which emit polluting fumes are inacceptable. The design of clean systems of biomass pyrolysis requires numerical tools allowing an accurate prediction of pollutants emission; and taking into account all the influential parameters relating to dynamics, kinetics and thermodynamics [1]. The objective of this work is to analyze a biomass pilot plant designated for the pyrolysis of the biomass and the combustion of the fumes released by the process. We proposed an experimental and a numerical model of the pilot plant. Effect of gray or non gray radiative heat transfer on temporal evolution of temperatures is presented and compared with experimental results. We showed that the results obtained by FDS with non gray radiation approach the experimental results at the beginning of the pyrolysis process. At the end of the pyrolysis process the error increases this is due to thermal inertia which is not taken into account in the developed model. The effect of gray radiation, non gray radiation or without radiation on pollutant emission is also studied and demonstrated to have an important effect.

NOMENCLATURE

C_{a1}	[molm^{-3}]	Air concentration
C_g	[molm^{-3}]	Gas concentration
C_p	[Jmol^{-1}K^{-1}]	Heat capacity at constant pressure
F_{a1}	[mols^{-1}]	Air molar flow rate
F_{a2}	[mols^{-1}]	Inlet molar flow rate
F_{a2R}	[mols^{-1}]	Regulation molar air flow rate
F_{GE}	[mols^{-1}]	Mass loss rate
F_{GS}	[mols^{-1}]	Gas molar flow rate
h	[WK^{-1}m^{-2}]	Overall heat transfer coefficient
I	[W/m^2 Sr]	radiant intensity
Ib	[W/m^2 Sr]	radiation blackbody intensity
K	[WK^{-1}]	Global conductance coefficient
m_A	[Kg]	Biomass mass at moment t
$m_{A\infty}$	[Kg]	Residual solid mass at the end of pyrolysis cycle
M_G	[Kg]	Average molar mass of pyrolysis gas
P_0	[Nm^{-2}]	Total pressure
Q_1	[m^{3}s^{-1}]	Volumetric flow rate of pyrolysis gases
q_r	[W/m^2]	Radiative heat flux vector
Sc	[-]	Schmidt number
T_{ex}	[K]	Exterior temperature
(u,v,w)	[m/s]	Velocity vector
V_i	[m^3]	Volume of zone i
Special characters		
α	[-]	CH_4 molar fraction
β	[-]	CO_2 molar fraction
γ	[-]	H_2 molar fraction
ε	[-]	Emissivity
μ	[kg/ms]	Dynamic viscosity
δ	[-]	Tar molar fraction

η	[-]	CO molar fraction
χ	[-]	H_2O molar fraction
ν	[-]	Stoichiometric coefficient
ΔH	[Jmole^{-1}]	Enthalpy variation
Subscripts		
a		Air
A		Biomass
g		Gas

FIRE DYNAMIC SIMULATOR (FDS)

Computational Fluid Dynamics (CFD) modeling of fires is inherently complex because it incorporates aspects of bluff body aerodynamics, multi-phase flow, turbulent mixing, combustion, radiative transport, convective heat transfer, and conductive heat transfer. The fire dynamics simulator (FDS) is a large eddy simulation (LES) model, which was developed by the National Institute of Standards and Technology (NIST). FDS was developed specifically to deal with problems related to fire; it can be broken up into several major sub-models. The transport equations are simplified using techniques developed by Rehm and Baum [2] and are widely referred to as the low Mach number. FDS solves the equations by dividing the model space into a large number of rectangular cells and calculating the temperature, gas velocity, species concentration, and other pertinent variables within each cell. In FDS, the governing equations for three-dimensional Eulerian-Lagrangian scheme are adopted to analyze the two phase combustion (gas and particles) [3]. For gas phase, the hydrodynamics model includes an elliptic type of momentum, energy and species equations with a single step chemical reaction model. However, Lagrangian particles are used to simulate smoke movement. Elliptic partial differential equations are obtained by filtering out of acoustic waves while allowing for large variations in temperature and density. The Large Eddy Simulation (LES) technique is used to model the dissipative processes (viscosity, thermal conductivity, and material diffusivity) [3]. The radiative heat transfer is introduced in FDS by the solution of the radiative transfer equation (RTE). The RTE is given by a nonlinear integro-differential form with its properties which are spectrally related to participating gas and soot.

Description of the biomass pyrolysis pilot plant

The biomass pyrolysis pilot plant (Figure 1) is made up of two metallic chambers for biomass pyrolysis connected to a combustor of pyrolysis gases by two insulated gas channels. The unit walls are thermally insulated by a thick layer of glass wool. The combustor is connected to a chimney for the evacuation of the combustion products. The pilot plant (Figure 1) can be divided into three homogeneous zones as shown in Figure 2. Each zone is supposed to be a perfect stirred reactor with uniform temperature. Zones 1 and 2 correspond respectively to the biomass pyrolysis chambers and the pyrolysis gases combustor. Zone 3 consists of a heat exchanger between zones 1 and 2. We associate respectively to each zone a temperature T_1, T_2 and T_3. The temperature of the feeding air at zone 2 is T_{ex}.

Operating cycle

To start the operating cycle, the biomass inside the two pyrolysis chambers is heated and dried by the combustion of a quantity of biomass wastes in the combustor. At the beginning of biomass decomposition, the pyrolysis gases are premixed with the ambient air before introduced in the combustor.

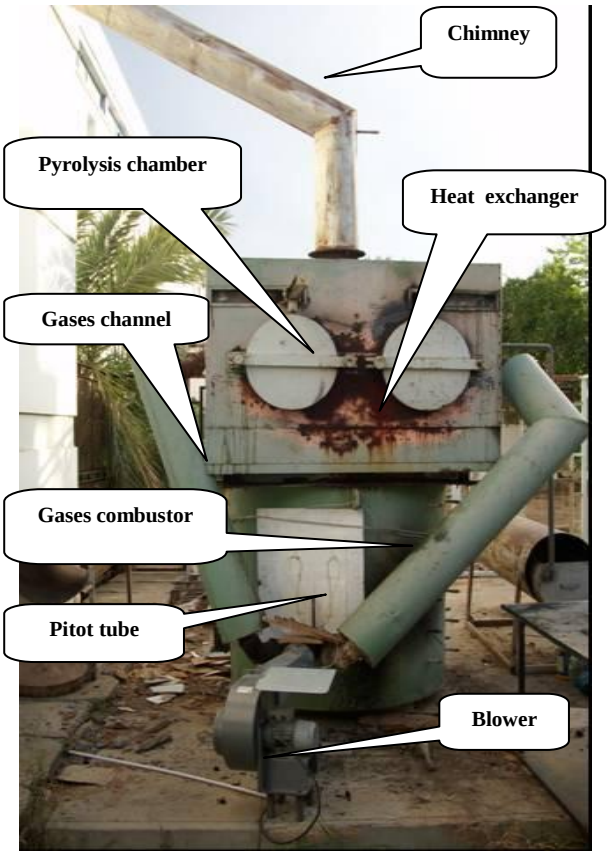

Figure 1 Pilot plant of biomass pyrolysis with combustion of pyrolysis products

When the pyrolysis reactions produce a sufficient quantity of fuel gas to ensure the needed energy for biomass pyrolysis, the alimentation of the combustor by biomass wastes is stopped. The combustion gases energy is used to heat the biomass pyrolysis chambers before being rejected into the atmosphere via a chimney.

Thermal cracking of tar

Tar is one of the important products released in a biomass pyrolysis process. It has a very complex structure which depends on the biomass composition, temperature, type of used catalyst. Wurzenberger et al. [4] considered in their study that tar follows an overall reaction as the following:

$$\mathrm{TAR} \rightarrow \nu_{CO}\mathrm{CO(g)} + \nu_{CO_2}\mathrm{CO_2(g)} + \nu_{CH_4}\mathrm{CH_4(g)} + \nu_{H_2}\mathrm{H_2(g)} + \nu_{\text{tar inert}}\,\text{tar inert} \quad (1)$$

In fact biomass pyrolysis undergoes a first step called primary pyrolysis in which the solid phase thermally decomposes into gases, tar, and charcoal, then a secondary pyrolysis which takes place in zone 1 of the pilot plant where tar decomposes as given by (1).

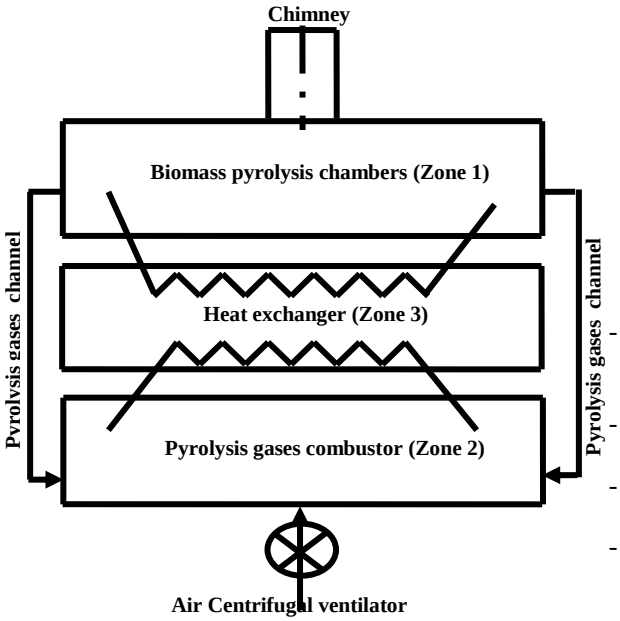

Figure 2 Schematic diagram of the pilot plant

Measurements and operating control of the plant

In order to control the operating cycle of the pilot plant, several experimental tests were carried out to determine its duration and stability conditions. The temperatures are measured with six thermocouples type K. During primary tests of the pilot plant it was noticed that the quantity of the feeding air introduced in the pyrolysis gases combustor (zone 2) has an important role. If a great quantity is introduced the flame will extinguish and the process is stopped. If we decrease this quantity the temperatures of the three zones increase and for critical values of the feeding air we noticed that the functioning of the pilot plant becomes very fast; this phenomenon is called "runaway regime". This phenomenon was studied in a paper by the authors [5].

FDS MODELLING

Inside the pilot plant the thermochemical processes include description of the fluid flow, heat and mass transfer, and chemical reactions. An approximate form of the Navier-Stokes equations appropriate for low Mach number applications is used in the model. The basic conservation of mass, momentum and energy equations can be written as follows:

$$\frac{\partial \rho}{\partial t} + \nabla . \rho \vec{u} = 0 \tag{2}$$

$$\frac{\partial}{\partial t}\left(\rho Y_i\right) + \nabla . Y_i \vec{u} = \nabla . \rho D_l \nabla Y_l + \dot{m}_l''' \tag{3}$$

$$\rho\left(\frac{\partial \vec{u}}{\partial t} + \left(\vec{u}.\nabla\right)\vec{u}\right) + \nabla p = \rho \vec{g} + \vec{f} + \nabla . \vec{\tau} \tag{4}$$

$$\frac{\partial\left(\rho h\right)}{\partial t} + \nabla . \rho h \vec{u} = \frac{Dp}{Dt} - \nabla . \vec{q}_r + \nabla . k \nabla T + \sum \nabla . h_l \rho D_l \nabla Y_l \tag{5}$$

where ρ is the density, $\vec{u} = \left(u, v, w\right)$ is the velocity vector, Y_l is the mass fraction of l^{th} species, D_l is the diffusion coefficient of l^{th} species, $\dot{m}_l'''$ is the mass production rate of l^{th} species per unit volume, p is the pressure, $\vec{g}$ is the acceleration vector of gravity, $\vec{f}$ is the external force vector, $\vec{\tau}$ is the viscous stress tensor, h is the enthalpy, h_l is the enthalpy of l^{th} species, $\vec{q}_r$ is the radiative heat flux vector. The accuracy of the model results is highly dependent on the grid resolution, with a smaller grid resolution producing more accurate results. A parametric study of the effect of the grid will be presented in this work.

Assumptions

- In the pyrolysis chambers (zone 1), the temperature gradients within the pyrolysing solid particles is neglected.
- The combustion reaction of pyrolysis gases in the combustor (zone 2) is instantaneous and total.
- Heat exchange between the various zones and the external medium is negligible. (Adiabatic walls)
- The cylindrical shaped incinerator (length 1,3 m and 0,5 m of radius) is replaced by a parallelepipedic geometry (height 1,3 m, width 1m and length 1m).
- In the same way the chimney, which is of cylindrical shape (length 2 m and of radius 0,2m) is replaced by a parallelepiped of height 1m, width 0,2m and length 0,2m. It should be announced here that the height in the numerical simulation is taken equal to 1m instead of 3m for the reduction of the simulation domain.
- The thermophysical and thermoelastic properties of the various components of the installation are those which exist by default in the FDS data.
- The external air temperature outside the feeding zone 2 is taken equal to 300 K.
- At the begining of the process, the temperatures of the three zones are affected arbitrary values presumably equal to the inlet temperature of the fume; the initial concentration of gases is calculated by the perfect gases law and the various flows are taken equal to zero.

Combustion model

FDS uses the mixture fraction model as the default combustion model. The mixture fraction is a conserved scalar quantity that is defined as the fraction of gas at a given point in the flow field that originated as fuel. The combustion is represented by means of the mixture fraction where all calculations start at ambient initial conditions [3]. The mixture fraction assumes that the fire is essentially an infinitely fast reaction between fuel and oxygen, and this reaction is not dependent on the surrounding gas temperature. The temperature is found from the density and the pressure via the state equation. It also assumes that the reaction zone is an infinitely thin sheet with fuel on one side and oxygen on the other. It is noted that the specific heat is calculated as the sum of the individual specific heat of the mixture components. Detailed developing of the numerical techniques appropriate for combustion systems used here are presented by McGrattan [3]. In this mixture fraction-based combustion model, all species of interest can be described in terms of a mixture fraction $Z(x,t)$ [6]. It is defined as follows:

$$Z = \frac{sY_F - \left(Y_O - Y_O^\infty\right)}{sY_F^I + Y_O^\infty};\ s = \frac{\nu_O M_O}{\nu_F M_F} \tag{6}$$

where the numbers ν_i are the stoichiometric coefficients for the overall combustion process that reacts fuel "*F*" with oxygen "*O*" to produce a number of products "*P*"; the quantities M_F and M_O are the fuel and oxygen molecular weights, respectively; Y_O^∞ is the mass fraction of oxygen in the ambient; Y_F^I is the fraction of fuel in the fuel stream. The mixture fraction varies from *Z=1* in a region containing only fuel to *Z=0* in regions where only ambient air with undepleted oxygen is present. A mixing-controlled combustion is assumed in our combustion model. The chemistry is assumed with fast means that the reactions consuming fuel and reactant occur so rapidly that the fuel and oxidizer cannot co-exist.

Turbulent model

The mass, momentum, and energy equations differ primarily in the form and magnitude of the transport coefficients (i.e., viscosity, thermal conductivity, and material diffusivity), which are much larger in the turbulent case because of the additional transport caused by turbulent fluctuations. In order to simulate turbulence Large Eddy Simulation (LES) and Direct Numerical Simulation (DNS) are developed in FDS. The Large Eddy Simulation (LES) technique has received much attention and been increasingly implemented in computing turbulent buoyant flow. In LES, the flow variables are decomposed into a large-scale component and a subgrid-scale component [3,7]. The analyses of Smagorinsky [8], where the Prandtl number (Pr), and the Schmidt number (Sc) are assumed to be constant for a given scenario, are used. In this study, Pr = Sc = 0.5 and Cs = 0.2 (empirical constant defined in the expression of μ) are considered. These parameters are replaced by surrogate expressions that model their impact on the approximate form of the governing equations [3].

Radiation model

The radiation model used by FDS is considred in this study. It solves the finite-volume-based radiation transport equations and considers soot as the most important combustion product controlling the thermal radiation from the fire and hot smoke. The Radiative Transport Equation (RTE) for an absorbing/emitting and scattering medium is:

$$\mathrm{r}.\nabla \mathrm{I}_\lambda(\mathrm{x},\mathrm{r}) = -\left(\mathrm{k}(\mathrm{x},\lambda)+\sigma_\mathrm{r}(\mathrm{x},\lambda)\right)\mathrm{I}(\mathrm{x},\mathrm{r})+\mathrm{B}(\mathrm{x},\lambda) + \frac{\sigma_\mathrm{r}(\mathrm{x},\lambda)}{4\pi}\int_{\Omega=4\pi}\Phi\left(\mathrm{r},\mathrm{r}'\right)\mathrm{I}_\lambda(\mathrm{x},\mathrm{r}')\mathrm{d}\,' \quad (7)$$

The radiative transport equation (RTE) for a non-scattering gray gas is:

$$\nabla \mathrm{I}_\lambda(\mathrm{x},\mathrm{r}) = \mathrm{k}(\mathrm{x},\lambda)\left(\mathrm{I}_\mathrm{b}(\mathrm{x})\right)-\mathrm{I}_\lambda(\mathrm{x},\mathrm{r}) \quad (8)$$

The radiative loss term in the energy equation is

$$(9)\quad -\nabla.\mathrm{q}_\mathrm{r}(\mathrm{x}) = \mathrm{k}(\mathrm{x})\left(\mathrm{G}(\mathrm{x})-4\pi\mathrm{I}_\mathrm{b}(\mathrm{x})\right)$$

$$\mathrm{G}(\mathrm{x}) = \int_{4\pi}\mathrm{I}(\mathrm{x},\mathrm{r})\mathrm{d} \quad (10)$$

The net radiant energy gained by a grid cell is the difference between that which is absorbed and that which is emitted. The source term is defined as

$$\mathrm{kI}_\mathrm{b} = \begin{cases} \dfrac{\mathrm{k}\sigma\mathrm{T}^4}{\pi} \rightarrow \text{Outside} \\ \dfrac{\chi_\mathrm{r}\dot{q}'''}{4\pi} \rightarrow \text{Inside} \end{cases} \quad (11)$$

Here q is the chemical heat release rate per unit volume and is the local fraction of the energy emitted as thermal radiation. The radiant heat flux vector is defined as

$$\mathrm{q}_\mathrm{r}(\mathrm{x}) = \int_{4\pi}\mathrm{rI}(\mathrm{x},\mathrm{r})\mathrm{d}\Omega \quad (12)$$

Through the simulations, we use the default parameters for radiation calculation, since we have no better experimental result on radiation prediction in flames.

RESULTS AND DISCUSSIONS

Numerical study

The overall domain is a parallelepiped box discretized in parallelepiped grid cells. In each conservation equations, all spatial derivatives are approximated by second order finite differences. For temporal discretization, an explicit second order predictor-corrector scheme is used [4]. In this study, the thermo-physical properties of wood are presented in Table 1.

mbol	Definition	Value
$C_{3,4}H_{6,2}O_{2,5}$	Wood chemical formula	-
ΔH_v	Vaporization heat	3000 $kJ.kg^{-1}$
k	Thermal conductivity	0,1 $W.m^{-1}.K^{-1}$
α	Thermal diffusivity	1,11 10^{-7} $m^2.s^{-1}$

Table 1 Thermo-physical properties of wood

To study the effects of radiation three different cases are considered:

Case 1: model without radiation
Case 2: model with gray gas radiation
Case 3: model with non-gray gas radiation

To study the sensitivity of FDS results to the mesh space, three rectangular non-uniform meshes are considered: The first case (case 1) consists of 262440 cells (a grid of 54 × 54 × 90), the second case (case 2) consists of 524288 cells (a mesh of 64 × 64× 128), while the third case (case 3) contains 663552 cells (a grid of 64 × 64 × 162). We used a personal computer with Intel Pentium 4 with RAM equal to 512MB and a frequency of 3.06 GHz, the computation time of these three cases are listed in Table 2.

CASE	Time (h)
1	31,12
2	84,51
3	115,76

Table 2 Effect of spatial mesh on the computation time

These meshes are refined near the burner. It should also be noted that when the thermal radiation is highlighted, the same spatial mesh are used. For

these three meshes, Figure 3 shows the evolution of temperature T_1 of zone 1. We see clearly that for a coarse mesh (case 1), the temperature is largely poorly estimated. Whereas if the number of cells is increased (cases 2 and 3), the shape of the temperature seems almost the same values and the temperatures are quite close to experimental values determined in [5]. The relative error, calculated using equation (12), exceeds 35% when a coarse mesh is used. This difference does not exceed 10 and 8% for cases 2 and 3, respectively; whereas the CPU time is considerably increased. From Table 2 it is found that the computation time in the Case 2 is about 73% of the execution time of Case 3. As a result, the mesh of the Case 2 will be used throughout this paper; which gives a good compromise between accuracy and CPU time. FDS calculations are more time consuming but give more accurate results when compared with the global model.

$$e = \left(\frac{1}{N} \sum_{i}^{N} 2 \frac{|T_{cal} - T_{\exp}|}{T_{cal} + T_{\exp}} \right) \times 100 \quad (13)$$

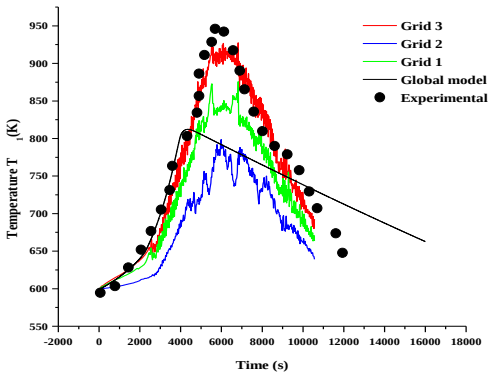

Figure 3 Effect of spatial grid on temperature T_1

Thermochemical modelling

The proposed balance equations model is simplified by using the following assumptions:

- In zone 1 two reactions will take place; the biomass decomposition reaction and tar cracking reaction. These two reactions will be represented here by the unique and overall reaction scheme (3).
- Only at the beginning of the pyrolysis process we suppose the existence of small quantity of air in the pyrolysis rooms (zone 1).
- Temperature in each of the three zones (1, 2 and 3) of the pilot plant is supposed uniform instantaneously.
- In the pyrolysis rooms (zone 1), the temperature gradients within the pyrolysing solid particles is neglected.
- The combustion reaction of pyrolysis gases in the combustor (zone 2) is instantaneous and total.
- Heat exchange between the various zones and the external medium is negligible.
- The gas mixture is perfect and the total pressure in the three zones is constant and equal to the atmospheric pressure.

The energy and mass balance equations in the different zones of the plant will be written according to the following general form:

{Accumulation}={Inletflow}-{Outlet flow}+{Generation} (14)

Mass balance at biomass pyrolysis rooms

The kinetic scheme decomposition of the biomass is given by:

$$A(\text{ Biomass }) \rightarrow \eta CO + \alpha CH_4 + \beta CO_2 + \gamma H_2 + \chi H_2O \quad (15)$$

The mass loss in the pyrolysis chambers is expressed by a first order Arrhenius law:

$$\frac{dm_A}{dt} = -k_{0A}(m_A - m_{A\infty}) \exp\left(-\frac{E_A}{RT_1}\right) \quad (16)$$

The molar flow of pyrolysis gases at zone 2 obeys to the following balance equation:

$$V_1 \frac{dC_G}{dt} = -F_{GS} + F_{GE} \quad (17)$$

As shown by the general equation (14) the accumulation of gas in zone 1 is equal to inlet molar gas flux (which is equal to zero) minus the outlet molar gas flux (F_{GS}) added to the generation which is the molar gas flux generated by the decomposition of biomass and tar cracking (F_{GE}) given by:

$$F_{GE} = -\frac{1}{M_G} \frac{dm_A}{dt} \quad (18)$$

The initial air concentration at zone 1 obeys also the general equation (14) and is equal to:

$$V_1 \frac{dC_{a1}}{dt} = -F_{a1} \quad (19)$$

The gaseous products molar flow rate at the outlet of zone 1 is related to the gas volumetric flow rate at the outlet of zone 1 and the gas concentration by the following equation:

$$F_{GS} = Q_1 C_G \quad (20)$$

Similarly the air molar flow rate at the outlet of zone 1 is related to gases volumetric flow rate at the outlet of zone 1 and the concentration of the air present initially in zone 1:

$$F_{a1} = Q_1 C_{a1} \quad (21)$$

Taking into account the above assumptions, the equation of state for gases at zone 1 is:

$$P_0 Q_1 = (F_{GS} + F_{a1}) R T_1 \quad (22)$$

Heat Balances

In zone 1, the heat exchange is made by convection, conduction and radiation with zone 3. The total enthalpy balance is written as:

$$\underbrace{\frac{d}{dt}\left(m_A C_p^* T_1\right)}_{\text{Accumulation}} = \underbrace{KT_3}_{\text{inlet flux}} - \underbrace{\left\{K + F_{a1} C_{pa} + F_{GS} C_{pG}\right\} T_1}_{\text{outlet flux}} + \underbrace{F_{GE}(\Delta H)_G}_{\text{generation}} \quad (23)$$

Where $(\Delta H)_G = (\Delta H)_{\text{Pyrolysis}} + (\Delta H)_{\text{Tar-Cracking}}$

For zone 2, the enthalpy balance can be written as:

$$\underbrace{V_2 \mathbf{C_{F2}} C_{VF} \frac{dT_2}{dt}}_{Accumulation} = \underbrace{\left\{F_{a_2} C_{pa} T_{ex} + F_{GS} C_{pG} T_1 + F_{a_1} C_{pa} T_1\right\}}_{Inlet\ \mathbf{flux}} \quad (24)$$
$$\underbrace{-F_F C_{PF} T_2}_{Outlet\ \mathbf{flux}} \underbrace{-F_{GS} (\Delta H)_{comb}}_{Generation}$$

Where C_{PF} is the molar specific heat of the gas mixture, C_{F2} is the gas mixture concentration at the temperature T_2. $(\Delta H)_{comb}$ is the enthalpy of the global combustion reaction. The heat exchanges between zones 1 and zone 3 are carried without mass transfer. The enthalpy balance is written as:

$$\underbrace{V_3 C_{F_3} C_{pF} \frac{dT_3}{dt}}_{Accumulation} = \underbrace{KT_1 + F_F C_{pF} T_2}_{Inlet\ flux} - \underbrace{\left\{K + F_F C_{pF}\right\} T_3}_{Outlet\ flux} \quad (25)$$

The effect of radiation is studied by plotting the pyrolysis temperature (T_1), the flame temperature (T_2) and the pollutant (CO, CO2) concentration as function of time for the different cases. The study of gases composition concentration is studied based on experimental considerations. In fact the main present gases which are energetically valuable by combustion are CH4, H2, and CO. The heat of combustion of H2 and CO is comparable, whereas the heat of combustion of CH4 is lower. Furthermore when temperature is increased from 673K to 1173K H2 molar proportions is increased from 0,024 to 0,478 whereas CO molar proportions is slowly decreased from 0,3 to 0,287 which is in good agreement with [8] who showed that for pyrolysis at high temperatures a larger generation of light incondensable gases mainly composed of hydrogen. This experimental results permits to us focusing only on the effects of H2 molar proportions on the inlet molar air flow (Fa2), the mass loss rate (FGE) and temperature T2 (Figure 4).

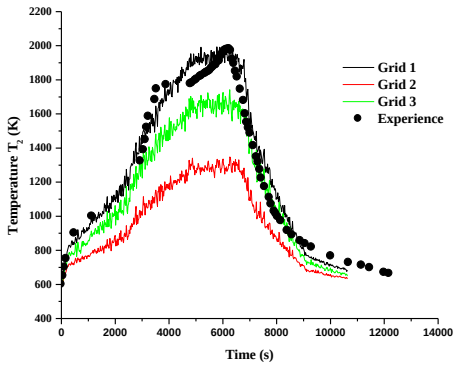

Figure 4 Effect of spatial grid on temperature T_2

Effect of radiative heat transfer on temperature T1

The analysis of the temporal evolution of temperature T_1 shows the important effect caused by the inlet air flow on the values of temperatures in the incineration chamber. The values are taken during the steady state operation of the pilot plant, during which the incineration chamber is regularly fed by gas from both pyrolysis chambers. The average temperature profiles on the axis of the incinerator are plotted in Figure 5 for the three models: without radiation, with gray gas radiation and with non-gray gas radiation. The experimental measurements of [5] are presented in this Figure 5 to compare the ability of these models for this type of simulation. In this application, we used the same conditions of the experience of [5]; an inlet air flow equal to 11mol/s and an ambient temperature equal to 25 °C. Figures 5 and 6 show that when radiation is taken into account, the calculated values from the model are qualitatively in good agreement with experimental measurement values. Indeed, the relative error, calculated by equation (13) does not exceed 15% for gray gases and equal to 8% for non-gray model radiation. However, the error becomes significant, exceeding 35%, when the radiative transfer is neglected.

Effect of radiative heat transfer on temperature T2

In the case of non gray radiation the by default model developed in FDS is adopted. Figures 5 and 6 show comparison between FDS results, global model and experience for temperatures T_1 and T_2. It is seen that there is a difference in the combustion zone between measurements and the three FDS models. This is because more heat loss occurs when thermal radiation is included. Compared with gray gas radiation, non gray gas radiation makes the temperature much less than in the gray case. The difference between calculated temperatures for the three cases appears in the middle of the functioning process (around *t*=600s, Figures 5, 6), in the beginning and at the end of the process temperature values are similar.

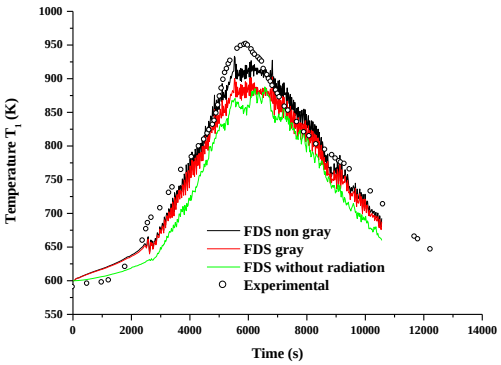

Figure 5 Comparison between FDS results, global model and experience for temperature T_1

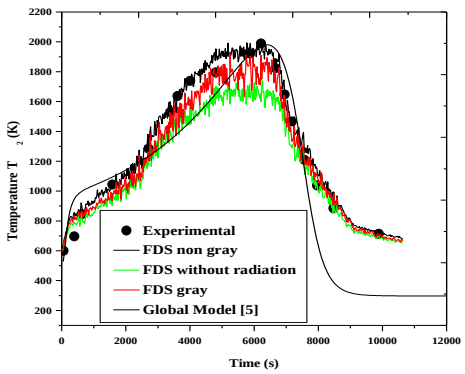

Figure 6 Comparison between FDS results, global model and experience for temperature T_2

The model with non-gray radiation is always the most efficient model. However, it should be noted that the maximum error obtained by comparison with the experience is about 8%, 15% and 32% respectively for the model with non-gray gas radiation, the model with gray radiation and the model neglecting heat radiation. Furthermore, results show that the temperature of the flame zone 2 (T_2) increases gradually to a maximum corresponding to the adiabatic temperature of combustion fumes in the pyrolysis chamber. Towards the end of the cycle, the inlet molar air flow rate of pyrolysis gas decreases causing the reduction of fuel mixture and therefore a decrease in temperature in the flame zone until it reaches the room temperature. At the end of the pyrolysis cycle we found differences between measured and calculated temperature T_2, these differences can be explained by the following:

- The simplified kinetic model used by the FDS code that supposes a single chemical reaction describing the chemical kinetics.
- There are many weight loss and energy that are not controlled during the experiment and which are not calculated by FDS.
-The inertia of the pilot plant which is not taken into account in the numerical models.

Radiative heat transfer effect on CO production

Figure 7 gives the effect of radiation on carbon monoxide emissions. When radiation is included, the CO emission is reduced due to radiative heat loss. In the case of no radiation, the CO emission is overestimated compared with the non gray gas radiation case. Therefore, it is reasonable to include the effect of radiation. Prediction of CO emission based on nongray gas radiation is lower than of gray gas radiation, because temperature is low.

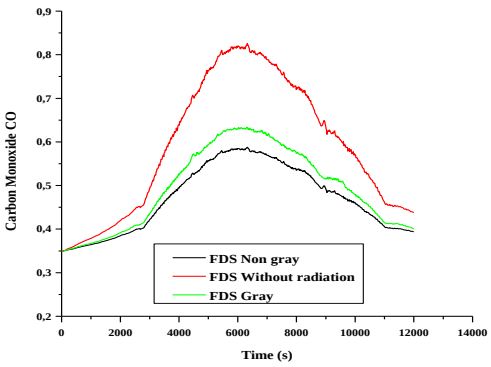

Figure 7 Effect of radiation on carbon monoxyde emissions

Radiative heat transfer effect on CO2 production

Figure 8 gives the effect of radiation on carbon dioxide emissions. The effects of radiation are studied by plotting pollutant (CO2) distributions with the different radiation models. When the radiation effect is not considered, CO2 emission is underestimated. However, CO2 emission is enhanced by the effect of gray and non-gray gas radiation. Therefore, the radiation effect should be included appropriately to simulate a real incinerator.

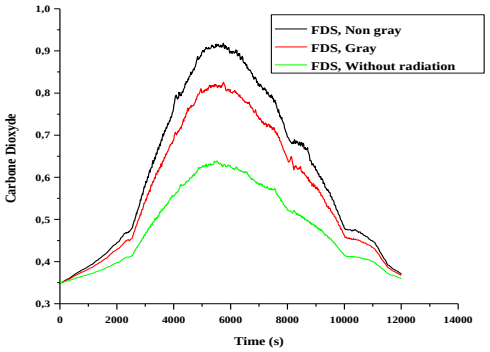

Figure 8 Effect of radiation on carbon dioxide emissions

Effect of H_2 proportions on inlet air molar flow

The effect of H_2 proportions on inlet air flow is given by Figure 9 for catalyzed or uncatalyzed experiments. Dolomite is used as catalyst agent. In this figure Fa2 is adjusted to obtain results with agreement with measured data and avoiding racing reactions described in [9].

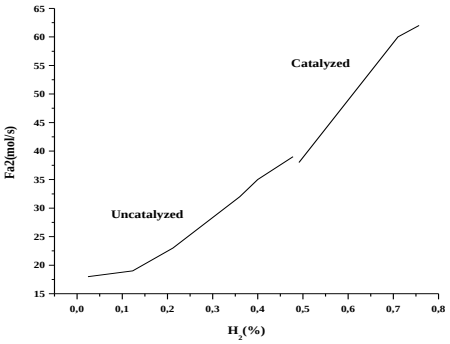

Figure 9 Effect of H_2 proportions on inlet air flow

Effect of gases composition

The main present gases which are energetically valuable by combustion are CH_4, H_2, and *CO*. The effects of H_2 and *CO* is comparable, whereas the effect of CH_4 is less because the heat of combustion of CH_4 is lower than the heat of combustion of H_2 and CO. Furthermore when temperature is increased from 673K to 1173K H_2 molar proportions is increased from 0,024 to 0,478 whereas CO molar proportions is slowly decreased from 0,3 to 0,287. This experimental results permits to us to focus only on the effect of H_2 molar proportions the inlet molar flow (Fa2), the mass loss rate (FGE)

The molar air flow increases with increasing H_2 proportions. Indeed, when the H_2 proportion is increased it is injected into the combustion chambers then the heat of combustion of H_2 contributes to the augmentation of temperatures T_2 and T_3. Therefore T_1 increases and the pyrolysis process becomes faster. If a catalyst is used (100g of dolomite/1kg of biomass) the proportions of of H_2 released is increased therefore the inlet air flow needed, which avoids racing reaction, is also increased.

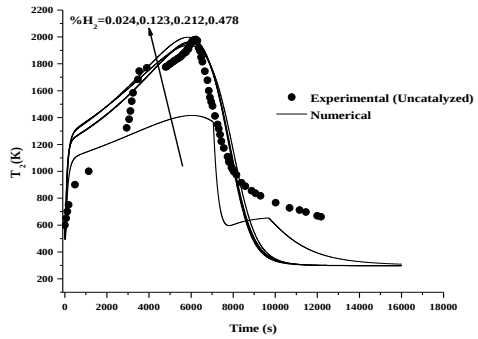

Figure 10 Comparison between experimental measures and calculated results of temperature T_1 in zone 1

Effect of H_2 proportions on T_2

The effect of H_2 molar proportions on temperature T_2 of zone 2 is plotted on Figure 11. The molar proportions of H_2 for the uncatalyzed case are equal to $\%H_2$ = 0.024, 0.123, 0.212, 0.36, 0.4 and 0.478. For the catalyzed case the molar proportions of H_2 are taken equal to $\%H_2$ = 0.757, 0.71 and 0.491. For the two cases temperature T_2 of zone 2 increases with increasing molar proportions. For the catalyzed case the increase of T_2 is more pronounced due to the increase of $\%H_2$ which by combustion gives more energy to zone 2.

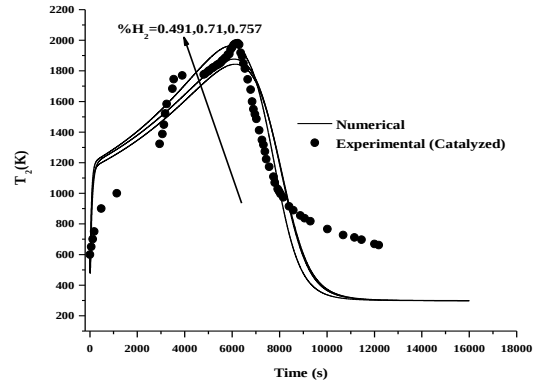

Figure 11 Effect of inlet air molar flow rate on biomass mass loss

Conclusion

A thermochemical model allowing the control and the regulation of a pilot plant of biomass pyrolysis coupled with a pyrolysis gases combustor is presented. This device contributes on the one hand to a clean production of charcoal and on the other hand to increase the charcoal yield mass and the energy efficiency of the process. The effect of the pyrolysis products composition on combustion temperature, inlet molar air flow and mass loss rate is presented for catalyzed or uncatalyzed experiments. The following conclusions are found:

- The temperature of combustion zone increases with increasing H2 molar proportions. This increase is more pronounced for the catalyzed case.
- If H2 molar proportions are increased the inlet air molar flow is also increased for catalyzed or uncatalyzed cases.
- Mass loss rate increases with increasing H_2 molar proportions.
- Temperature results from the model with non gray gas radiation give results in good qualitative and quantitative with experiments. The model with non-gray radiation is always the most efficient model, but it needs more CPU time.
- Prediction of CO emission based on nongray gas radiation is lower than of gray gas radiation. So if non gray radiation is not taken into account CO emission will be overestimated.
- When the radiation effect is not considered, CO2 emission is underestimated.
- The non gray radiation effect should be included to simulate real incinerator.

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