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Sugarcane Bagasse Combustion Stability in an Industrial Boiler in Cameroon

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Abstract-The sugarcane bagasse fuel is an energetic deposit opportunity for thermal and electricity generation in sugar society. Combustion behaviors, essential for effective operation of these devices is a necessity. A 3D numerical model has been developed in the commercial software ANSYS FLUENT. According to the fuel density and particle variable, this model took into account both suspension and grate model combustion. The contour of the temperature, spices and the particle trajectory provided a clear understanding of bagasse fuel combustion in the furnace as well as bagasse particle goes through from initial heating to char combustion and its conversion to ash. These results was used to analyze inexpensively the combustion process for looking the effect of design parameter change on the combustion stability. The result shows that, bagasse moisture content is the main responsible of combustion stability. The excess air adjust and air preheated has been permitted to accelerate the combustion process. But not significantly the radiation heat transfer to water walls. Compare to turbulent air pressure adjust, radiation heat transfer to water walls has been increased by 72 %.

Keywords- *Sugarcane Bagasse, Combustion, Sugar Mill Boiler*

I. INTRODUCTION

Sugarcane bagasse represents an energetic deposit opportunity in sub-Saharan Africa in general and in particular in Cameroon. [1-3]. It is largely used in sugarcane industry as a combustible fuel for electricity and thermal energy generation for process. [4-6]. Excess usually is connected to the grid for the stack holders populations, make it a source of factory income.

Fig. 1 and 2 present the temperature, pressure and steam flow variation according to the sugarcane bagasse humidity. They show the degradation of the steam quantity and quality with the growing of sugarcane humidity. The coincidence of the variation of the fuel properties with the steam shows that the sugarcane bagasse's quality is responsible for the down times or decreases of the production. Then, improving the efficiency of the boiler means improving the efficiency of combustion.

These problems have incited the curiosity of a scientific research trough the world. According to [9-11], the most important physics phenomena collected in the boiler are: the combustion stability, erosion and corrosion of water tube boiler, and the pollutants emission (NOx, SOx, CO, CO_2). Boiler optimization needs the comprehension of these physics phenomena and their interaction. Hostile environment of industries usually is not favorable to the data collection. Nevertheless, CFD numerical model offer today, with their capacity of prediction the lot of possibility to good apprehension [12-14]. Several works on the literature have been done to model bagasse combustion in an industrial boiler. A computer model FURNACE has been developed and validated using measured data obtained from an Australian full-scale mill boiler. This model has been applied to examine the limitation of the existing boiler. It has also been use to investigate the way to develop a new configuration of boiler [16-21]. And today, the must use is the commercial code ANSYS Fluent [22-29]. Even if, these developments has been adapting for bagasse combustion modeling, they still facing challenges due to significant differences between fuel composition and furnace configuration over the world.

The originality of this paper relates to the fact that the developed model is for typical industrial boiler which had not been studied yet. Moreover, the model validated could be used to examine the limitations of the conventional boiler configuration. Also, it could be used to investigate the ways of alternative configuration most efficient at minimum cost.

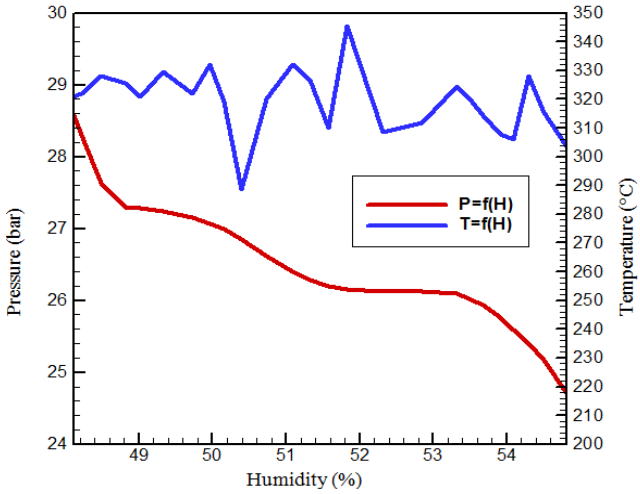

Figure 1. Effect of sugarcane bagasse humidity on the temperature and pressure of the boiler steam generation [3]

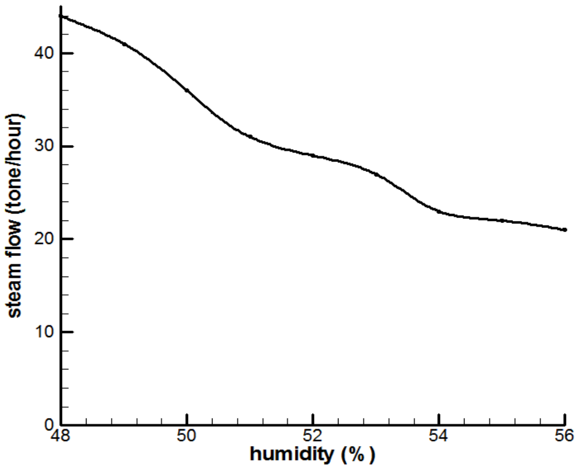

Figure 2. Effect of sugarcane bagasse humidity on the boiler steam flow generation [3]

A. *Background*

There have been a number of CFD studies concerned with the sugarcane bagasse combustion stability. [14] Has been demonstrating that critical sugarcane bagasse water content has an influence on the combustion stability. [32] Has been demonstrating that the high moisture content on sugarcane bagasse is the first source of combustion instability. According the fact that the high moisture content causes an ignition delay and the sugarcane bagasse accumulating on the grate. The parameter of combustion stability is the secondary air turbulent pressure. Turbulent pressure can permit to limit the bagasse accumulating on the grate and contribute to establish the ignition zone for approximately on half of the furnace height. More, to make sure that the effects of refractory addition contribute to combustion stability, the furnace zone can be divided in zone as shows by [22]. Figure 3 confirm that the ignition zone must be on half of the furnace height.

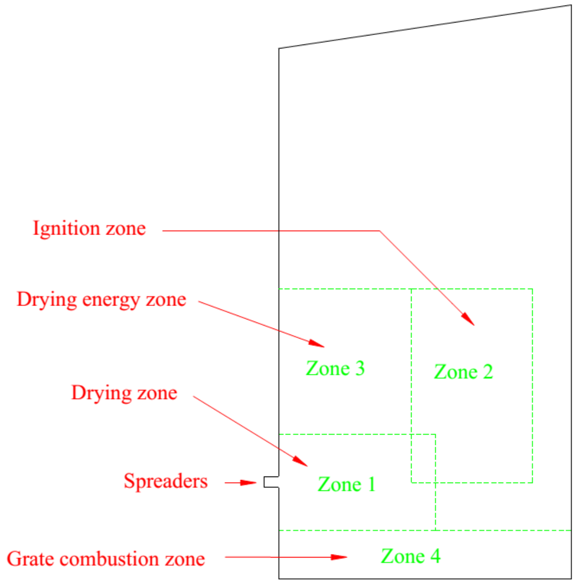

Figure 3. Location of different furnace zones used to assess the effect of refractory addition on combustion stability [22]

For well-designed suspension fired furnaces, excess air requirements generally follow the empirical curves shown in Figure 4 below. If excess air is minimized, piles form on the grate. These inhibit the combustion process.

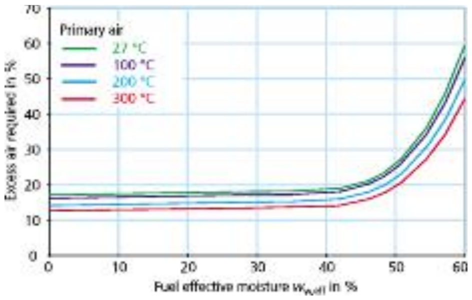

Figure 4. Excess air requirement for fuel effective moisture content [33]

Preheated air is also an option for sugarcane bagasse combustion stability [34 and 35].

II. MATERIAL AND METHODS

A. *Description of experimental device*

Typical boiler of Cameroonian Sugar Society is BR2 43 x 680, the N°1 boiler installed at Nkoteng factory (fig.1). With the moving grate, it produces steam with the following characteristics (tab. 1). The side of the combustion chamber is: 18.3 x 9.46 x 7.56. The bagasse is injected through six (06) fuel chute on the front wall of the 2 m above the grate. It is pneumatic spreading. The primary air is fed through the grate and the turbulent air is fed through the rear furnace wall. The major part of bagasse is burn in suspension with only small portion burn on the grate.

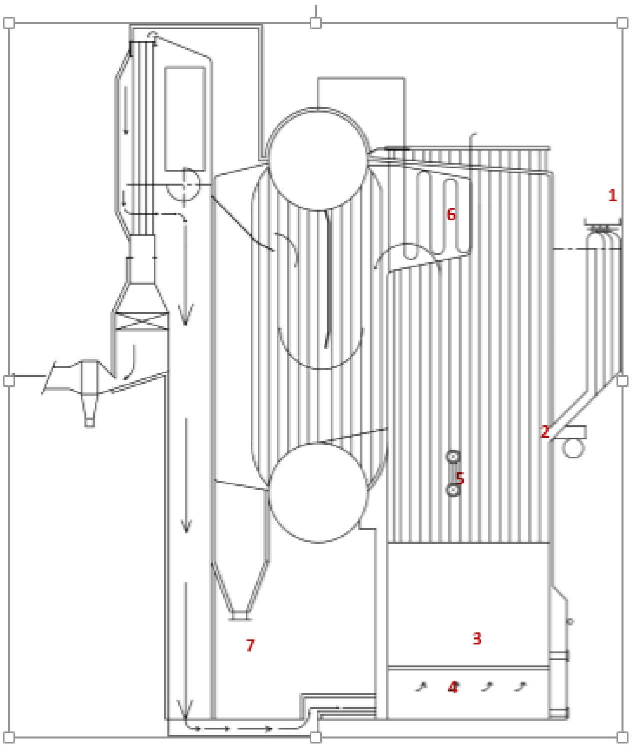

Figure 5. Sketch of the Nkoteng N°1 bagasse boiler. 1: bagasse from mill turbine, 2: bagasse spreading, 3: furnace grate, 4: primary air on the grate, 5: supplementary fuel, 6: super heater, 7: ash and solid particle hoper in the U-turn of the exhaust gas dust.

TABLE I. STEAM CHARACTERISTIC

Power	60 - 70 t/h
Pressure	27 – 30 bars
Temperature	300 – 400 °C

B. Furnace operating conditions

Bagasse is introduced into the boiler according to his elementary chemical composition. With the difficulties of analysis, the data of the following table is the synthesis of the literature.

TABLE II. BAGASSE ELEMENTARY COMPOSITION

C (%)	22,16
H (%)	2, 84
O (%)	21,00
N (%)	0,00
S (%)	0,00
H_2O (%)	50
k (%)	0,4

C. Mathematical modeling of physics phenomena in the furnace

As soon as sugarcane bagasse and air enter in the furnace through different streams, the model is a non-premixed combustion model. The model is the combining hot gaze and particulars as show by fig.

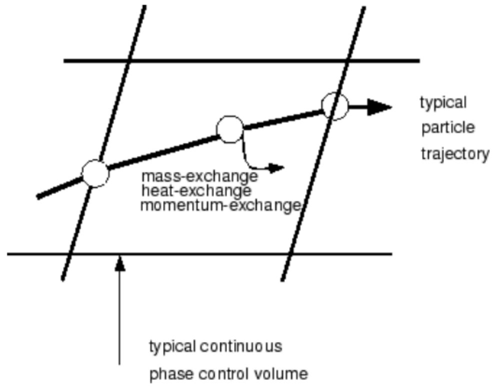

Figure 6. Interactions between discrete and continuous phases

To take into account the two phase, the model will divided in two phases model: the continuous phase model and discrete phase model.

1) Continuous Phase

The mathematical model developed in this part will be combined for gaseous mixing. This model integer the classic equation of fluid dynamic (1) defined by:

$$div\,(\rho\phi u_i) = div\,(\Gamma grad\,\phi) + S_\phi + S_d \qquad (1)$$

As, it is non-premixed combustion model, for the simulation it will be necessity to take into account stimulatingly the mixing and the reaction of chemical element present. By introduction of supplementary equation: the conservative spices equation (2)

$$\frac{\partial \rho Y_i}{\partial t} + \frac{\partial \rho u_i Y_i}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\left(\rho D_{i,m} + \frac{\mu_t}{Sc_t}\right)\frac{\partial Y_i}{\partial x_i}\right] + R_i + S_i \qquad (2)$$

Statistic realizable $k - \varepsilon$ model approach (3) will be used to take into account the turbulent phenomena. Base on Bossiness approach: assuming that the flow is incompressible.

$$-\tilde{\rho}\widetilde{u_i'' u_j''} = \mu_t\left(\frac{\partial \tilde{u}_i}{\partial x_j} + \frac{\partial \tilde{u}_j}{\partial x_i}\right) - \frac{2}{3}\bar{\rho} k \delta_{ij} \qquad (3)$$

The interaction between turbulent and chemical reaction are solve (4) to implement the fast chemistry PDF combustion model.

$$\partial(\rho \overline{u_i}\,\overline{\varphi}) / \partial x_i = \partial(\Gamma_\varphi (\partial \overline{\varphi} / \partial x_i)) / \partial x_i + S_m \qquad (2)$$

In the most combustion process, convective and radiation are the most transfer energy mechanism. These phenomena are introduced by the source term of energy equation (5).

$$S^h = -\nabla . q(\vec{r}) = -\int_0^\infty \int_0^{4\pi} \frac{dI_\lambda}{ds} \partial\Omega\partial\lambda \tag{3}$$

The transfer model will be tested the P-1 approach with is a differential equation in the elliptic form (06):

$$\begin{aligned} \frac{dI}{ds} &= aI_b - aI - \sigma_s I + \\ &\frac{\sigma_s}{4\pi} \int_{\theta=0}^{2\pi} \int_{\varphi=0}^{\pi/2} I\,(x_1, x_1, x_1\,, \theta, \varphi\,) sin\theta d\theta d\varphi \end{aligned} \tag{4}$$

assuming that we have simultaneous reaction of gas and solid in the furnace means the medium is now as porous. The taking into account of this porosity in the model is done by addition of a source term (08) to the standard equations of the flow of the fluid [24].

$$S_i = -\left(\sum_{j=1}^{3} D_{ij} \mu v_j + \sum_{j=1}^{3} C_{ij} \frac{1}{2} \rho |v| v_j\right) \tag{5}$$

2) *Discrete phase:*

The bagasse entrained flow to the furnace is considered as a group of particle with various sizes, shape and the density. Is another particles could be assimilate at cylindrical, the other ones could be assimilate to spherical according to their sizes. To take into account this diversity on the combustion process, an additional equation (9) is necessary according to Rosin-Rammler hypothesis,

$$Y_d = \exp(-d_d / \overline{d_d})^n \tag{6}$$

Follow their sizes, shape and their density, the particles could be take a lot time to consume on the grate or in suspension. The particle trajectory is tracked using a Lagrange equation of motion (10). This model is based on Newton second low.

$$du_d / dt = F_d (u - u_d) + g(\rho_d - \rho) / \rho_d \tag{7}$$

In the discrete phase, bagasse particle are supposed to follow the fundamental process of combustion: heating and devolatilization. Devolatilization is complicate phase and consisting for: pyrolysis, char gasification and char oxidation. When $T_p < T_{vap}$, the heating processe begin which is described by one model (11). Bagasse particle is heated rapidly by the convective and radiation heat at the surface.

$$m_p C_p \frac{dT_p}{dt} = hA_p (T_\propto - T_p) + \varepsilon_p A_p \sigma (\theta_R^4 - T_p^4) \tag{8}$$

When $T_p \geq T_{vap}$, the devolatilazattion process begin. Means when the particle is at devolatilization temperature, the model is bose on the Arrhenius kinetic energy (12-15):

$$\frac{d\alpha}{dt} = k \left[exp\left(\frac{-E_a}{RT_p}\right)\right] (1 - \alpha)^2 \tag{9}$$

$$\frac{d\alpha}{dt} = k \left[exp\left(\frac{-E_a}{RT_p}\right)\right] (1 - \alpha)^3 \tag{10}$$

With:

$$\alpha = \frac{m_0 - m}{m_0 - m_\propto} \tag{11}$$

$$k = Aexp\left(\frac{-E}{RT}\right) \tag{12}$$

After drying and devolitilization of the particle, the residual char burnout models are (16 and 17):

$$\frac{dm_p}{dt} = -A_p P_{ox} \frac{D_o \psi}{D_o + \psi} \tag{13}$$

With diffusion coefficient:

$$D_o = \frac{0{,}5 C_1 (T_p - T_\propto)^{0{,}75}}{d_p} \tag{14}$$

The kinetic rate is: $\psi = C_2 e^{\left(\frac{-E_c}{RT_p}\right)}$

3) *Phase interaction*

The transfer of momentum of the continuous phase to the discrete phase is calculated on Fluent with examine way momentum of a particle change when it passes through each volume of control in the model. This change is calculated by the equation (18):

$$F = \sum \left(\frac{18\mu C_D R_e}{\rho_p d_p^2 24} (u_p - u) + F_{other}\right) \dot{m}_p \Delta t \tag{15}$$

The heat transfer from the continuous phase to the discrete phase is modeling by equation (19):

$$Q = \left[\frac{\overline{m}_p}{m_{p,o}} c_p \Delta T_p + \frac{\Delta m_p}{m_{p,o}} (-h_{fg} + h_{pyrol} +)\right] \dot{m}_{p,o} \tag{16}$$

D. Resolution method

The system of equations obtained is solved using a finite volumes numerical method which makes it possible to translate the partial derivative equations by algebraically expressions corresponding to a discrete distance of the fluid domain. This system of algebraic equations obtained makes it possible to predict the mass, the momentum, energy and the species chemical in all the discrete points of the domain of calculation. The numerical code Fluent has been used. The first order upwind and second order upwind diagram have been used. The convergence criteria have been 10^{-6} for both energy equation and radiation flow and 10^{-3} for other one.

III. RESULTS AND DISCUSSION

A. Calculus domain and grid sensitivity analysis

An experimental device has been introduced, and consist of several geometrical and thermodynamically components. For mathematic compute, several grids have been created on gambit to address different requirement of research. The final version of grid is shown in figures 7 and 8 and consisting of 109510 tetrahedral individual cells. It is tighter at the fuel and air entries.

B. Grid sensitive analysis

After choosing both turbulence and radiation model, it remains to verify the independence of the solution compared to the number of mesh. In this paragraph, the same plan constituted in points A and B was used. The mesh is adjusted for cell numbers equal to 1 for one case and equal to 0 for the other. The result is shown in the fig. 9.

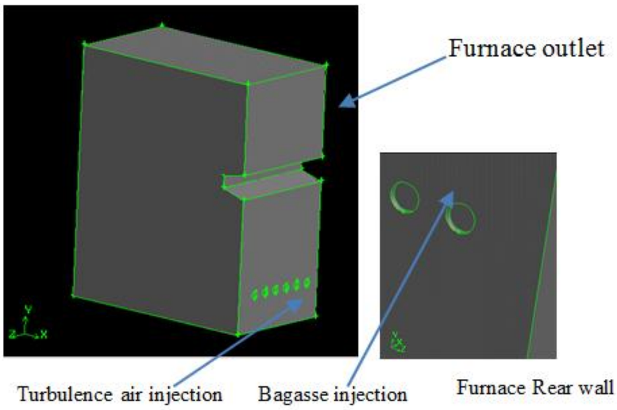

Figure 7. Calculus domain

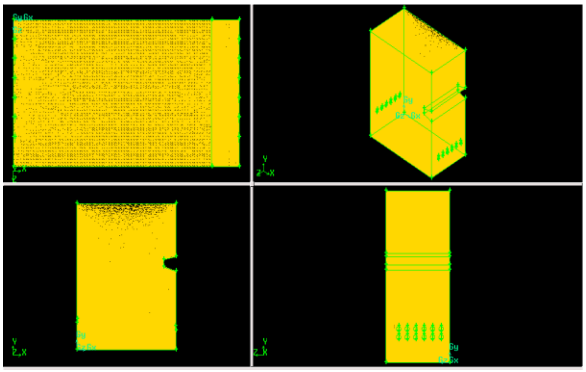

Figure 8. Grid

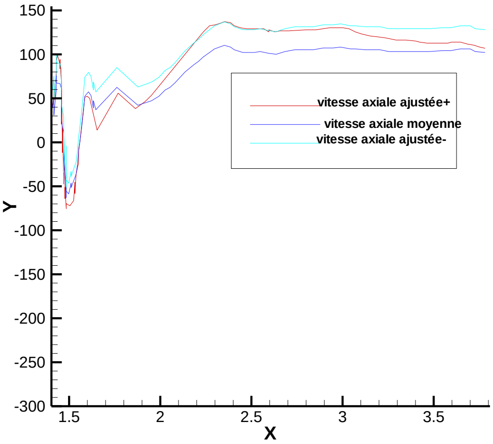

Figure 9. Axial velocity profile for tree grids

The two meshes and the previous mesh give roughly the same solution. It is therefore concluded that the solution is independent of the number of cells. The main grid is considered to provide rationally accurate precision while achieving a reasonable computational efficiency.

C. *Concentration of species*

Figure 10, 11 and 12 shows the mass fraction distribution of carbon monoxide (CO), the masse fraction distribution of CO_2 and the masse fraction of O2 respectively in the furnace. Its lower part also presents the four zones defined previously. The oxygen and carbon monoxide depletion zone, the CO_2 masse fraction reaches peak value corresponds to the zone 1 above the grate. Means, the volatile matter of bagasse combust quickly after being release.

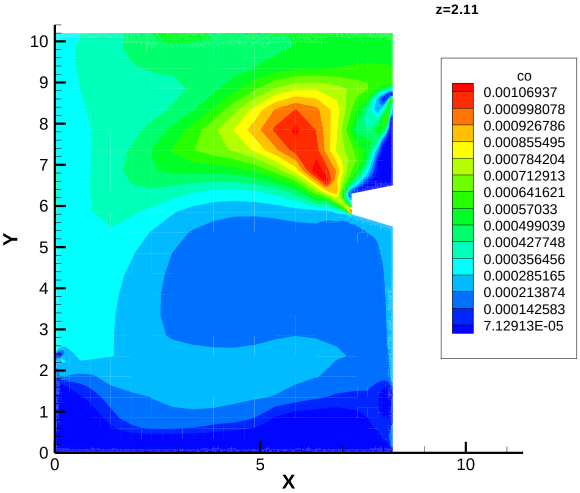

Figure 10. Masse fraction of CO in the furnace

The ignition zone (denoted zone 3) shows the continuous flow of mass fraction of CO_2, CO and O_2 respectively. This is because of the continue reduction of volatiles matter release (the ending of combustion) by the secondary air (turbulence air) system. The turbulent mixing region, intersection from zone 2 and zone 3 correspond to depletion zone of CO means the approximate stoichiometric mixing.

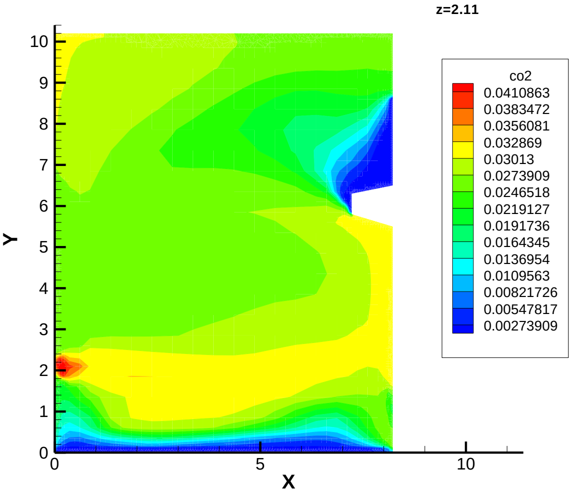

Figure 11. Masse fraction of CO_2 in the furnace

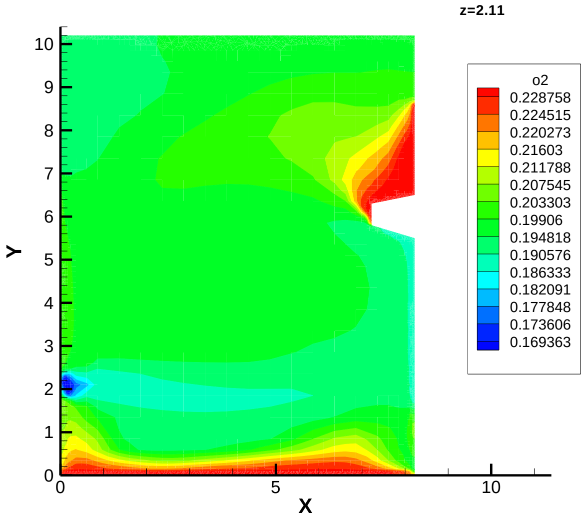

Figure 12. Masse fraction of O_2 in the furnace

D. Temperatures Distribution

Figure 13 shows the temperature contour in the symmetric plan of the boiler at Z = 2.11 m from the side wall. This figure shows the ignition zone near the rear wall of the boiler with the peak as high as 1694 K.

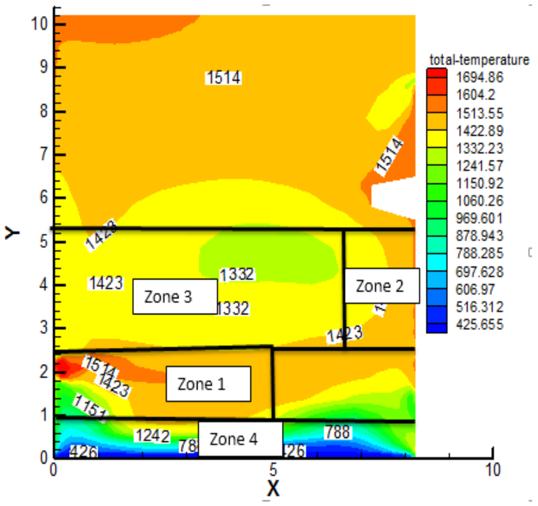

Figure 13. Temperature contour in the symmetric plane (2.11 m from the side wall)

Careful observation of this figure makes it possible to divide it into four zones corresponding to the zones defined by [21].

The first zone (zone 1) is the drying zone of the bagasse. Once admitted into the furnace, the bagasse is heated and drying by the radiation energy from zone 3 and begin to release volatile into the furnace. The volatile matter will join the ignition zone (gaseous combustion zone 2) above the grate. The remaining char will combust on the grate (zone 4).

E. Particles Trajectory

Figure 14 represents the trajectory of the bagasse particles colored by residence time. As predicted by the temperature contour, a lot of bagasse particles are near the back wall of the furnace and on the grate. Then the combustion takes place on the grate and near the back wall.

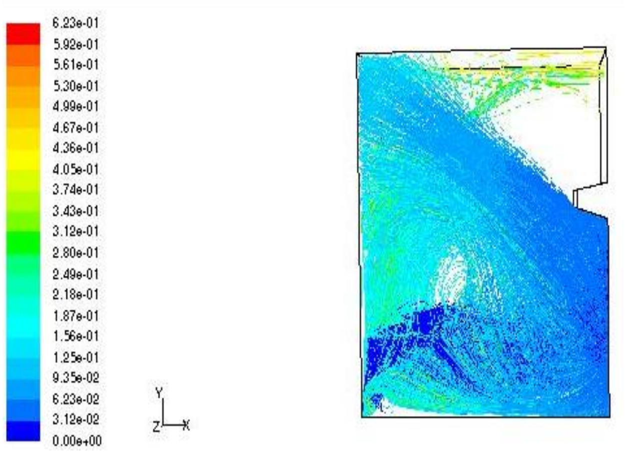

Figure 14. Particle trajectory colored by residence time

The normal operating condition is not adequate for sugarcane bagasse combustion stability. It is imperative to find the source of income and the ways of combustion stability.

F. Effect of sugarcane bagasse moisture content on the flame stability

Fig shows the effect of sugarcane bagasse humidity on the combustion stability. For the 47 %, 50 % and 55 % sugarcane bagasse water content, the higher temperature in the furnace is 1741 K, 1694 K and 1507 K respectively. Means the lower the bagasse water content, the higher the temperature in the furnace. The fast combustion is observed in the fig with 47 % bagasse water content. Then, bagasse water content influences the flame stability.

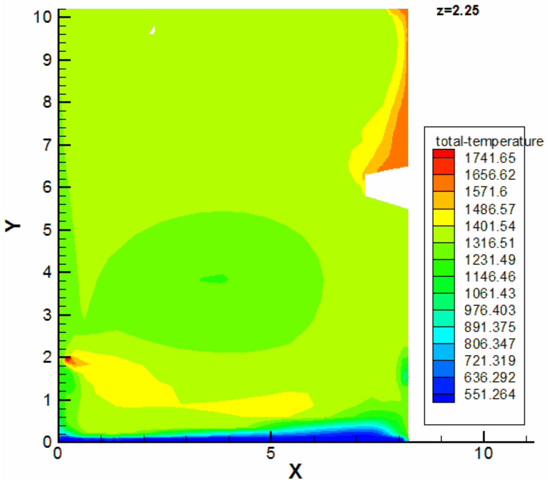

Figure 15. Contour of temperature at 47% moisture content on bagasse

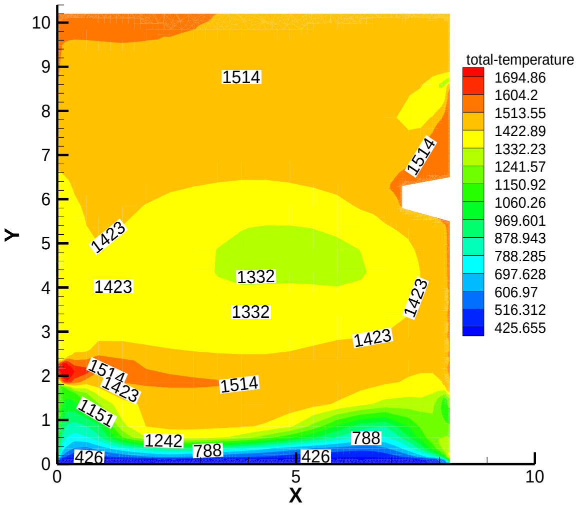

Figure 16. Contour of temperature at 50 % moisture content on bagasse

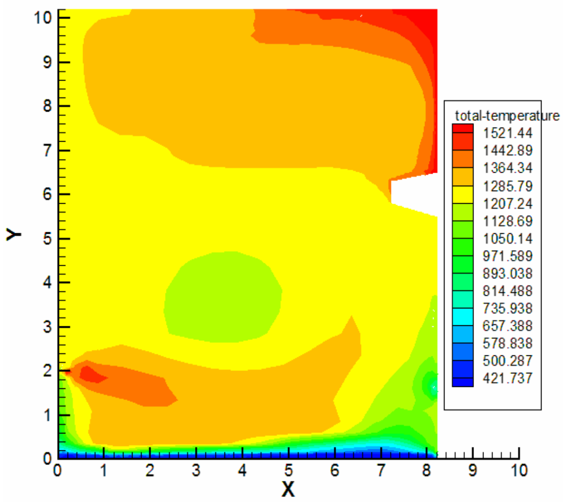

Figure 18. Contour of temperature for 30% excess air

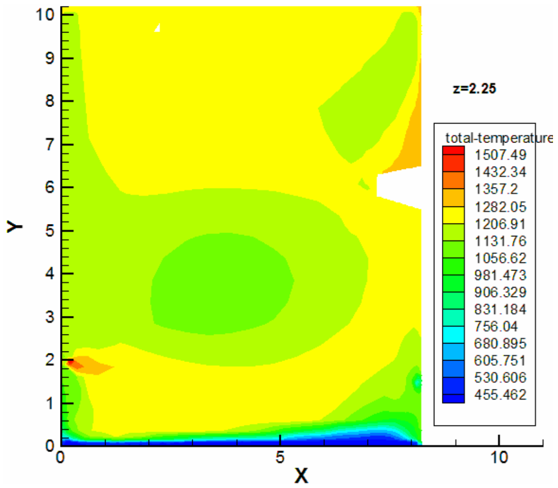

Figure 17. Contour of temperature at 55% moisture content on bagasse

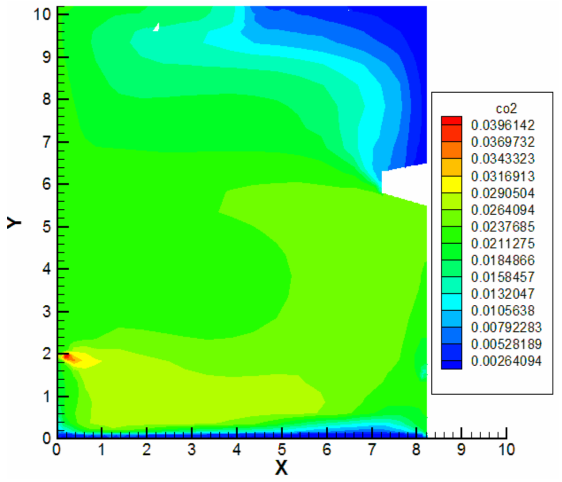

Figure 19. Contour of CO2 for 30 % excess air

G. *Flame stability in the boiler*

1) *Effect of excess air*

Fig. 18 and 19 show the furnace temperature and CO2 contour for 30 % excess air. They show the effect of excess air on the flame stability. Compare to fig.16, fig.18 shows that with 30 % of excess air combustion take place very fast compare to the industrial normal condition (16 % of excess air). 30 % of excess air can help to stabilize the flame on the furnace as shows on the table 3 as soon as the flame takes place in the middle of the furnace.

TABLE III. EFFECT OF EXCESS AIR ON HEAT TRANSFER TO THE WALL

	Temperature (K)	Radiation heat (MW)
Increased excess air	1442	9.8
Normal conditions	1513	9.3

2) *Effect of under grate air preheated*

Figure 20 and 21 show the temperature and CO_2 distribution with undergrate air preheated. Compare to Figure 9 and 16, we can see the effect of air preheated on the flame stability as soon as the flame take place in the middle of the furnace not near the back wall as show in Figure 16. Table 4 shows that preheated air contribute to the flame stability as soon as the temperature in the furnace grow from 1513 K to 1521 K, and radiation heat from 9.3 MW to 9.4 MW.

TABLE IV. EFFECT OF AIR PREHEATED ON HEAT TRANSFER TO WALL

	Temperature (K)	Radiation heat (MW)
Air preheated	1521	9.4
Normal conditions	1513	9.3

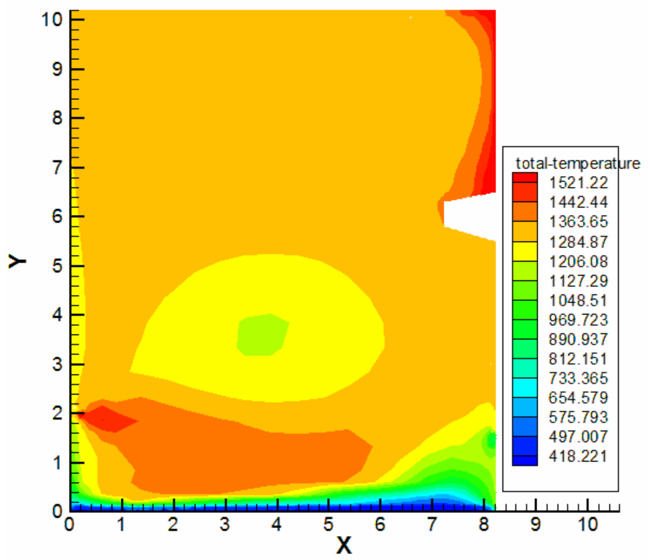

Figure 20. Temperature contour with air preheated

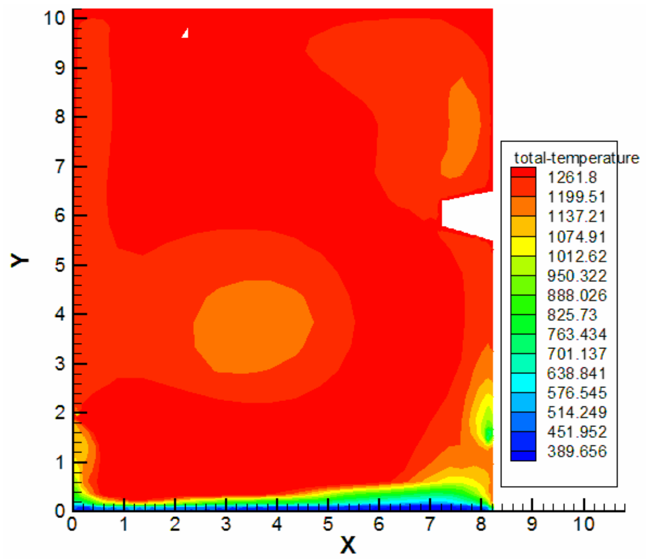

Figure 22. Contour of temperature at 4 kPa turbulent air

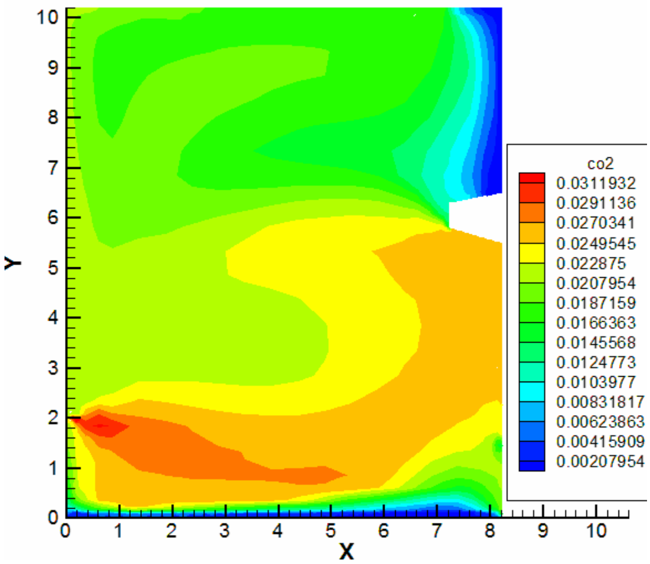

Figure 21. Contour of CO2 with air preheated

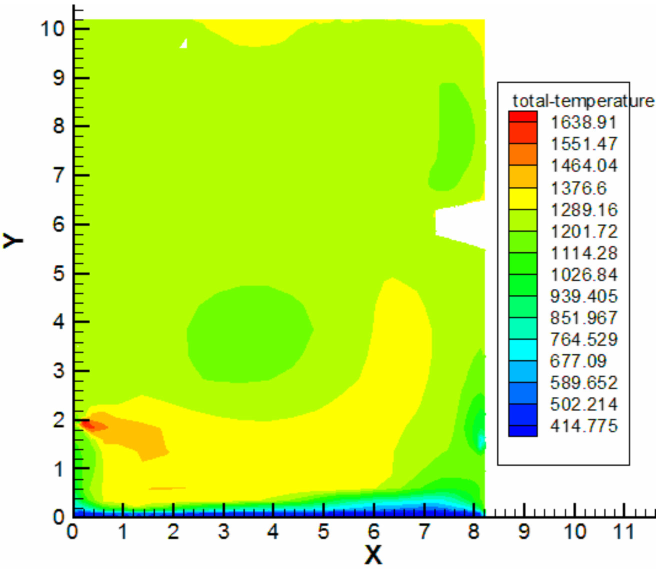

Figure 23. Contour of temperature at 3 kPa turbulent air

3) *Effect of turbulent air pressure*

Figure 22 and 23 shows the temperature contour for furnace at 4 kPa and 3 kPa turbulent airs. The flame takes place at the middle of the furnace for the two cases. For the case with 4 kPa turbulent air, the high temperature zone in the furnace moves upwards. Then, the lower part of the water walls receives less radiation (tab). On the contrary for 3 kPa case the flame occupied the middle high of the furnace near the convection zone. It is why the radiation transfer to the wall for the case with 3 kPa is more than for the case with 4 kPa.

Figure 24 shows effect of turbulent air variation (3 kPa) and 55 % sugarcane bagasse moisture content. The contour shows that, with the variation of sugarcane bagasse moisture content the flame region is the same compare to the total temperature contour in figure 23.

IV. DISCUSSION

The effect of sugarcane bagasse water content shows that the high water content limits the temperature level in the furnace. The results from excess air variation, grate air preheated and turbulent air pressure shows that there are a lot of solution for stabilizing sugarcane bagasse combustion in an industrial furnace. The surplus excess air permitted to accelerate the combustion. The same thing take place in the furnace with air preheated. But compare to the effect of turbulent air pressure variation, the air preheated and excess variation didn't permit to ameliorate considerably radiation transfer to water walls. On the contrary, even with the high moisture content, the 3 kPa turbulent air permitted to maintain the ignition region at the middle of furnace as predicted by [22]. Table shows the synthesis of effect of refractory on the radiation heat transfer to water walls.

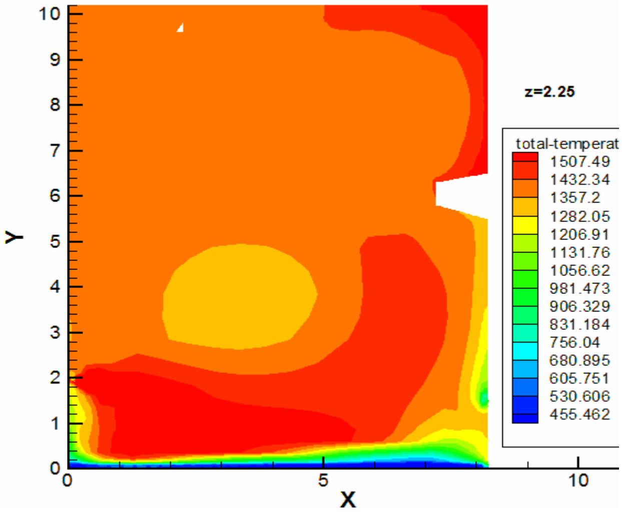

Figure 24. Contour of temperature at 3 kPa turbulent air for 55 % sugarcane moisture content

TABLE V. SYNTHESIS OF EFFECT OF REFRACTORY ON THE RADIATION TRANSFER TO WATER WALLS

Modifications	Contribution (%)
30 % excess air	5.37
3kPa turbulent air	72
4 kPa turbulent air	50.33
Tai and Stanmore, 2000	60.5

From this table, turbulent air pressure is the serious option for combustion stability as soon as it permitted to grow the radiation transfer up to 72 % compare for another solution which is less than 51 %.

V. CONCLUSIONS

A 3D numerical model for the bagasse boiler including two-phase turbulent combustion, the flow of hot gases, and the interaction between the solid and gaseous phases has been developed. The simulation helps to understand bagasse combustion process. The model was used to analyze bagasse boiler for looking of sources of instability. The main sources of combustion stability are sugarcane bagasse moisture content. The effect of excess air variation and air preheated permitted to accelerate the combustion, not significant conges on radiation heat transfer to water walls. The turbulent pressure air variation shows that 3 kPa can permitted to increase radiation heat transfer by 72 %. Then, turbulent air pressure became the serious option for combustion stability.

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