Numerical Modeling of Sugarcane Bagasse Combustion in Sugar Mill Boiler

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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 are 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 realizable k- ϵ turbulent model with the P-1 model shows its advantage of describing such king problems and has been applied on the numerical model. The contour of the temperature, spices and the particle trajectory provided a clear understanding of bagasse fuel combustion in the furnace as well, bagasse particle goes through from initial heating to char combustion and its conversion to ash. The results obtained were in accordance with those of the literature. These results could be used to analyze this inexpensive combustion process for looking for the effect of design parameter change on the furnace performance.

Key words: Sugarcane bagasse, combustion, sugar mill boiler.

Nomenclature

A_p	Particle surface (m^2)	$\dot{m}_{air}$	Total air masse rate (kg/s)
C_p	Pressure heat capacity (J/kg·K)	$\dot{m}_c$	Bagasse masse rate (kg/s)
C	Carbone	O ₂	Oxygen
CO ₂	Carbon dioxide	θ_R	Radiative temperature (K)
C_{ij}	Inertial resistance	p	Pressure
D_{ij}	Viscous resistance	Re	Reynolds number
D_h	Hydraulic diameter (m)	R	Universal gaz constant (8.31 J/K mol)
d_h	Hydraulic diameter (m)	T_p	Particle température (K)
G	Incident radiation	T_∞	Continue phase locale temperature (K)
H ₂	Hydrogen	t	Time (s)
H ₂ O	Water bagasse content	u	Gaz velocity (m/s)
h	Convectif heat transfer coefficient (W/m ² ·K)	u_i	Axis velocity (m/s)
H	Specific enthalpy of mixing (J)	x	Distance (m)
I	Turbulent intensity (%)	Y	mass fraction
K	Turbulent kinetic energy (m ² /s ²)	y	Distance (m)
k	Bagasse Ash content (%)		
m_p	Particle masse (kg)		

Greek Symbols

α	Conversion fraction
δ	Kroneker delta
ϵ	Emissivity
μ	Viscosity
ρ	Density (kg/m ³)

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τ	Stress tensor
σ	Stefan Boltzmann constant
ψ	Porosity

1. Introduction

Sugarcane bagasse represents an energetic potential 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, making it a source of factory income.

The multiple factoring problems according to the using of bagasse as a fuel are the poor quality of the steam [7] with usually constraints operators to stop the production. These problems have incited the curiosity of a scientific research through the world with the objectives to find the origins.

Several visits within the Nkoteng sugarcane factory (Cameroon) made it possible to identify some of these problems with a particular reference to bagasse fuel combustion in the boiler [8]. The better understanding of this process is important for a better regularity of the steam quality, and a reduction of the sugar production costs.

According to Refs. [9-11], the most important physics phenomena collected in the boiler are: the combustion flammability, erosion and corrosion of water boiler tube, and the pollutants emission (NO_x, SO_x, CO, CO₂). 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 offers today, with their capacity of prediction the lot of possibility to good apprehension [12-14]. According to this idea, the modeling of the dynamic flow proceeded there will be undertaken. The aim of this work is to contribute to thermal energy and electricity efficiency for Nkoteng surrounding populations and sugarcane factory [15].

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 used to investigate the way to develop a new configuration of boiler [16-21]. In parallel, with the development of the techniques of coal combustion, other numerical code has been developed. And today, the must use is the commercial code ANSYS Fluent [22-29]. Even if, these developments have been adapted for bagasse combustion modeling, they are 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.

The sugarcane bagasse combustion is a successive reaction of oxidation of the chemical elementary element, which is influenced by their sizes and their water content. According to the fact that the reaction will be in the solid particle and flow gaseous, the turbulent combustion model developed will take into account the interaction between the two mixing phase.

2. Material and Methods

2.1 Description of Experimental Device

Typical boiler of Cameroonian Sugar Society is BR2 43 × 680, the N°1 boiler installed at Nkoteng factory (Fig. 1). With the moving grate, it produces steam with the following characteristics (Table 1). The side of the combustion chamber is: 18.3 × 9.46 × 7.56. The bagasse is injected through six (06) fuel chutes 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

Fig. 1 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 hopper in the U-turn of the exhaust gas dust.

Table 1 Steam characteristic.

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

furnace wall. The major part of bagasse is burnt in suspension with only small portion burn on the grate.

2.2 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 tables (Tables 2 and 3) are the synthesis of the literature.

One of the most significant aspects of the numerical simulation is the determination of the operating conditions. In the Fluent code, we can find: flow rate (fuel or air), pressure, temperature, speed and so one. In case of turbulent combustion as this case, it is important to determine the turbulent kinetic energy (k) and the energy dissipation rate (ϵ). Table 3 presents operating conditions using for simulation.

Table 2 Bagasse elementary composition.

C (%)	22.16
H (%)	2.84
O (%)	21.00
N (%)	0.00
S (%)	0.00
H ₂ O (%)	50
K (%)	0.4

Table 3 Furnace operating condition.

	Flow (kg/s)	T (K)	D_h (m)	Re 10^5	i (%)
Bagasse	9.22	315	1	5	3.08
Projection air	2.42	315	1	5	2.2
Under grate air	29.44	315	1	10	1.89
Turbulence air	9.5	315	1	10	2.46

Two types of outlet function are found on Fluent: the outlet pressure and the simple outlet. The outlet pressure presents the most option for solution convert. The temperature, the pressure, turbulent intensity and hydraulic diameter are: 1,600 K; 760 bars; 3.08% and 5.6 m. The boiler will be supposed to be adiabatic without thermal lost. The internal wall reflectivity will be 0.8 and the limit temperature 1,300 K.

2.3 Physical Models

Being a solid fuel, a bagasse particle introduced in the boiler must be drying, pyrolysis, and char consume. The model can be therefore divided into two phases: the continuous phase model and discrete phase model.

2.3.1 Continuous Phase

The mathematical model developed in this part will be combined for suspension combustion (gaseous mixing) and grate combustion as soon as the part of bagasse burn on the grate. This model takes into account integer the classic equation of fluid dynamics (Eq. (1)) defined by:

$$\text{div}(\rho \phi u_i) = \text{div}(\Gamma \text{grad} \phi) + S_\phi + S_d \quad (1)$$

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

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

statistic approach based on $k-\varepsilon$ model (Eq. (3)) will be used to take into account the turbulent phenomena. Two approaches of $k-\varepsilon$ model will be experimented based on Boussinesq approach: Standard $k-\varepsilon$ and realizable $k-\varepsilon$ base on the assumption that the flow is incompressible.

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

The interaction between turbulent and chemical reaction is solved (Eq. (4)) to implement the fast chemistry PDF combustion model.

$$\partial(\rho \bar{u}_i \bar{\phi}) / \partial x_i = \partial(\Gamma_\phi (\partial \bar{\phi} / \partial x_i)) / \partial x_i + S_m \quad (4)$$

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

$$S^h = -\nabla \cdot \mathbf{q}(\vec{r}) = -\int_0^\infty \int_0^{4\pi} \frac{dI_\lambda}{ds} \partial \Omega \partial \lambda \quad (5)$$

Additional equation will be needed to solve Eq. (5), two transfer models will be tested: the P-1 approach and Discrete Ordinate Model (DO).

The P-1 approach is a differential equation in the elliptic form (Eq. (6)):

$$\frac{dI}{ds} = aI_b - aI - \sigma_s I + \frac{\sigma_s}{4\pi} \int_{\theta=0}^{2\pi} \int_{\varphi=0}^{\pi/2} I(x_1, x_1, x_1, \theta, \varphi) \sin \theta d\theta d\varphi \quad (6)$$

The DO model is Eq. (7):

$$\nabla \cdot (I(\vec{r}, \vec{s}) \vec{s}) + (a + \sigma_s) I(\vec{r}, \vec{s}) = a n^2 \frac{\sigma T^2}{\pi} +$$

$$\frac{\sigma_s}{4\pi} \int_0^{4\pi} I(\vec{r}, \vec{s}) \Phi(\vec{s}, \vec{s}') d\Omega' \quad (7)$$

The accumulation and the combustion of bagasse on the grate and its influence on the combustion and heat transfer to water oblige are taken into account in the total model of combustion. Event is the pile accumulating of bagasse on the grate is small compare to furnace dimension, (9 m >> 20-30 cm) [16], it is important to take it into account. This accumulation can be sketched by Fig. 2.

Fig. 2 shows the pile accumulation of bagasse on the grate with the wire of time. The pile high is caculated using the specific package density defined by Ref. [16]. From now, we have simultaneous reaction of gas and solid on the grate : the medium is now as porous. The taking into account of this porosity in the model is done by addition of a source term (Eq. (8)) to the standard equations of the flow of the fluid [24].

$$S_i = - \left(\sum_{j=1}^3 D_{ij} \mu v_j + \sum_{j=1}^3 C_{ij} \frac{1}{2} \rho |v| v_j \right) \quad (8)$$

2.3.2 Discrete Phase

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

Fig. 2 Grate configuration of the pile accumulative of bagasse.

$$Y_d = \exp(-d_d / \overline{d_d})^n \quad (9)$$

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

$$du_d / dt = F_d(u - u_d) + g(\rho_d - \rho) / \rho_d \quad (10)$$

In the discrete phase, bagasse particles 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 process begins which is described by one model (Eq. (11)). Bagasse particle is heated rapidly by the convective and radiation heat at the surface.

$$m_p C_p \frac{dT_p}{dt} = hA_p(T_\infty - T_p) + \varepsilon_p A_p \sigma (\theta_R^4 - T_p^4) \quad (11)$$

When $T_p \geq T_{vap}$, the devolatilization process begins. It means when the particle is at devolatilization temperature, devolatilization process begins. The model is based on the Arrhenius kinetic energy (Eqs. (12-15)):

$$\frac{d\alpha}{dt} = k \left[\exp\left(\frac{-E_a}{RT_p}\right) \right] (1 - \alpha)^2 \quad (12)$$

$$\frac{d\alpha}{dt} = k \left[\exp\left(\frac{-E_a}{RT_p}\right) \right] (1 - \alpha)^3 \quad (13)$$

$$\text{With: } \alpha = \frac{m_0 - m}{m_0 - m_\infty} \quad (14)$$

$$k = A \exp\left(\frac{-E}{RT}\right) \quad (15)$$

After drying and devolatilization of the particle, the residual char burnout model is (Eqs. (16) and (17)):

$$\frac{dm_p}{dt} = -A_p P_{ox} \frac{D_o \psi}{D_o + \psi} \quad (16)$$

With diffusion coefficient:

$$D_o = \frac{0.5C_1(T_p - T_\infty)^{0.75}}{d_p} \quad (17)$$

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

2.3.3 Phase Interaction

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

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

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

$$Q = \left[\frac{\dot{m}_p}{m_{p,o}} c_p \Delta T_p + \frac{\Delta m_p}{m_{p,o}} (-h_{fg} + h_{pyrol} +) \right] \dot{m}_{p,o} \quad (19)$$

2.4 Resolution Method

The system of equations obtained is solved using a finite volume numerical method which makes it possible to translate the partial derivative equations by algebraical 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.

3. Results and Discussion

3.1 Standard Comprehensive Model

3.1.1 Grid

An experimental device has been introduced, and consists of several geometrical and thermo-dynamical 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 Fig. 3 and consisting of 109,510 tetrahedral individual cells. It is tighter at the fuel and air entries.

3.1.2 Turbulent Model

In this paragraph, it will be given the model of turbulence with the corresponding radiation model. It

Fig. 3 Grid.

means, both standard $k-\epsilon$ model and realizable $k-\epsilon$ model will be applied to describe the fluid dynamics. These models have been considered and adopted separately in the comprehensive model. At the first time the standard $k-\epsilon$ model includes separately the radiation P-1 model and DO method. The second time has been concerned by realizable $k-\epsilon$ model including also separately the radiation P-1 model and DO method. In this work, there are two criteria used to choose both turbulent and radiative model. The first one is the velocity amplitude and the second one the axial velocity. In this way, the standard $k-\epsilon$ model combined with both the P-1 model and DO model has been studied separately. And then, the realizable $k-\epsilon$ model also combined with both the P-1 model and DO

model has been study separately. The sketch of these profiles (Fig. 4) was made on the plane passing through two points A (0.1, 2, and 2.11) and B (4.11, 2.5, and 2.11). The choice of this plant is based on the desire to observe the phenomenon of turbulence at the same time on the area of takeoff of the flame. The observation of (a) shows an outgrowth of the velocity range between 1.2 and 1.7 m with peak at 1.5 m from the front wall of the boiler. The peak is just below the fuel-air mixture region (2 m). It is showing a good fit for the profile with the $k-\epsilon$ realizable model independently of the radiation pattern. The observation of (b) shows the axial velocity profile. Even if it is showing a higher velocity for the realizable $k-\epsilon$ model combined with the two models of radiation.

These curves show that the combination of models resulted in roughly the same solution. But the realizable $k-\epsilon$ model seems more faithful and very little influenced by the radiation model. For reasons of speed to convergence, this model will be combined with the spherical harmonic radiation model P-1.

3.2 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

Fig. 4 Velocity profile for the combined $k-\epsilon$ models with radiative methods.

one case and equal to 0 for the other. The result is shown in the following (Fig. 5):

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.

3.3 Temperatures Distribution

Fig. 6 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 back wall of the boiler with the peak as high as 1,694 K.

Fig. 5 Axial velocity profile for tree grids.

Fig. 6 Temperature contour in the symmetric plane (2.11 m from the side wall).

Fig. 7 Location of different furnace zones relative to the spreaders used to assess the effect of refractory addition and changed air flow distribution on combustion stability [21].

Fig. 8 Comparative study of the temperature in different zone defined by Ref. [21].

Careful observation of this figure makes it possible to divide it into four zones corresponding to the zones defined by Ref. [21] presented in Fig. 7.

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 begins 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).

Fig. 8 presents a comparative study of the temperature values in the various zones of the boiler

resulting from the cutting of Ref. [21].

From this figure, there are slight differences between the temperature values for different zone. It is because the present furnace is too hot compared to Ref. [21] furnace where the peak temperature is 1,300 K. It can be seen that the temperature on the grid is the lowest, and it is higher in zone 2. These values being accessed near, it becomes obvious that the model developed is valid.

Fig. 9 presents the temperature profile above the grate. This profile is compared with the result of Ref. [32]. The peak value observed for the two profiles corresponds to the ignition zone defined previously. It is explained why this zone is the hottest zone. The difference between these values is explained by the quality of fuel as well as Ref. [32] one is Wood compared to sugarcane bagasse.

3.4 Concentration of Species

Figs. 10-12 show the mass fraction distribution of carbon monoxide (CO), the masse fraction distribution of CO_2 and the masse fraction of O_2 respectively in the furnace. Its lower part also presents the four zones defined previously. In the oxygen and carbon monoxide depletion zone, the CO_2 masse fraction reaches peak value corresponding to the zone 1 above the grate. It means the volatile matter of bagasse combusts quickly after being release.

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. In the turbulent mixing region, intersection from zone 2 and zone 3 corresponds to depletion zone of CO which means the approximate stoichiometric mixing.

3.5 Particles Trajectory

Figs. 12-14 represent the trajectory of the bagasse particles colored by residence time, diameter and temperature respectively in the furnace. In these three

figures, turbulent mixing zone satisfies the predictions of the temperature contour and mass fraction of spices.

Fig. 9 Profile of temperature height above the grate compare with profile of wood obtained by Ref. [32].

Fig. 10 Masse fraction of CO in the furnace.

Fig. 11 Masse fraction of CO_2 in the furnace.

Fig. 12 Masse fraction of O_2 in the furnace.

From the trajectory of the bagasse particles colored by residence time in the furnace (Fig. 12), it is observed that the particles that have taken more time in the boiler eventually end up at the upper part of the overheating zone.

Fig. 13 shows the trajectory of the particles colored by the diameter. The small particles are mainly carried away to consume in suspension. For large particles, they are partly accumulated on the grid and another part, transported by the turbulence movement and are found at the outlet of the boiler. The joint observation of Figs. 12 and 13 shows that it is the large particles that put more time in the furnace. These same particles are found at the outlet of the boiler. This shows that the residence time of the particles is not sufficient for them to consume completely in suspension.

Fig. 14 shows the temperature contour colored by the trajectory of the particles in the furnace. It is observed that the drying zone (zone 1) is the zone where the particles are steel cold (ambient temperature). The temperature increases progressively from this zone towards zones 2 and 3, which means the dying due to vaporization that is followed by volatiles release.

Figs. 12-14 show that volatilization seems to be completely distributed all over the furnace and take place through all zone. Therefore, it could be

concluded that, based on the initial size of the bagasse particle the residual char either burns on the grate or dragged to the exit of the furnace. Compared Figs. 12-14 to Fig. 16, the particle trajectory, the front ignition and turbulence region are in concordance.

Fig. 13 Particle trajectory colored by residence time.

Fig. 14 Particle trajectory colored by diameter.

Fig. 15 Particle trajectory colored by temperature.

Fig. 16 Ignition zone colored by particle trajectory defined by Ref. [32].

4. 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 realizable $k-\epsilon$ turbulent model combined with spherical harmonic radiation model P-1 was adopted as model in this work. A comparative study of the temperature contour with the results of the literature was in conformity, which means the model developed is adequate for the bagasse boiler N°1 of Cameroon Sugar Society Nkoteng factory. The simulation also helps to understand bagasse combustion process. Such analysis could be used as an inexpensive measure to diagnose bagasse boiler for looking of sources of instability and propose a new configuration before taking any costly decision.

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