ENERGY EXCHANGE IN THE COMBUSTION ZONE IN A FLUIDIZED BED BIOMASS GASIFIERS

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Abstract. *The restructuring of the Brazilian electrical sector provides technological innovations in the electricity generation system of the state. The process of integrated gasification in combined cycle (Brayton cycle + Rankine cycle) is consider an innovative technology. This technology, that is still in an improvement phase, presents excellent prospects for commercial viability and higher efficiency than the conventional technology. Among the various types of biomass, the bagasse and the cane straw are great options to substitute the fossil fuels, in special in Brazil, where they are abundant. However, due to its fibrous nature, low bulk density and high moisture content, bagasse is a difficult fuel and can not be used directly in a fluidized bed combustor apparatus, which is actually one of most efficient method to convert biomass to energy. A valid alternative to bagasse combustion process is represented by gasification technology. Gasification is, in fact, a process in which solid and liquid fuels which have to be burned are converted into combustible gases. In this work, the study was limited to energy transfer phenomenon in the combustion zone in a fluidized bed gasifiers. To this zone it was developed a mathematic model to analyze the effects of the energy transfer phenomenon. The simulation of this mathematic model promotes a decoupling of the variables that characterize this phenomenon so, statistic models can be used to ensure reliability to results of the obtained variables. In this way, the present work has as objectives: the validation of the computational code developed to the proposed model with results present in the literature, the analysis of the temperature profiles of the solid and gas phases, and, finally, the study of the sensibility analysis with the parameters of gas phase entrance temperature, flow and porosity.*

Keywords: *fluidized bed gasifiers; gasification technology; energy transfer phenomenon; bagasse*

1. INTRODUCTION

Dependence on fossil fuels as the main energy sources has led to serious crisis and environmental problems, such as fossil fuel depletion and pollutant emission. The increasing energy demands will speed up the exhaustion of the finite fossil fuel. Moreover, combustion of fossil fuel produces substantial greenhouse effect and toxic gases, such as CO_2, NO_2, NO_x and other pollutants, causing global warming and acid rain.

Continuous effort has been made in exploration of clean and renewable alternatives for a sustainable development. Biomass is one of the most abundant renewable resources. (FILIPPISA et. al., 2005).

Biomass has been used for centuries. Currently, biomass contributes about 12% of world energy supply, while in many developing countries it contributes about 40% to 50% of their energy supply. Biomass researches are receiving increasing attention because of the waste of a possible energy source. For instance, 150 GT of vegetable bio-matter generated globally every year can produce about 1.08×10^{10} GJ energy. (MENG NI et. al., 2006).

It is traditionally used as fuel to satisfy the heat and electricity demand, but this is generally achieved with low conversion efficiency. Bagasse could also be used for the production of biofuel (ethanol). However, processes involving bagasse for ethanol production needs a hydrolysis step, which requires the use of large amount of cellulases enzymes of saccharification or treatments with strong acids either concentrated or diluted. Both processes give rise to some interest but they do not show economic feasibility at present. Hence further efforts should be made for finding new routes achieving it.

A valid alternative to combustion process of bagasse is represented by gaseification technology. Gasification is, in fact, not only claimed as an environmental clean process, but also appears to offer one of the most attractive technology in the biomass conversion for the energy production. (DERMIBAS et. al., 2001). It involves an integration process of the fluidized bed gasifier and the gas turbine, in a combined cycle (Brayton / Rankine).

Fluidized bed gasifiers have been used to converting agricultural wastes, such as biomass, into energy. The advantages of fluidized bed reactors include: good gas-solid contact, excellent heat transfer characteristics, better temperature control, large heat storage capacity, good degree of turbulence and high volumetric capacity. The existing models of fluidized bed gasification can be classified as thermodynamics models, flow regime models and transient models. (SADAKA et. al., 2002)

This fluidized bed gasifier has been object of several studies in recent decades for the reasons already mentioned. The result has been the development of numerous empirical relationships for the coefficients of transfer between the fluid and solid phases. In parallel to theoretical works, many experimental studies were developed in the search for explanations of the mechanism of heat transfer. However, with the growth of computational capacity, the numerical simulations have become important tools in the study of fluid dynamics and heat transfer.

The computational modeling of heat transfer in a fluidized bed biomass gasifier involves thermal convection, thermal dispersion and effects of exchange among solid and liquid phases. But, as the equations of energy balance are insufficient to solve the problem, it is necessary to supplement them with constitutive equations obtained from independent experiments.

The aim of this work was to develop a comprehensive model capable of describing the biomass gasification phenomenon in fluidized bed gasifiers, specifically to energy balance. So, the model must be capable of predicting the temperature distribution of each species in the vertical direction of the bed.

2. MATEMATICAL MODEL DESCRIPTION

The mathematical modeling acts of significant form to explain the behavior of the temperatures in the gaseous and solid phases. In this paper, energy balance equations assumption the follow restrictions: the referring equation the gaseous phase only involves convection term, thermal dispersion term and heat exchange between gas-solid term, while, the equation linked to solid phase only have the convection term, the thermal dispersion term and the heat exchange between solid-gas term. Thus:

- Energy balance to the gaseous phase:

$$\varepsilon_g K_{g,eff}\,\frac{d^2T_g}{dz^2} - \frac{\varepsilon_g\, C_{p,g}\, Q_g\, \rho_g}{A_s}\,\frac{dT_g}{dz} - (ha)_{gs}\left(T_g - T_s\right) = 0 \tag{1}$$

- Initial and contour conditions to the gaseous phase:

$$\left.\frac{dT_g}{dz}\right|_{z=0^+} = \frac{\rho_g\, C_{p,g}\, Q_g}{A_s\, K_{g,eff}}\left[\left.T_g\right|_{z=0^+} - T_{g,0}\right] \tag{2}$$

$$\left.\frac{dT_g}{dz}\right|_{z=H} = \frac{\rho_g\, C_{p,g}\, Q_g}{A_s\, K_{g,eff}}\,\left.T_g\right|_{z=H} \tag{3}$$

- Energy balance to the solid phase:

$$\frac{\varepsilon_s\, C_{p,s}\, G_{t,s}}{A_s}\,\frac{dT_s}{dz} = \varepsilon_s\, K_{s,eff}\,\frac{d^2T_s}{dz^2} + \frac{(ha)_{sg}}{S_x}\,(T_s - T_g) \tag{4}$$

- Initial and contour conditions to the solid phase:

$$\left.\frac{dT_s}{dz}\right|_{z=0^+} = \frac{C_{p,s}\, G_{t,s}}{A_s\, K_{s,eff}}\left[\left.T_s\right|_{z=0^+} - T_{s,0}\right] \tag{5}$$

$$\left.\frac{dT_s}{dz}\right|_{z=H} = \frac{C_{p,s}\, G_{t,s}}{A_s\, K_{g,eff}}\,\left.T_s\right|_{z=H} \tag{6}$$

3. IMPLEMENTATION OF THE ADIMENTIONALIZATION

When the equations, from (1) to (6), are adimentionalizated, they can be expressed in the following form:

- Gaseous phase;

$$\alpha_1\frac{d^2\theta_g}{d\eta^2} - \alpha_2\frac{d\theta_g}{d\eta} - \alpha_3\left(\theta_g - \theta_s\right) = 0 \tag{7}$$

$$\left.\frac{d\theta_g}{d\eta}\right|_{\eta=0^+} = \alpha_4\left[\left.\theta_g\right|_{\eta=0^+} - 1\right] \tag{8}$$

$$\left.\frac{d\theta_g}{d\eta}\right|_{\eta=1} = \alpha_4\left.\theta_g\right|_{\eta=1} \tag{9}$$

- Solid phase;

$$\beta_1\frac{d^2\theta_s}{d\eta^2} - \beta_2\frac{d\theta_s}{d\eta} + \beta_3\left(\theta_s - \theta_g\right) = 0 \tag{10}$$

$$\left.\frac{d\theta_s}{d\eta}\right|_{\eta=0^+} = \beta_4\left[\theta_s|_{\eta=0^+} - \beta_5\right] \tag{11}$$

$$\left.\frac{d\theta_s}{d\eta}\right|_{\eta=1} = \beta_4\theta_s|_{\eta=1} \tag{12}$$

The parameters of the gaseous phase, α_1, α_2, α_3 and α_4, and of the solid phase, β_1, β_2, β_3 and β_4, are present in the Tab.1 below:

Table 1. Adimentionalizated parameters

α parameters	β parameters
$\boldsymbol{\alpha_1 = \varepsilon_g K_{g,eff}}$	$\boldsymbol{\beta_1 = \varepsilon_s K_{s,eff}}$
$\boldsymbol{\alpha_2 = \frac{\varepsilon_g\, C_{p,g}\, Q_g\, \rho_g L}{A_s}}$	$\boldsymbol{\beta_2 = \frac{\varepsilon_s\, C_{p,s}\, G_{t,s}\, L}{A_s}}$
$\boldsymbol{\alpha_3 = (ha)_{gs}\, L^2}$	$\boldsymbol{\beta_3 = \frac{(ha)_{sg}\, L^2}{S_x}}$
$\boldsymbol{\alpha_4 = \frac{\rho_g\, C_{p,g}\, Q_g\, L}{A_s\, K_{g,eff}}}$	$\boldsymbol{\beta_4 = \frac{C_{p,s}\, G_{t,s}}{A_s\, K_{s,eff}}}$
———	$\boldsymbol{\beta_5 = \frac{T_{s,0}}{T_g}}$

4. SOLUTION OF THE ORDINARY DIFFERENTIAL EQUATIONS SYSTEM

The equations (7) and (10) were transformed into an ordinary differential equations system, that characterizes the initial value problem shown below. The ordinary differential equations system was solved using the Runge Kutta Gill method (Rice e Do, 1995). By the way, it was developed a program using the MATLAB software to solve these equations.

5. DISCUSSION AND RESULTS:

In this section, the results of the model simulation will be present. The resolution of the model gives the behavior profile of solid and gaseous phases temperatures in the combustion zone of the fluidized bed gasifiers. These equations were solved using the Runge Kutta Gill method. In the sequence was developed a computer program in the MATLAB language to provide the results of the variables Tg and Ts. The program was fed with the constitutive parameters from independent experiments shown in Tab 2.

Table 2. Gaseous and solid phase parameters used in simulation

Gaseous phase			Solid phase		
Symbols	Names	Values	Symbols	Names	Values
ε_g	Porosity	0,58	ε_s	Porosity	0,68
$C_{p,g}$	Calorific Capacity	3,02 x 10^{-2}	$C_{p,s}$	Calorific Capacity	2,80 x 10^{-2}
Q_g	Flow	3,06 x 10^2	$G_{t,s}$	Flow	3,06 x 10^2
ρ_g	Density	0,0843	$K_{fg,eff}$	Thermal conductivity	1,875
$K_{g,eff}$	Thermal conductivity	20,46 x 10^{-2}	S_x	External Surface	150,00
L	length	1,00	A_s	Transverse section area	6,06
$(ha)_{gs}$	Global coefficient of gas-solid heat transfer	9,50 x 10^{-2}	–	–	–

The results are presented in the graphical form. In Figure 2, we have the behavior of the solid and gaseous phases temperatures inside the fluidized bed gasifiers. As we can see, the calorific capacity of the gaseous phase is higher so it reaches higher temperatures.

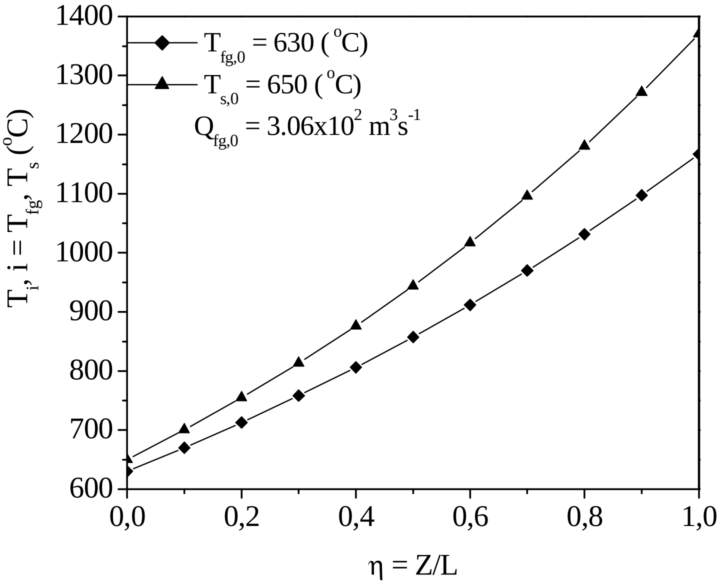

Figure 2. Gaseous and solid phases temperatures inside of the combustion zone of the fluidized bed gasifiers.

It was analyzed the heat flow profile in fluidized bed gasifier forward several kinds of flows. Then, it was seen that the higher flow inside of gasifier, better heat flow we got. The Figure 3 shows this:

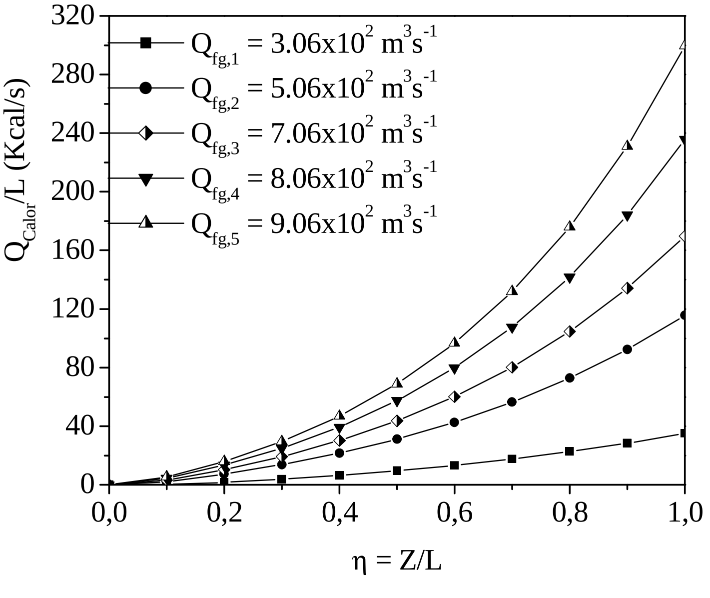

Figure 3. Analysis of the heat flow in the combustion zone of the fluidized bed gasifiers.

5.1. Parametric sensibility study

In this section some parameters in the simulation are studied so its effects in the process can be seen. In both, gaseous and solid phases, two parameters were studied: the thermal conductivity and the calorific capacity so the effects in gas and solid temperatures could be seen.

Is good to notice that is better for the process when we can get higher temperatures. So, in this parametric sensibility study we want the situation that gives us the higher temperatures.

In Figure 4. The effect of the gaseous phase thermal conductivity can be seen. As this parameter grows up, the temperature of the gaseous phase also gets higher.

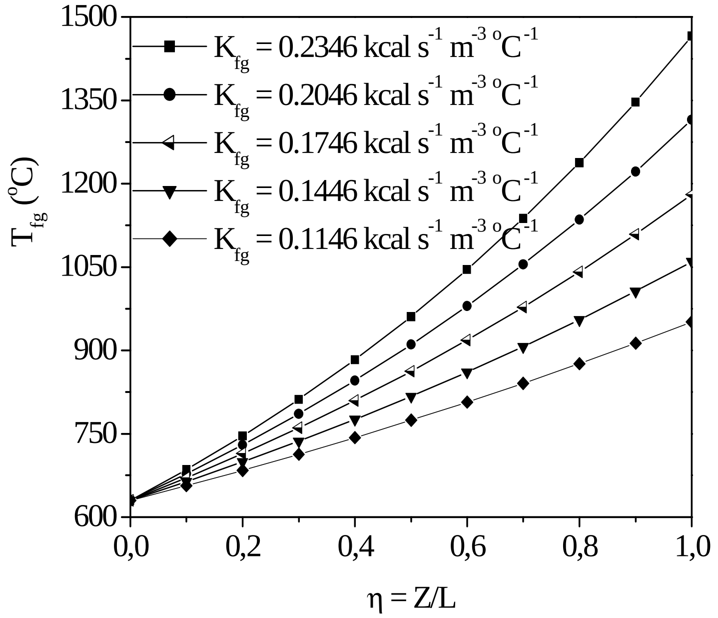

Figure 4. Analysis of the effect of the thermal conductivity of the gaseous phase in the gaseous phase temperature in the combustion zone of the fluidized bed gasifiers.

In Figure 5. The effect of the gaseous phase calorific capacity can be seen. In this graphic, either, as this parameter grows up, the temperature of the gaseous phase also gets higher.

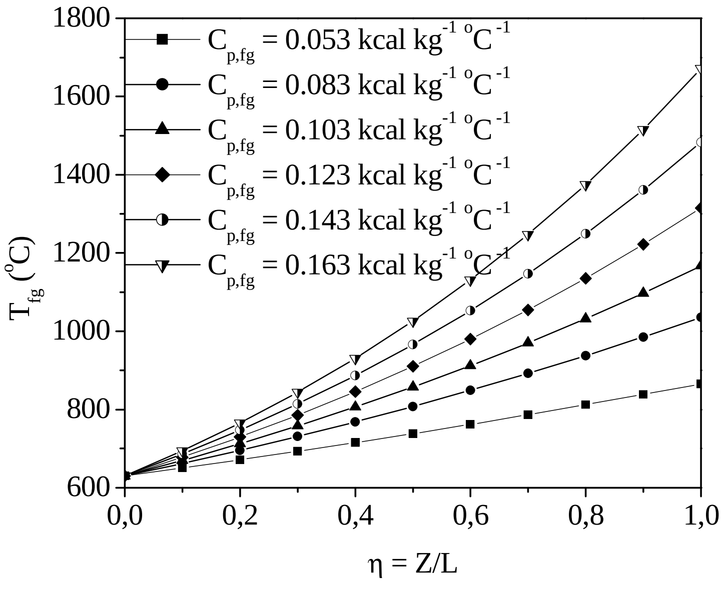

Figure 5. Analysis of the effect of the calorific capacity of the gaseous phase in the gaseous phase temperature in the combustion zone of the fluidized bed gasifiers.

Now, from the next graphic, we start to analyze the effect of the solid phase parameters in the solid phase temperature. In Figure 6. the effect of the thermal conductivity can be seen. As this parameter grows up, the temperature of the solid phase also gets higher.

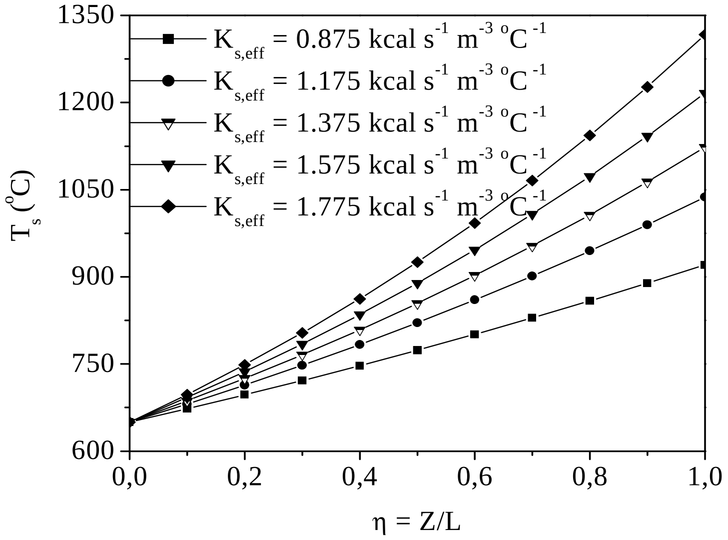

Figure 6. Analysis of the effect of the thermal conductivity of the solid phase in the solid phase temperature in the combustion zone of the fluidized bed gasifiers.

And finally, in Figure 7. the effect of the calorific capacity can be seen. And, again, as this parameter grows up, the temperature of the solid phase also gets higher.

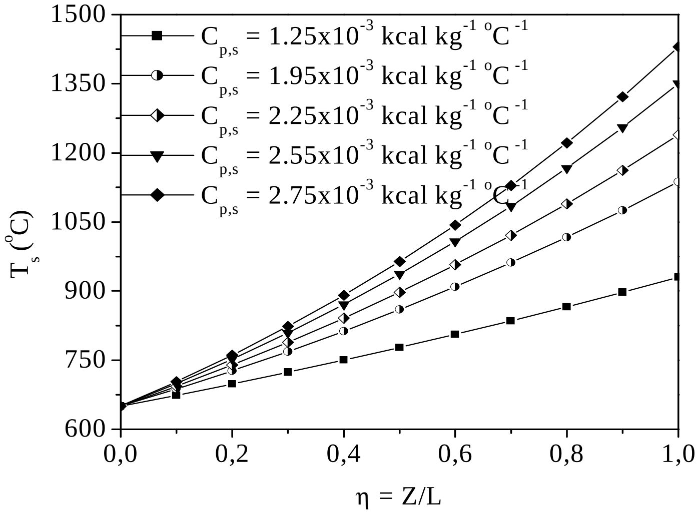

Figure 7. Analysis of the effect of the solid phase calorific capacity in the solid phase temperature in the combustion zone of the fluidized bed gasifiers.

As the graphics show us, theses parameters are crucial in the study of a fluidized bed gasifier since that they are determinants in the reaction and for this reason, in the whole process. Therefore they are analyzed in this paper.

Moreover, the temperature profiles in the solid and gaseous phase gets from the mathematical modeling develop to this reactor showed the forecast of the variables T_g and T_S. This allowed determining the temperatures profiles across of fluidized bed and the behavior of this to some basic parameters of process.

6. CONCLUSIONS

Estimates of the gaseous and solid phases (Tg and Ts) temperatures behavior in the combustion zone of the fluidized bed gasifiers was shown in this paper. And also the effects of some parameters in the process. For that a mathematic model to the gaseous and solid temperatures was developed. The simulation of this model provided the behavior of the variables and led to the following conclusions:

- When the entrance flow was varied the analysis of the heat flow in the combustion zone of the fluidized bed gasifiers showed that it is an important parameter in the process, because it had a great influence in the heat flow.
- The developed model allowed the analysis of the Tg variable sensibility with two parameters: the thermal conductivity and the calorific capacity of the gaseous phase ($K_{g,eff}$ and $C_{p,g}$). Beside that, it also allowed the analysis of the Ts variable sensibility with the same parameters but from the solid phase ($K_{s,eff}$ and Cp_s).
- The studied parameters, thermal conductivity and the calorific capacity of the solid and gaseous phase, presented huge influence on the variables of the case, the temperatures profiles of the gaseous and solid phases.

7. ACKNOWLEDGEMENTS

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8. NOTACIONS

T_g	gaseous phase temperature
T_s	solid phase temperature
$K_{g,eff}$	gaseous phase thermal conductivity
$K_{s,eff}$	solid phase thermal conductivity
Cp_g	gas calorific capacity
Cp_s	solid calorific capacity
L	reactor's length
A_s	transverse section area
S_x	external surface
Q_g	gaseous phase flow
Q_s	solid phase flow
$(ha)_{gs}$	global coefficient of gas-solid heat transfer
$(ha)_{sg}$	global coefficient of solid-gas heat transfer

9. GREEKS LETTERS

ρ_g	gas density
ρ_s	solid density
ε_g	gas porosity
ε_s	solid porosity

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