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MODELLING AND SIMULATION OF THE WOOD CARBONIZATION PROCESS IN A RECTANGULAR OVEN

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Abstract. *Minas Gerais is the major charcoal producer in Brazil, having its steel mill* sector *as the principal consumer. The substitution of the surface ovens by rectangular ones by Mannesmann Florestal, called MAFLA, in the last decade, has brought some benefits to the carbonization process efficiency and productivity. In the present work the possibilities of energy saving and productivity improvement are described. It's also presented a prototype installation scheme, constructed on one of the MAFLA's charcoal plants, with a data acquisition system for the wood carbonization monitoring. A numerical model of wood carbonization process, based on the representation of the global thermo-chemical system by adequate sub-systems, and its computational simulation are proposed. These sub-systems, in a future publication, will be represented by physic-mathematical models of the following processes: tar and non condensed gas combustion, gaseous stream mixing, head loss and heat transfer on the distribution piping and on the wood bed loaded in the oven, and wood drying and carbonization. The solution of the resulting equation system, with transient boundary conditions, will provide the time evolution of the interesting variables, specially the gas and wood temperature and the oxygen fraction in the oven. Comparison of the experimental and simulated results will supply conditions to validate the numerical model.*

Keywords: *Charcoal, Biomass, Carbonization, Simulation, Rectangular Oven.*

1. INTRODUCTION

Minas Gerais is the major charcoal consumer in Brazil, with approximately 4100 x 10^6 kg of charcoal per year, being 93% of this destined to the steelmill sector. MANNESMANN industry, called MAFLA, has an annual production of 280 x 10^6 kg of *eucalyptus* charcoal for its steel plant. Metallurgical Coke is the main charcoal competitor with a consumption around 3000 tEP per year.

Under a financial point of view, both of these energetic products have, approximately, the same cost. However the imported coke price is more sensible to Brazilian economy stability and currency rate exchange than the production cost and price of charcoal.

Under an ecologyc point of view, the use of charcoal has many advantages against the mineral coal usage. The production cycle and consumption of charcoal cause a zero balance of carbon dioxide, what doesn't happen with mineral coal. About 50% of the wood mass is constituted of carbon, and so the oxided carbon generated in the charcoal production and consumption will be reabsorbed by the photosynthesis process of the growing tree. The *eucalyptus* forest doesn't contribute to the greenhouse effect during the charcoal production and, better than this, it contributes to maintain a fixed CO_2 storage until the cut time. The SO_x formation during the charcoal production can be neglected, since there is only about 0,018% of sulfur present in the wood weigh constitution. The NO_x formation only occur with high temperatures, then it is probably present in small amounts in the charcoal production process, since the highest temperatures is about 1000 ^{0}C in the ignition zone or *'tatu'* zone.

The inherent difficulties on the global process of the actual charcoal production and its low productivity are factors that limit charcoal participation on the Brazilian energetic matrix. There is almost no control and automatization of the wood carbonization process. Very few research works have been developed, in this field, aiming to improve the process and the quality of the charcoal produced in a way to make it a practicable energy source for the Brazilian industries.

A prototype instalation provided with a data aquisition system has been constructed at one of the MAFLA's charcoal plants aiming to experimental studies and control tests of the drying and carbonization process. In the present work it is proposed the development of a numerical model for the carbonization process that occurs in this instalation. The global thermo-chemical process is represented by the following sub-systems: Combustor, Mixing chamber of air and combustion gas, Gas distribution piping, Oven – drying phase, Oven – endothermic carbonization phase, Oven – exothermic carbonization phase. These sub-systems will be represented, latter on, by physic-mathematical models of the following processes: tar and non condensed gas combustion, gaseous stream mixing, head loss and heat transfer on the distribution piping and on the wood bed loaded in the oven, and wood drying and carbonization. The solution of the result equation system, with transient boundary conditions, will provide the time evolution of the interesting variables, especially the gas and wood temperature and the oxygen fraction in the oven. Comparison between the results of experimental tests and model simulation will supply conditions to validate the numerical model.

2. MAFLA ACTUAL CARBONIZATION PROCESS

2.1 Rectangular ovens

Mannesmann Florestal (MAFLA) started the constrution of bricken rectangular ovens in the end of 1989, being the first one at Brazil to work with this device in the wood carbonization. Figure 1 shows the principal dimensions of a typical rectangular oven used in the MAFLA's carbonization process.

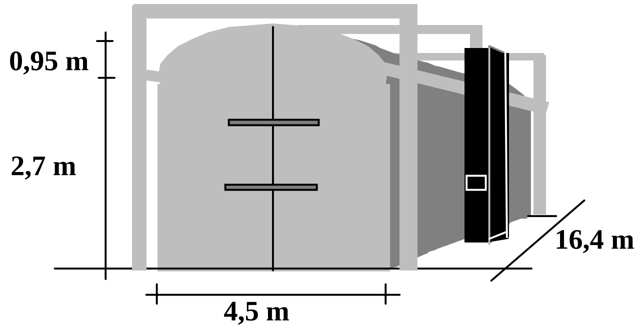

Figure 1 – Carbonization rectangular oven scheme - Type FR190S.

2.2 Charcoal production chronogram

The *eucalyptus* wood, which is going to be carbonized, is cut in pieces of 1,80 meters long with diameters varying from 5 to 25 cm. These pieces are left in the field to dry until they reach a moisture of 30 to 35% dry base (d.b.). The actual wood drying period at MAFLA's charcoal plant is about 90 days, after what the wood is transported, loaded in the oven and finally carbonized. Figure 2 represents the processes that the wood pass through, since its cut until it's completely transformed in charcoal.

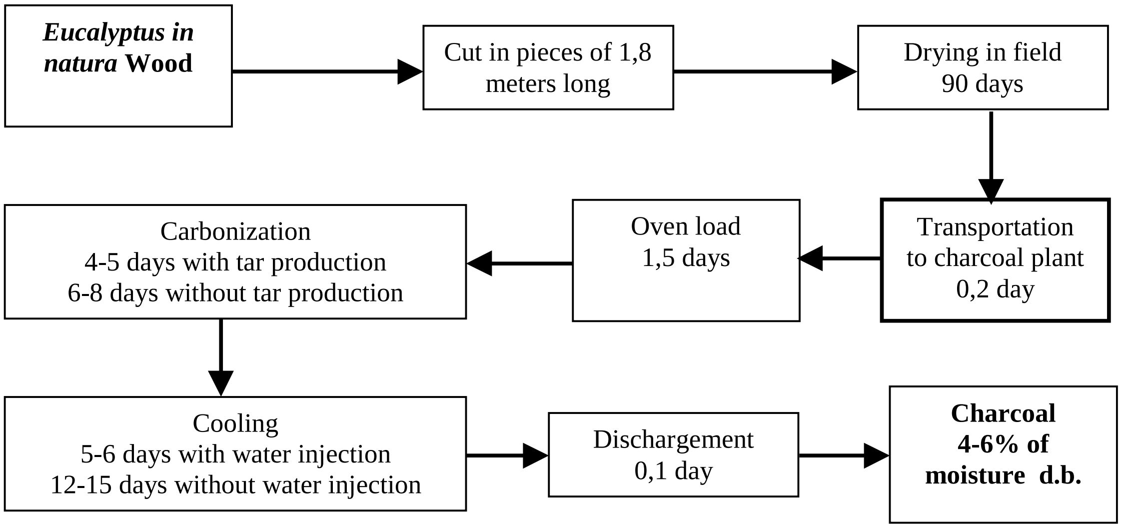

Figure 2 – Charcoal production chronogram at MAFLA.

2.3 Mass and energy balances in rectangular oven

Mass and energy balances have been realized (França *et al.*, 1998) aiming the evaluation of carbonization process efficiency and also the quantification of energy saving potentials in the rectangular ovens . The acquisition of the necessary data for these balances elaboration is very difficult in consenquence of the simultaneous processes of wood drying, wood carbonization and wood combustion occuring inside the oven. Part of the wood is burned to generate energy for drying and carbonizing (endothermic phase) the rest of wood inside the oven. The poor external control of these processes makes difficult the accurated identification and quantification of products formed in wood combustion and carbonization. So it's accepted 10% of uncertainty in these balances results.

Figures 3 and 4 present the results of mass and energy balances of the carbonization process that has been taken in one of the MAFLA's rectangular ovens, considering:

- Initial wood temperatue: 25 °C
- Initial average moisture of wood: 31% dry base.
- Final average temperature of charcoal: 350°C

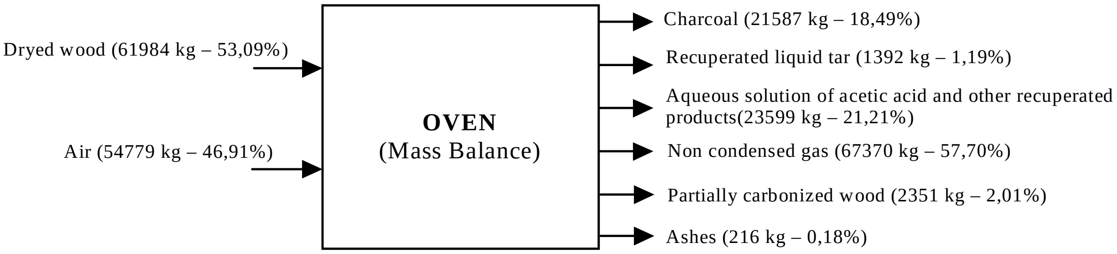

Figure 3 - Mass balance.

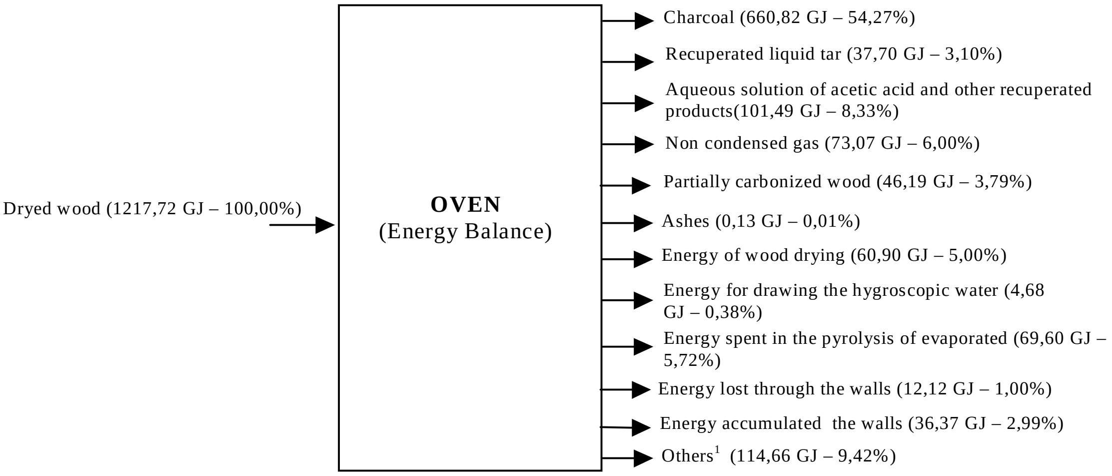

Figure 4 - Energy balance.

1 - Others:

a) Uncertainties in measurements and thermophysical properties of materials.
b) Energy of hot gas that escapes from the oven by holes and breaches.

Taking into consideration that these mass and energy balances are representatives of the MAFLA's rectangular oven carbonization process, it can be concluded:

- The energy efficiency of the carbonization process is 54,3%;
- The mass efficiency of the carbonization process is 35,3%.

The analysis of the carbonization process and of the results presented in Fig. 3 and Fig. 4 lead to the conclusion that these efficiencies may be improved by the adoption of the following procedures:

- Utilization of the tar produced in the process itself to supply part of the heating for wood drying and carbonization.
- Reduction of the gas and wood temperature inside the oven, during the drying and carbonization phases, by means of forced exhaustion of gas, adequated positioning of the igniton holes and adequated layout of the exhausted gas channels.

- Control of carbonization temperature in the minimum level allowed.
- Synchronization of carbonization processes in three or four sequential ovens to take advantage of the sensible heat of hot gas exhausted from an oven to another.

3. PROTOTYPE INSTALLATION

It has been designed and constructed an oven prototype, shown in Fig. 5, where a certain number of tests are being taken aiming the better knowledgement of the stages of wood carbonization and the stablishment of operational procedures for the process improvement. This instalation is comprised, basically, of two rectangular ovens of 1,8x2,0x1,8 meters, an external combustor for burning Diesel oil, tar and combustible gas generated in the process and pipes, valves and blowers arrangement for gases streams mixing, exhaustion and recirculation. A data acquisition system allows 24 wood and gas temperatures measurements in the installation. A combustion gas analyser and a Pitot tube are also available for measuring the gas composition, pressure and flow rate.

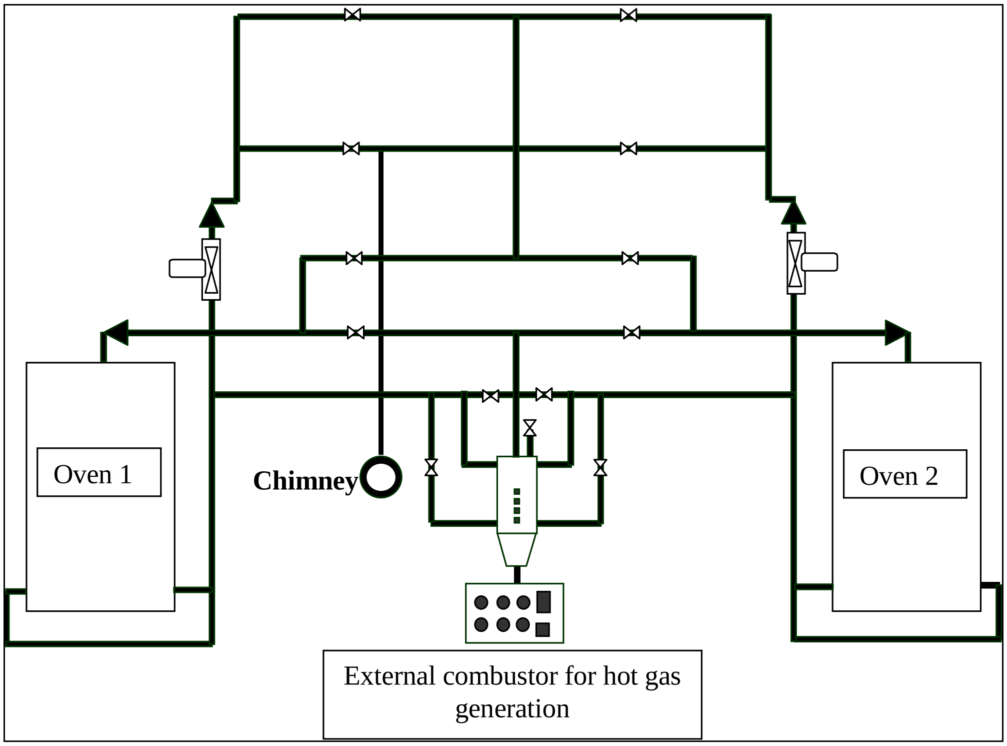

Figure 5 – Prototype instalation scheme.

4. PROCESS MODELLING

4.1 Considerations

The development of a numerical model for the transient wood carbonization process that occurs at the prototype instalation, is based on the division of the global thermo-chemical system into four sub-systems representatives of the following mainly phases of the process:

- Wood drying , from surrounding temperature until 170°C.
- Exothermic carbonization, from 170°C until 340°C

- Endothermic carbonization, from 340°C until the highest carbonization temperature (≤400°C)
- Charcoal cooling, from 400 °C until 60 °C.

In the numerical model, it is also considered that all the energy necessary for the wood drying and for the wood carbonization in the endothermic phase is supplied by the hot gas generated during the combustion of tar or Diesel oil in the external furnace, what means, there is no wood burning in the igniton zones.

The proposed model can be considered as a semi-empiric one, since it is going to be adjusted and calibrated by relations and experimental results obtained from tests in the prototype instalation.

4.2 Block diagram representation

The first step to be accomplished in the modelling of the global process is its representation by block diagrams, with the identification of the related variables in each one of the blocks. Figure 6 presents the block diagram proposed in this work.

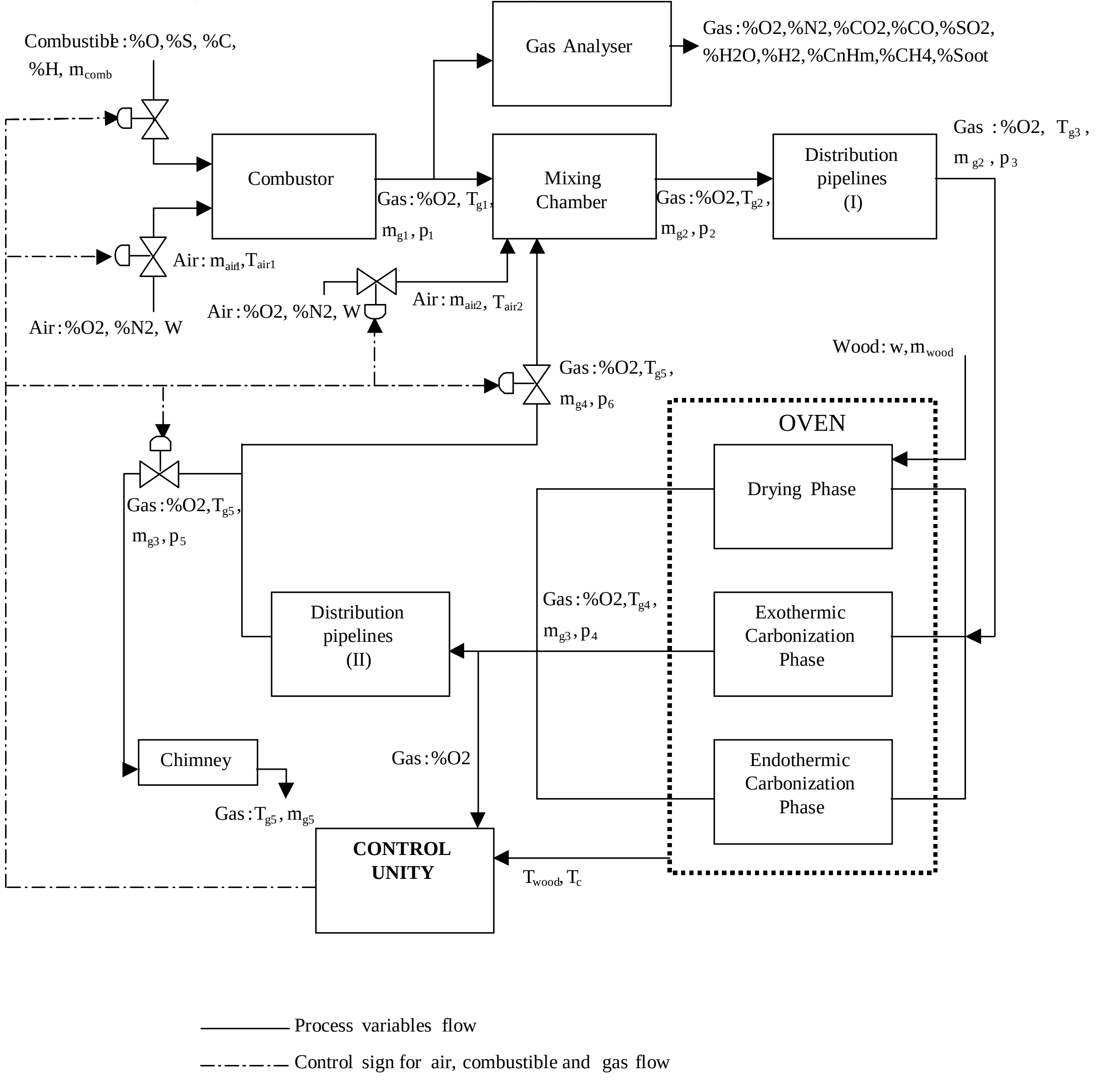

Figure 6 – Block diagram for the carbonization process in the prototype instalation.

External combustor. This device burns tar or Diesel oil and supply the energy for the drying and carbonization phases. The inlet related variables in this block are:

- combustion air flow rate, $\dot{m}_{air1}$
- combustion air temperature, T_{air1}
- combustion air composition (%O_2, %N_2)
- humidity ratio of combustion air, W
- combustible flow rate, $\dot{m}_{comb}$
- combustible composition (%O, %C, %S, %H)
- combustion gas composition (%O_2, %N_2, %CO_2, %CO, %SO_2, %H_2O, %H_2, %CnHm, %CH_4, %Soot, no NO_x control is predicted due its small quantity in the discharge gas), obtained from ORSAT analyser

and the outlet variables are:

- combustion gas flow rate, $\dot{m}_{g1}$
- combustion gas temperature, T_{g1}

The basic equations of modelling external combustor are:

- Mass Balance

$$\dot{m}_{air1} + \dot{m}_{comb} = \dot{m}_{g1} \tag{1}$$

- Energy Balance

$$\dot{m}_{air1} cp_{air1} T_{air1} + \dot{m}_{comb} \left(cp_{comb} T_{comb} + PCI\right) - \dot{q}_{loss} = \dot{m}_{g1} cp_{g1} T_{g1} \tag{2}$$

Mixing chamber. It is a chamber to adequate the gas temperature to the desired value at the current stage of the carbonization process, by means of the mixing of combustion gas and ambient air. The inlet variables of interest in the mixing chamber are :

- inlet gas flow rate, $\dot{m}_{g1}$
- inlet gas temperature, T_{g1}
- O_2 percentage in the inlet gas stream
- recirculated gas flow rate, $\dot{m}_{g4}$
- mixing chamber air flow rate, $\dot{m}_{air2}$
- mixing chamber air temperature, T_{air2}
- O_2 percentage allowed inside the oven at the current stage

The outlet variables are:

- outlet gas flow rate, $\dot{m}_{g2}$
- outlet gas temperature, T_{g2}
- O_2 percentage in the outlet gas stream

The basic equations of modelling mixing chamber are:

- Mass Balance

$$\dot{m}_{g1} + \dot{m}_{air2} + \dot{m}_{g4} = \dot{m}_{g2} \tag{3}$$

- Energy Balance

$$\dot{m}_{g1}\, cp_{g1}\, T_{g1} + \dot{m}_{air2}\, cp_{air2}\, T_{air2} + \dot{m}_{g4}\, cp_{g4}\, T_{g5} = \dot{m}_{g2}\, cp_{g2}\, T_{g2} \tag{4}$$

- O2 Balance

$$\dot{m}_{g1} [\%O_2]_{g1} + \dot{m}_{air2} [\%O_2]_{air2} + \dot{m}_{g4} [\%O_2]_{g4} = \dot{m}_{g2} [\%O_2]_{g2} \tag{5}$$

Gas recirculation system. It is comprised by pipes, junctions, valves and blowers to distribute the gas into the installation. The inlet variables of interest in this block are:

- inlet gas flow rate, $\dot{m}_{g2}$ e $\dot{m}_{g3}$
- inlet gas temperature, T_{g2} e T_{g4}
- inlet gas pressure, p_2 e p_4
- inlet gas density
- inlet gas viscosity
- global heat transfer between gas piping and the air surronding
- performance curves of the blowers

and the outlet variables are:

- outlet gas flow, $\dot{m}_{g2}$ e $\dot{m}_{g3}$
- outlet gas temperature, T_{g3} e T_{g5}
- outlet gas pressure, p_3 e p_5

The basic equations of modelling gas recirculation system are:

- Energy Balance

$$\dot{m}_{g2}\, cp_{g2}\, T_{g2} - \overline{U} A_s \Delta Tml = \dot{m}_{g2}\, cp_{g3}\, T_{g3} \tag{6}$$

$$\overline{U} = \frac{1}{\dfrac{1}{h_{inner}} + R''_f + \dfrac{r_{inner}}{r_{outer}} \dfrac{1}{h_{outer}}} \tag{7}$$

where

r_{inner} = tube inner radio
r_{outer} = tube outer radio
R_f" = incrstation resistance (its value depends on the operational temperature, fluid velocity and time of operation)
h_{inner} = coeficiente convectivo no escoamento interno
h_{outer} = coeficiente convectivo para o ambiente

$$A_s = 2\pi r_{outer} L \tag{8}$$

where

L = tube length

$$\Delta Tml = \frac{(T_{g3} - T_\infty) - (T_{g2} - T_\infty)}{\ln\left[\dfrac{(T_{g3} - T_\infty)}{(T_{g2} - T_\infty)}\right]} \tag{9}$$

where

T_∞ = Environment temperature

Oven. It is the main device on the instalation, where the wood drying and carbonization occurs by action of the generated and recirculated hot gas. Its analysis is developed considering three distinct phases, each one characterized by duration and process temperature ranges. The oven block is the most complex one in the effort of model developing, since the internal environment presents great temperature changes and the diameters of the loaded wood vary from 5 to 25 cm in a randomic arrangement. The inlet variables of interest in this block are:

- inlet gas flow rate, $\dot{m}_{g2}$

- inlet gas temperature, T_{g3}
- inlet gas pressure, p_3
- inlet gas composition
- wood mass loaded in the oven, $\dot{m}_{wood}$
- moisture of wood loaded in the oven, w
- empiric relations for the temporal evolution of mean temperature and permeability of wood bed during the drying and carbonization phases.
- global heat transfer coefficient between oven walls and the surrounding
- time evolution of oven wall mean temperature
- oven dimensions and thermophysical properties of the materials used in the oven construction.

The outlet variables are:

- outlet gas flow, $\dot{m}_{g3}$
- outlet gas temperature, T_{g4}
- outlet gas pressure, p_4
- outlet gas composition
- wood mass inside the oven
- energy lost to the surrounding
- wood and charcoal mean temperatures, T_{wood} e T_c

The basic equations of modelling oven in the drying phase are:

- Mass Balance - Gas

$$\dot{m}_{g2} + \dot{m}_{vapor} = \dot{m}_{g3} \tag{10}$$

where

$\dot{m}_{vapor}$ = water mass evaporated from the wood

- Mass Balance - Oven

$$\frac{dM_{wood}}{dt} = \dot{m}_{vapor} \tag{11}$$

- Energy Balance

$$\dot{m}_{g2}\ cp_{g3}\ T_{g3} - \dot{q}_{loss} - \dot{q}_{wall} - \frac{dM_{wood}}{dt} h_{lv(H2O)} = \dot{m}_{g3}\ cp_{g4}\ T_{g4} \tag{12}$$

$\dot{q}_{loss}$ = heat loss by oven walls

$\dot{q}_{wall}$= heat loss as sensible heat in ovens walls

$h_{lv(H2O)}$ = water enthalpy of evaporation

And for the carbonization phase, the basic equations are:

- Mass Balance - Gas

$$\dot{m}_{g2} + \dot{m}_{pir.gas} = \dot{m}_{g3} \tag{13}$$

where

$\dot{m}_{pir.gas}$ = mass of the pyrolysis gas formed

- Mass Balance - Oven

$$\frac{dM_{wood}}{dt} = \dot{m}_{pir.gas} + \dot{m}_{charcoal} + \dot{m}_{ash} \tag{14}$$

where

$\dot{m}_{charcoal}$ = mass of charcoal formed

$\dot{m}_{ash}$ = mass of ashes formed

- Energy Balance

$$\dot{m}_{g2}\, cp_{g3}\, T_{g3} - \dot{q}_{loss} - \dot{q}_{wall} - \left(\frac{dM_{wood}}{dt} - \dot{m}_{pir.gas} - \dot{m}_{charcoal} \right) PCI_{wood} = \dot{m}_{g3}\, cp_{g4}\, T_{g4} \tag{15}$$

Control Unity. It is the device that allows a semi-automatic control of the process based on the measurement and monitoring of important variables such as gas temperature, wood and charcoal temperature and oxygen fraction in gas. The analysis of the values obtained from the measurement will provide procedures for setting the combustible flow, combustion air flow and recirculation gas flow, by the adequate handling of the valves opening. However, the control actions depend on the antecipated choice of the variables wich will be monitored and on the time evolution of these variables during the process. Preliminary studies suggest the control of the carbonization process by controling the time evolution of both the following variables:

- mean temperature of a piece of wood strategically positioned inside the oven
- oxygen fraction in the gas inside the oven.

5. CONCLUSIONS AND PERSPECTIVES

The numerical modelling and simulation of the wood carbonization in rectangular ovens are very important steps to the process automation and control. They can contribute to rationalize the use of wood and to make the carbonization activity more efficiency and less agressive to man and nature. This work presents the first stage of the development of a semi-empiric numerical model for industrial wood carbonization process. In spite of the work to be still in an initial stage, it has allowed the advance in the state of art of wood drying and carbonization process in industrial rectangular bricken oven. The mass and energy balances realized, have led to the identification of process deficiencies and to the quantification of potencials of energy savings. Preliminary tests realized in a prototype installation suggest that the control of the carbonization process may be, at first, sucessfully made by controlling the time evolution of the mean temperature of a piece of wood strategically positioned into the oven and the time evolution of the oxygen fraction in the gas inside the oven. Others experimental studies that are being developed in the prototype installation will contribute to adjuste and calibrate the numerical model proposed and they will also provide important information for improvements of MAFLA's industrial ovens.

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