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Temperature control of a bubbling fluidized bed combustor burning forest residues without in-bed heat exchanger.

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Abstract

The purpose of this paper is to discuss the temperature control of a bubbling fluidized bed combustor (BFBC) for bark chip combustion in a 6 MW cogeneration plant. The bed temperature is one of the most important parameter in BFBC control. Usually, BFBC systems are designed with in-bed tubes for heat extraction due to the high heat coefficient in a hot fluid bed. Those systems improve bed temperature control and keep the bed temperature under critical value (ash melting point, eutectic and material damage). During summer period, the fuel moisture decreases. This makes the temperature to overshoot the set point during normal operation. However, in this case, there is no in-bed tube to evacuate the excess heat. The temperature control must be done with air ratio (primary/secondary) and fuel flow rate. Also, the bed height and the sand particles diameter affect the bed temperature. Investigation of the thermal plant control system, data analysis and solutions for thermal control are discussed in this paper.

Key-words : Fluidization, combustion, temperature control, waste fuel

1. Introduction

The ever increasing level of greenhouse gas emissions combined with the overall rise in fuel prices (although fluctuations occur) are the main reasons behind efforts devoted to improve the use of various sources of energy. Economists, scientists, and engineers throughout the world are in search for: (1) strategies to reduce the demand; (2) methods to ensure the security of the supplies; (3) technologies to increase the energy efficiency of power systems; and (4) new and renewable sources of energy to replace the limited and harmful fossil fuels.

Nowadays, biomass (organic wastes) receives an ever increasing interest for energy production because this renewable source of energy reduces the demand of fossil fuels, diversifies the sources of traditional energy, ensures the supplies at a local level, and is carbon neutral.

Fluidized beds are found in several industrial applications such as coal and biomass furnaces. Boilers involving such a technology are generally more efficient that their counterparts with fixed or mobile grids and this is why bubbling fluidized beds combustors (BFBC) are often selected to transform waste into energy. An efficient combustion of low calorific power fuels is possible with appropriate controls: according to Oka [1], efficiency could reach up to 99%. Moreover, bubbling fluidized bed combustion of solid residues also becomes attractive for thermal steam generators because it can allow for variations in the regime by up to 4% per minute [2]. The bed temperature, which influences combustion stability, boiler efficiency and the rate of pollutants emission [3,12,17], is one of the most significant parameters in the operation of these types of systems. The control of a BFBC bed temperature without in-bed heat exchanger could be done by maintaining the substochiometric conditions within the bed [2,12] or by cooling it with an important air excess. The role of the secondary air supply is to complete the combustion of the volatiles emissions from the solid fuel [13].

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2. Thermal plant overview

The size of the unit corresponds to the heating demand of a lactoserum powder plant. The boiler delivers 10 t/h of steam at 32 bars and 315°C to a 1 MWe turbogenerator and from there to the process. The design of the 6 MWth cogeneration plant (Figure 1) is optimized for bark chip fuel with average moisture of 50% to 60%. The boiler is a water tube type, originally designed for a fired grate system. Thus, the overall floor plan area of the bed was pre-determined. And that, in turn, determined the nominal operating fluidization velocity of the unit.

2.1 Fluidization grid design

The fluidization grid and the nozzles (Figure 2) were designed, tested, and validated [19]. The fluid bed plan area is about 2.3 m×2 m wide and 0.3 m deep. The fluidization velocity is approximatively 1.5 m/s. The primary air is provided by a 100 hp fan, with 1.27 m of water column pressure drop under normal operating conditions, while the secondary air is supplied by a 40 hp fan with 0.38 m of water column pressure drop. The primary pressure drop is composed of the resistance proportional to the bed height plus the pressure drop across the air nozzles [4,5,14, 19]. In this case, experimental tests were performed on nozzles to obtain the real pressure drop [19]. The pressure drop across the bed is equal to the weight of the granular bed (sand) during fluidization [5,14].

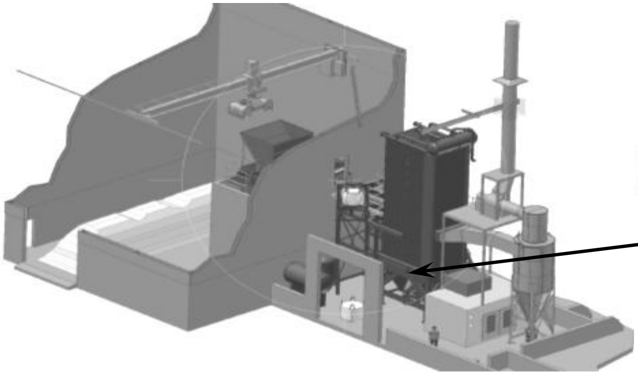

Figure 1. Computational view of the cogeneration plant (left, storage room ; right boiler room, in dark gray: the BFBC)

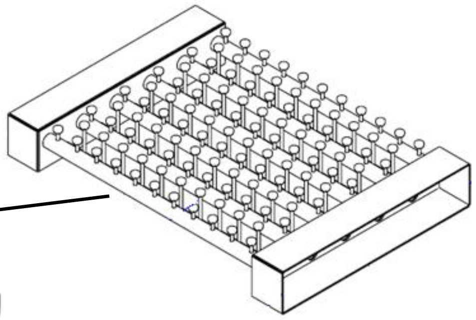

Figure 2. Schematic of the fluidization grid

The grid design (Figure 2) was based on mathematical modeling and on table top laboratory experiments [19]. The software Ergun [6], specially developed for the design of fluidized bed reactors, was used. This software does not provide specific nozzle designs as a result, but permits to determine the correlation between the number of air injection holes, diameters, minimal required fluidization velocities, and air velocity at the exit section of the nozzles [5,7,14,15].

For the design of the fluidization grid, the homogeneous distribution of the air is sought, while the interaction of the individual jets needs to be avoided [16]. This requires a well balanced compromise between the air velocity, nozzle parameters, and fan power. The nozzle size, the number and diameter of the holes as well as the air velocity need to be determined with regards to the homogeneity of the air flow rate and fluidization, in order to ensure the optimal conditions for combustion. In addition, the bed height and the corresponding pressure drop are important parameters for the design of the bed [8,9,5,14]. Detailed discussions on this topic lay outside the scope of this paper. Following the aforementioned principles, the selected grid design is composed of 130 nozzles each with 6 air injection holes and the bed height is approximatively 0,3m (Figure 2).

3. Thermal balance model

The thermal balance of the steam generator and the fluidized bed was performed in a genuine code specially developed by our group for this particular application.

The code uses a database which contains the thermophysical parameters (density, viscosity and so on) of the water, gases, and sand for each calculated temperature. The chemical composition of the combustion gases is also present in the data base. The simplified overall energy balance of the system is given by (eq1):

$$GCV \cdot m_b = m_g Cp_g \left(T_f - T_{g,o}\right) + m_s \left(h_{s,o} - h_{s,i}\right) + Losses \tag{1}$$

The energy *losses* are trough the walls, by the stack, and in air moisture. The gross calorific value *(GCV)* use has to take into account the moisture of the fuel. The energy balance is calculated in each part of the boiler (Figure 3) and subdivided in 8 sections and given by (eq2):

$$m_g Cp_g (T_n - T_{n+1}) = h_t A_n \left(\frac{T_n + T_{n+1}}{2} - T_{s,w} \right) \tag{2}$$

The total heat transfer coefficient h_t is given by (eq3):

$$h_t = \frac{1}{Ah_e} + R_w + A\left(h_c + h_r\right) \tag{3}$$

Where h_e is the pool boiling coefficient, R_{wall} is the conduction resistance across the wall (some of the walls are made of refractory concrete), h_c is convection resistance on the gas side (calculate at the mean temperature between the tubes and the gases) and h_r is the flue gas radiation (CO_2 and H_2O) on the tube using *Hottel and al* method [10].

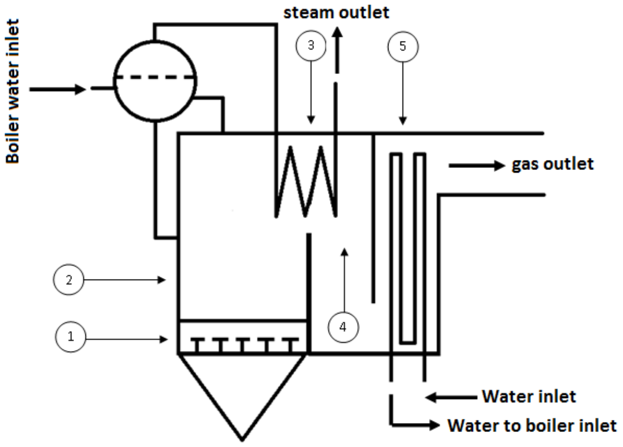

Figure 3. Boiler parts: combustion chamber-1, fluidized bed-2, superheater-3, convection chamber-4, and the economizer-5.

In eq3, the temperatures are unknowns. The temperature in the combustion chamber and the flue gas temperature at the exit have to be determined.

In this code, the proportion of the combustion which takes place in the bed and over the bed is not taken into account since the simulation assumes that all the combustion takes place in the bed. So, the flame temperature equilibrium is equal to the bed temperature [19]. The combustion temperature in the fluidized bed has to be approximate with the adiabatic flame temperature for the first iteration and given by (eq4):

$$m_{air} h_{air} + m_b h_b + m_b GCV = m_g Cp_g \left(T_a - T_{ref}\right) \tag{4}$$

The reference temperature T_{ref} is 25°C. The results provided by the simulator are presented in the figure 4. The upper curve (triangle) is the temperature variation with respect to the steam flow rate for fuel moisture of 40% while the lower curve (diamond) is for fuel moisture of 55%.

As expected, the result of the simulation (Fig 4) shows that highly moisturized fuels decreases the bed temperature for a similar operating condition (steam flow rate). The water evaporation heat rates call for important energy fluxes. This energy consumption (absorption) results in a proportional decrease in the bed temperature.

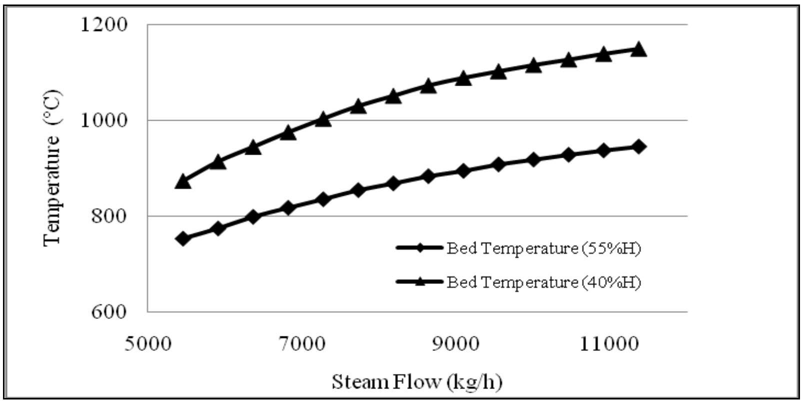

Figure 4. Predictive Temperature for fuel moisture influence function of steam flow

4. Investigation

The thermal plant has been operated for 1 year and a half at the time of the writing. In summer, the temperature control of the sand bed is problematic, since the bark chips were found to be too dry with respect to the original design moisture criteria (50% to 60%). For example, during the tests presented here, the biomass moisture is approximatively 40%. If there is not enough water to be evaporated, the temperature could reach unacceptably high values in the boiler. To avoid this situation, appropriate temperature control must be achieved with the primary and secondary air ratio and fuel flow rate, since there is no in-bed tubes to remove excess heat in this design.

This alternate temperature control approach has been experimented during one week period. The data acquisition system recorded parameters every 30 seconds on 10 different channels. The data allow the production of combustion charts and graphics to be ultimately used as analysis tools. We have recorded the following parameters: bed temperature (3 thermocouples), primary air rate, secondary air rate particles diameters, bed height, steam flow, and the ash level in the removal system. Those parameters were analyzed for understanding their respective and joint influences on the fluctuation of the bed temperature.

5. Results and discussion

Two different strategies for bed temperature control were used. The first one (figure 5) maintains the bed on substochiometric condition by decreasing the primary air fan flow [2,12]. This method decreases the heat release which takes place in the bed. On figure 6, the mean bed temperature is 861°C, but it oscillates around this value. The temperature of the bed rises until it reaches the critical temperature (920°C) allowed by the system. Then, as a safety protection, the controller stops the fuel flow, the oxygen rate increases, and the primary air fan cools the bed until an acceptable temperature is reached. This mechanism explains the periodic fluctuation shown in figure 5. As expected the oxygen flow rate follows the same fluctuation. It decreases during combustion along with the bed temperature; then the fuel feeding restarts at nominal rate and the opposite behaviour is observed.

The second method (figure 6) is to increase the primary air fan flow and carry out the excess heat [19]. In figure 6, the mean bed temperature was 860°C. The speed of the primary air fan was increased at each rate of combustion for bed cooling. The state of fluidization was not respected anymore due to a change in parameters. The fluidization velocity increased but the fluidization grid was not optimized for such air flow (that is the fluidization regime, which should be “bubbling”, approaches the “turbulent” regime for which sand particles may no longer stay in the bed). Consequently the efficiency of biomass combustion decreases due to a high air/fuel ratio [18] and the quality of flue gases also decreased, due to a high content of fine sooth and/or particles (the filtration system is overloaded, brown smoke appeared in flue gases, etc). Consequently, the ash level in the removal system increased. The limit of air cooling is the terminal velocity of particles.

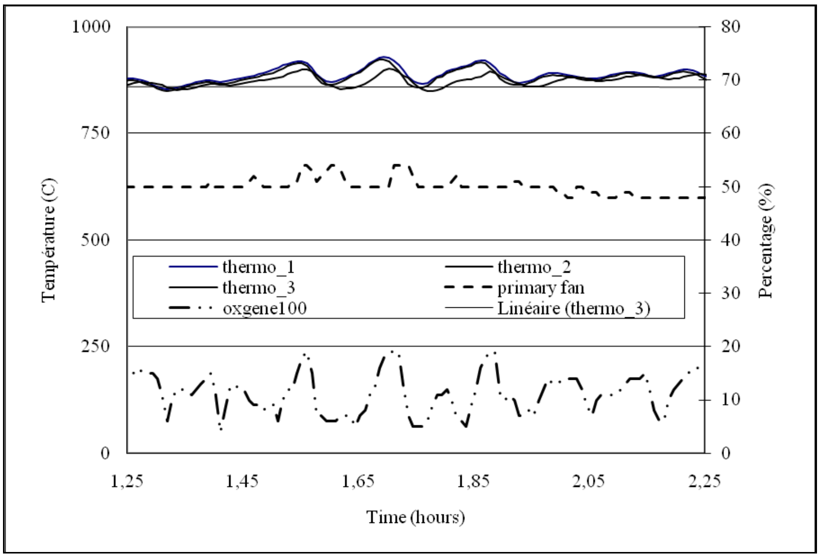

Figure 5. Fluctuation of temperature with control strategy no.1 (Steam demand of 5,000kg/h)

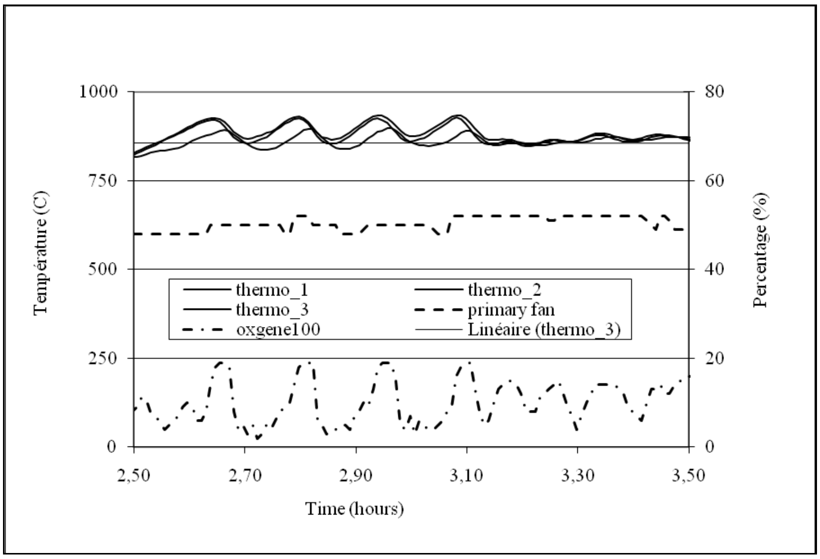

Figure 6. Fluctuation of temperature with control strategy no.2 (Steam demand of 5,000kg/h)

In figure 6, the system oscillations are produced by the combustion process controller. When the temperature increases and reaches the critical value, the system stops automatically the fuel the feeder until the bed temperature decreases to its nominal value. For results presented in figure 6, the fuel is dryer than the moisture content design range of the system. In such conditions, the temperature of the bed will be higher unless primary air flow is increased to extract the excess heat. Once the air flow reaches the onset of turbulence in the bed, the only parameter able to change the bed temperature is the fuel flow, which has a direct link with the steam flow in term of heat equilibrium. When the fuel flow decreases, the steam flow is not respected and the output power of the system drops. Once the desired temperature of operation is reached, the fuel flow resumes to the desired power output.

With both control strategies, we observed steady periods between fluctuation periods which suggest that stable operating conditions are possible with the proper control structure. In addition, more investigation should be done with the bed height. Pressure drop caused by bed height might allow larger air flow before the onset of turbulence in the fluidised bed.

6. Conclusion

The temperature control of a BFBC without in bed tube heat exchanger was investigated as this particular BFBC was designed for one type of fuel with specific gross calorific value and humidity. When these characteristics fall outside the design criteria, the new bed temperature equilibrium may be shifted outside the desired range and should be controlled accordingly. Two control strategies were investigated: The first maintains the bed on substochiometric conditions by decreasing the primary air fan flow; the second is to increase the primary air fan flow to carry out the excess heat.

It was found that maintaining the bed in substochiometric conditions does not offer a significant improvement. On the other hand, cooling the bed with the primary air fan is limited by the fluidization regime limit. In fact, both methods were found insufficient for large variations of moisture content in the fuel. The amount of heat in the bed is difficult to extract without in-bed heat exchangers. This solution could be considered for a wide range of variation of the humidity content of the fuel.

Otherwise, the classical solution for a plant without exchanger is to ensure that the feedstock (fuel) respects the design criteria (moisture control in the storage room) all year long. Alternatively, another control strategy (we have not tried it yet) would be to control the bed height. This might allow to broaden the stable combustion operating range.

A BFBC without a heat exchanger is basically a one fuel type combustor. However, nowadays a power plant using a technology such as fluidization must be able to burn a wide variety of incoming residues and keep the combustion efficiency high while remaining environmentally friendly. Development of improved temperature control techniques responds to this requirement, and this is what were are now investigating.

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