A bubbling fluidized bed combustion system for forest residues

Anthony Goncalves[1,2], Laszlo Kiss[2], Marie-Isabelle Farinas[2], Daniel Rousse[1,*]

[1] *t3e Industrial research chair, École de technologie supérieure, Montréal, Canada*
[2] *GRIPS, Université du Québec à Chicoutimi, Chicoutimi, Canada*
* *Corresponding author. Tel: +1 (418) 833-2110, Fax: +1 (514) 396-8950, E-mail: daniel@t3e.info*

Abstract: The main objective of the project was to develop or adapt a combustion technology that would permit a stable operation of a boiler fed with a combustible with a high level (50%) of humidity. The size of the unit was determined by the heating demand of a lacto-serum plant. Computer simulations and small scale laboratory experiments were used to design a fluidized bed, then fluid flow and heat transfer calculations were carried out to verifiy the heat balance (or energy balance) of an existing fixed boiler to be converted into à fluidized bed one. A grid involving 130 nozzles with 6 equally distributed holes (10 mm) was designed. The intake has a 23.37 mm I.D. It has been in operation for more than a year now and operation results are presented. It was found that the key aspect of the combustion process in such boilers is the homogeneity of the fluidized bed and the temperature control. We are now working on a way to broaden the range of type of wood and humidity levels.

Keywords: *Renewable energy source, Boiler, Bubbling fluidized bed*

Nomenclature

ΔP	*effective pressure drop across the bed*.... Pa
A	*area of the bed* .... m^2
Ar	*Archimedes number* .... -
D	*particle diameter* .... m
g	*gravity* .... $m{\cdot}s^{-2}$
h	*convective transfer coefficient* .... $W\,m^{-2}\,K^{-1}$
H	*height of the bed* .... m
K	*fluidized bed constant, usually 5* .... -
Nu	Nusselt number .... -
Pr	Prandtl number .... -
Re	*Reynolds number* .... -
S	*surface to volume ratio* .... -
T	*temperature* .... K
U	*fluidization velocity* .... $m{\cdot}s^{-1}$

Greek symbols

ρ	*density* .... $kg{\cdot}m^{-3}$
λ	*thermal conductivity* .... $W\,m^{-1}\,K^{-1}$
μ	*dynamic viscosity* .... $kg{\cdot}m{\cdot}s^{-1}$
ε	*bed porosity* .... -

Indices

mf	*minimum fluidization*
g	*gaz*
p	*solid particles*
r	*radiation*

1. Introduction

1.1. Context

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,
- is carbon neutral?

Fluidized beds found several industrial applications such as coal and biomass combustion. 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 for low calorific power fuels is possible with appropriate controls: according to Oka [1], it 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].

1.2. Fluidized beds combustion

Fluidization refers to the conditions for which a granular material behaves such as a fluid. To obtain fluidization, a gas (generally air) crosses a bed of particles with an appropriate upward flow rate to create forces that separate particles: the result is a turbulent mixing of gas and solids. The key idea is to obtain the highest mixing rate possible. In practice, the mass flow rate must be high enough to ensure an appropriate mixing and low enough to keep the particles in the mixing. The rationale behind this technology is that the tumbling action provides more effective chemical reactions and heat transfer in the solid fuel particles that are added to the bed.

In this paper, the process involves BFBC. During preheating, the bed is heated up with an auxiliary source (here natural gas). Then, the process is fed with biomass. This initialization process is critical to ensure proper operation. During combustion, part of the ashes and fine particles must be collected with a cyclone. The other part of the ashes is recovered through the sand circulation. The bed temperature – which influences the stability of combustion, the efficiency of the steam generator, and the rate of pollutants are the preponderant factors for this type of system.

1.3. Process characteristics

BFBC boilers operate at lower temperature than other types of boilers (800-850°C). This may lead to less NOx emissions. However, burning at low temperatures also causes increased polycyclic aromatic hydrocarbon emissions. The temperature upper limit is intrinsically due to the melting point of the most commonly used solid particle: sand. The development of eutectic within the sand is a crucial phenomenon to avoid. The creation of agglomerates will seriously impact the efficiency and may stop fluidization and, eventually, the whole process. The melting point of silica diminishes when it is mixed with ashes and eutectics are formed when hot spots occur in the bed. BFBC reduces the amount of sulfur produced in the form of SOx.

1.4. Overview of the installation

The whole factory into which the boiler is installed produces lactoserum which requires 6MWth and electricity (1MWe). The boiler produces 10T/h at 32 bars and 315°C. The whole plant is shown in Fig. 1. On the left-hand side the storage and feeding systems (a) are shown while the boiler (b) is located in the center of the right-hand side of Fig. 1. The feeding system is a key element of the design as the process is continuous and cannot be stopped. The homogenization of the bark in terms of size and humidity is another key aspect. In Fig.1, the fuel is grabbed and thrown into the feeding system where some sorting occurs to avoid having large chunks of wood to get into the 40 cm worm gear. This gear feeds the combustion chamber. The fluidization grid is another key aspect of the process. The shape and size of the nozzles, the numbers and diameters of the orifices as well as the air outlet velocity have to be selected to maximize the homogenization. The height of the bed and the pressure drop are other key parameters [3,4] discussed in subsequent sections.

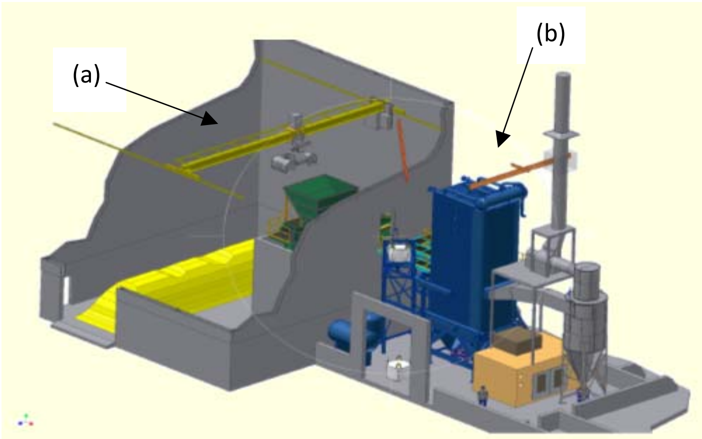


Fig. 1: Layout of the complete plant with: (a) Feeder and storage; (b) boiler, turbine and stack.

1.4.1. The storage system

In this area of the plant, the raw material is treated to maximize homogeneity in size, calorific power, and humidity. A mechanical treatment is applied to tear the biggest chunks of wood this to avoid mechanical failure of the feeding system. During winter, humidity and ice were initially found to cause mechanical blocking along the conveyors. Nowadays, by use of specific materials and appropriate controls of the feeding system, this problem vanished. Several tons of material can be stored in the area.

1.4.2. The feeding system

The feeding system has been designed for a rate of 4 tons per hour. Initially, the rough surface of the drop feed, made of refractory, involved too much friction. Suddenly, clusters of bark accumulated in the drop feed were inappropriately falling in the bed. A defluidization was occurring followed by several local hot spots in the bed. There was a high potential for eutectic formation. The refractory has been replaced to solve the problem.

1.4.3. The boiler

The Falmec boiler (B.F.I) was originally designed for a fixed grid (water tubes type). The main design limitation was then the size of the combustion chamber itself which limited the width of the fluidized bed. The overall area of the bed, *A*, was hence predetermined (2,3m x 2 m) and thus the imposed the minimal fluidization velocity (which also depends upon the particles size): U_{mf} =1,5 m/s. The primary fan delivers 75 kW with a pressure of 1,27 m CE (or 0,12 bars) during normal operation. This pressure allows for the circulation of the air through the sand bed. The secondary fan as a power of 30 kW with a pressure of 0,38 m CE (or 0,04 bars).

1.5. Start-up and control specifications

1.5.1. Start up

As mentioned earlier, during the start-up, the bed is preheated with an auxiliary burner then the biomass is fed-in. The crucial steps of this initialization process are: (1) verification of the minimal sand thickness of height; (2) start of the primary fan (to initiated fluidization); (3) start of the auxiliary burner; (4) heating of the sand until auto-ignition temperature (about

700°C); (5) low speed feeding; (6) progressive increase of the biomass flow rate to reach the appropriate average temperature of 850°C.

In the proposed boiler, the main difficulty with the auxiliary burner is that it is located above the bed and this causes poor heat transfer to the bed (between the flame and the sand). Afterwards, we realized that, due to its position, the auxiliary burner was undersized slightly. Moreover, the fluidization (process) air should have been heated to shorten the start-up procedure. One way to enhance the start-up process was to add oil (on a temporary basis) in attempts to improve it. Since then, we rely on drier bark at the beginning.

1.5.2. Controls

The control of a steam generator is largely documented [5,6] while that of fluidized beds is also quite documented [7, 8]. Start-up procedures are also documented [2]. The main parameters to control are the flow rates of the two fans, the stability of the combustion, and the bed temperature, with emphasis on the latter. An increase of the mass flow rate of fluidization air increases the temperature (increase in the combustion rate, internal heat release) and inversely [9, 1]. This indicates that the combustion takes place partly within the bed and partly above the bed (appearance of flames above the bed) in the combustion chamber. Several methods allowing for the control of the fluidization regime with primary air and bed temperature measurements could be carried-out but these methods have not been considered in our installation. It is the variation of the bark or wood chunks humidity, needed at about 50%, which was found to require a rigorous control and measurement here.

The system was started during winter 2009 and a data acquisition system permitted the continuous recording of the most important variables: (1) three thermocouples immersed in the bed; (2) the fan speed (primary, secondary, exhaust); (3) percentage of oxygen in the combustion products; (4) steam pressure. In this study, the fluidization regime was said to be in steady state when the three thermocouples showed similar temperatures (Fig.3 and 4).

2. The fluidized bed design and method

2.1. The pressure drop and critical velocity

The fluidization velocity is a basic parameter but its evaluation is rather complicated. Several correlations based on the pressure drop across the bed are available and this pressure drop varies linearly or nearly linearly with the fluidization velocity. In the case of a turbulent flow, Ergun [10] proposed the following expression:

$$\frac{-\Delta P}{H} = 150\frac{(1-\varepsilon)^2}{\varepsilon^3}\frac{\mu U_g}{D^2} + 1.75\frac{(1-\varepsilon)}{\varepsilon^3}\frac{\rho_g {U_g}^2}{D} \tag{1}$$

In the fluidization regime, the pressure drop in the bed corresponds to the weight of the particles minus the Archimedes force divided by the surface area of the bed. Since the solid volume is H x A x (1-ε), this yields:

$$-\Delta P = \frac{HA(1-\varepsilon)(\rho_p - \rho_g)g}{A} \tag{2}$$

It is possible to obtain the minimal fluidization velocity when the pressure drop, eq. 2. is inserted into eq.1, yielding:

$$(1-\varepsilon)(\rho_p-\rho_g)g = 150\frac{(1-\varepsilon)^2}{\varepsilon^3}\frac{\mu U_g}{D^2}+1.75\frac{(1-\varepsilon)}{\varepsilon^3}\frac{\rho_g U_g{}^2}{D} \tag{3}$$

Introducing the relevant Archimedes and Reynolds numbers gives:

$$\mathrm{Ar} = 150\frac{(1-\varepsilon)}{\varepsilon^3}\mathrm{Re}_{mf}+1.75\frac{1}{\varepsilon^3}\mathrm{Re}_{mf}{}^2 \tag{4}$$

Several researchers tried to correlate their results with this expression to evaluate the minimal fluidization velocity:

$$U_{mf} = \frac{\mu\left[\left(C_1{}^2+C_2 * \mathrm{Ar}\right)^{0.5}-C_1\right]}{D * \rho_g} \tag{5}$$

where C_1= 27.2 and C_2= 0.0408 according the results of Grace [11].

2.2. *Heat transfer and energy balance*

First, the heat transfer characteristic into the fluidized bed
The predominant parameters which influence the heat transfer coefficient are the fluidization velocity, the particle size and the temperature. The Nusselt number for a fixed object immersed in a particle bed was correlated by several researchers. For particle size lower than one millimeter, the refined correlation proposed by Baskakov [12] was used:

$$\mathrm{Nu} = 0.85\mathrm{Ar}^{0.19}+0.006\mathrm{Ar}^{0.5}\,\mathrm{Pr}\,0.33+\frac{h_r D}{\lambda_g} \tag{6}$$

This equation stands for an Archimedes number ranging between 10^2 and 10^9 and involves the radiative component of heat transfer calculated with respect to the bed and wall temperatures.
The overall energy balance was established to ensure that the existing boiler combined with the fluidized bed could reach the expected parameters (flow, temperature, pressure). A code was developed based on the temperature of the bed for overall balance calculations. The heat transfer by convection, radiation, and conduction was taken into account. This code permits to show that the combustible moisture level of 50% should be respected to ensure a proper operation in term of bed temperature.

2.3. *The nozzles design*

The Ergun software [13] has been used to design the bed. The software allows to obtain the suitable air velocities as a function of the fluidization regime, the temperature, the particle size, the height of the bed, and the heat transfer. It enables one to account for pressure drops and homogenization of fluidization. Although not straightforward to use, Ergun permits to correlate the number of holes in the nozzle, the diameter, the minimal fluidization velocity, and the exit nozzle velocity. Whereas several installations may use a perforated plate at the bottom, our combustion calls for a continuous ashes recovery. Hence, fluidization nozzles where used.

Fifteen different nozzles where designed, built, and investigated (two of them are shown in Fig.2a). All were satisfying the design constraints and criteria. The one respecting the minimum pressure drop required to ensure a stable and homogeneous fluidization was ultimately selected. The tests were then carried out in the lab without combustion in a cylindrical sand bed (Fig. 2b).

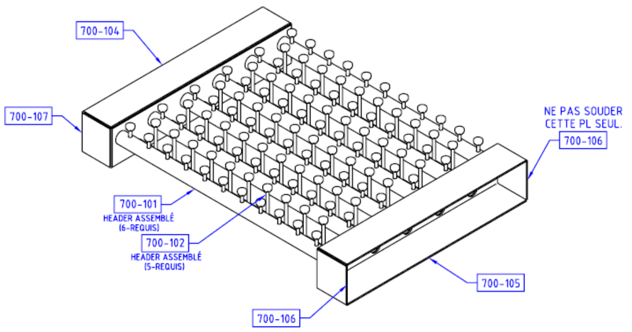
(a)

(b)

Fig. 2: (a) Two of the eight nozzles that were simulated. (b) The laboratory test bench.

Four different sizes of sand particles, ranging from 1 to 2mm, 0.841 to 1mm, 0.500 to 1mm, and 250 to 500µm were tested. Mixing was also carried out with bark samples of about 1 cm by 2 cm. We found that the bark size did not matter and that the mixing was occurring only in the upper level of the bed, close to the surface. It is however important to note that the cold tests were quite different than the flowing full-scale results.

Finally, a bed involving 130 nozzles (Fig. 3) with 6 equally distributed holes (10 mm) was selected. The intake has a 23.37 mm I.D. The pressure loss is 5kPa when the flow rate is maximum. This flow rate varies from 0.0185 m³/mn at 20ºC. 300 mm of sand was found to be the lowest limit for an homogeneous distribution of air while 600 mm was identified as the upper limit to avoid the over sizing of the fan.



(a)

(b)

Fig. 3: The fluidized bed: (a) Full scale model; (b) Actual bed with uncovered heads.

3. Results

Several preliminary tests (not reported here) were needed to fine-tune the operations at the beginning. We worked until uniform temperatures were obtained, thus obtaining a suitable fluidization regime. We also found out that the content of oxygen remained constant with the temperature increase which in turn was proportional to an increase in the mass flow rate of combustible. We noticed that the biomass (fir bark) involved sand that progressively increased the level of the bed (after 10-12 hours of operations) which had to be lowered (by a simple control of the sand circulation). Our first series of tests showed a temperature variation between 730°C and 838°C. The content in oxygen varied from 1% to 13%. A high content (near 21%) indicates that the combustion is almost completed while à low content shows that there is a high combustion.

Fig. 4 presents two test cases at two different temperatures and same pressure levels. Temperature and boiler pressure are indicated on the left axis (0-1000 range) while the oxygen content and the fan speed is reported in % on the right axis (0-100% range). The abscissa is time in hours.

Fig.4a shows, over a period of about one hour, that the control system maintains the steam pressure (represented by ×) constant at about 350 PSI (the set-point). Indeed, the pressure varied between 320 and 356 PSI (± 9%). In Fig. 4, decreases in the pressure occur with increases in the primary fan velocity (represented by ✳). This corresponds to a simultaneous increase in combustion as the content in oxygen (left axis, represented by Δ) decreases. This content is always below 16%, which is excellent. The temperature here varied from 650ºC to 785ºC.

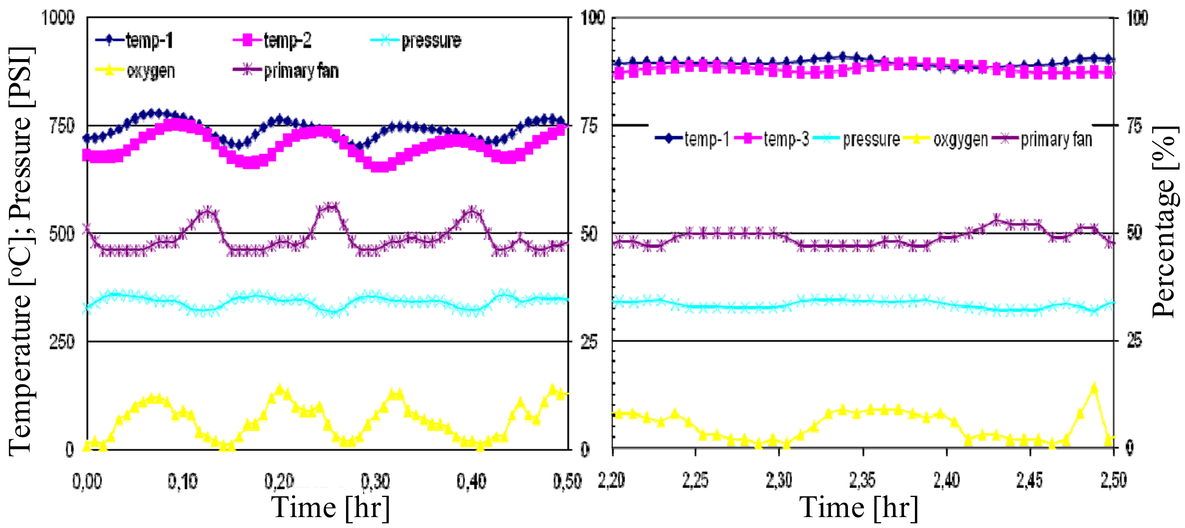


Fig. 4: Temperature, pressure, oxygen content and primary fan power as functions of time: (a) lower regime; (b) higher regime.

Fig. 4b illustrates, over a period of about one quarter of an hour, that the control system maintains the steam pressure constant at about 340 PSI (± 7%): A more stable regime is shown. In Fig. 4b, the trends are similar to those reported in its twin but the regime is higher with temperature ranging between 865ºC and 915ºC. This indicates a higher combustion regime also shown by a lower content in oxygen for the period. The temperature is also more homogeneous in this test case as the control loop improved with time and experience with the boiler.

An interesting feature of the installation is that the pressure settings remained constant during the test showing no need for manual adjustments after the tuning of controls.

4. Conclusion

A bubbling fluidized bed for the combustion of moist wood residues has been designed for an existing steam generator originally involving a fixed grid. The objective was to allow this generator to accept combustibles with a high level of humidity with no compromise over performance. This paper first presented the complete installation and insisted on a few design parameters and issues that pertain to the bed nozzles and lay-out. The format of the paper cannot permit to provide all relevant details.

When applied to the combustion of forest residues, the key aspects to address were found to be the proper size and humidity of the feed stock. And here, not only on an average basis: a homogeneous mixture ensures a stable process which avoids the generation of local hot spots that could provoke eutectics (agglomerates) and force the shut-down.

The positive points:

- The flexibility in terms of steam demand;
- The combustion efficiency (up to 99%);
- The low maintenance (changes of the sand) requirements.

The need for improvements:

- The design calls for a deep knowledge of fluidization which is not the case with other (simpler) technologies such as fixed grid boilers;
- The acceptance of a wider range of humidity variation of the feed stock;
- The training of the personnel.

The BFBC is nevertheless an excellent solution to burn humid residuals and recover the energy because of its flexibility, its efficiency, and its cleanness.

References

[1] S.N. Oka, Fluidized Bed Combustion, Marcel Dekker, Inc., New York 2004.

[2] P. Basu, Combustion and Gasification in Fluidized Bed, CRC Press, 2006.

[3] A. Delebarre, J-M. Morales, L. Ramos, Influence of the bed mass on its fluidization characteristics, Chemical Enginnering Journal, 98, 2004, pp.81-88

[4] A. Hepbsali, Estimation of bed expansion in a freely-bubbling three dimensional gas-fluidized bed, Int. J. Energy Res., 22, 1998, pp.1365-1380

[5] G.F. Gilman, Boiler Control Systems Engineering, 2005

[6] Stulz et Kitto, Steam-its generation and use, Babcock and Wilcox, 40th edition, 1992, pp.16-17

[7] D. Geldart, Gas fluidization technology, Ed. John Wiley & sons, 1986

[8] A.J Croxford, M.A. Gliberston, Control of the state of a bubbling fluidized bed, Chemical Engineering Science. 61, 2006, pp.6302-6315

[9] D.L. Kraft, Bubbling Fluid Boiler Emissions Firing Bark & Sludge, TAPPI Engineering Conference, 1998.

[10] S. Ergun, Fluid flow through packed columns, Chem. Eng. Prog, 48. 1952, pp.89-94

[11] J. R. Grace, Fluidized bed hydrodynamics, In Handbook of Multiphase Systems, Hestroni, G., Ed., Hemisphere, Washington, DC, chap.8.1, 1982

[12] A. P. Baskakov et al., Heat transfer to objects immersed in fluidized beds, powder technol.8, 1973, pp.273-282

[13] Khali Shakourzadeh, Ergun software – Instruction manual, University of Compiegne (UTC), Paris, France.