Agglomeration Detection in Circulating Fluidized Bed Boilers using Refuse Derived Fuels

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Abstract

The formation of agglomerates in a refuse derived fuel (RDF) fired circulating fluidized bed (CFB) boiler has been investigated by implementing a dynamic model of the combustion process. The nature of refuse derived fuel, which is complex in composition, leads to an increased tendency for agglomerate formation. Notwithstanding the fact that a robust control scheme is essential in preventing the decrease in boiler efficiency from accelerated agglomerate formation. Therefore, a mechanism for detecting agglomeration through a physical model by looking at the minimum fluidization is presented. As agglomerates form between the fuel ash and bed sand the average diameter of the sand will increase and therefore the minimum fluidization velocity. Samples of bed material have been sieved and measured from a 160 MW circulating fluidized bed boiler fired with refuse derived fuel to determine bed material size distribution. The findings have been correlated and match an increase in the minimum fluidization velocity during a seven day sampling period where the bed material size distribution increases above the average sand diameter.

Keywords: circulating fluidized bed, agglomeration, detection, RDF

1 Introduction

The role of waste management in the 21st century is essential in maintaining the excessive amount of waste produced each year in the world. Most developed countries have modern routines and guidelines for dealing with municipal solid waste (MSW) by sorting out recyclable, toxic, and organic materials. Some of these countries are utilizing MSW for producing refuse derived fuels (RDFs). These are used in waste incinerators for the purpose of producing heat and power. When compared to other alternatives, such as land-filling, waste incineration is more reliable and environmentally friendlier (Hernandez-Atonal et al., 2007).

Due to the complex nature of RDF, a viable option for thermal waste treatment is to use them as a source of fuel in circulating fluidized bed (CFB) boilers to produce heat and power, simultaneously solving waste and energy issues. CFB boilers are unique in design and allow for a high degree in fuel flexibility, high combustion efficiency, lower emissions, and relatively fast response to load change (Basu and Fraser, 2015; Hernandez-Atonal et al., 2007; Gungor, 2009), and therefore can handle the complexities of RDF.

Typically, CFBs operate at a combustion temperature between 750 °C and 900 °C and use sand to fluidize the bed material. However, a large portion of the combustible material in RDF contain high levels of alkali and chlorine compounds, which both have low melting and low vaporization temperatures (Pettersson et al., 2013), and can react with the fluidizied sand to form low melting eutectics. It is crucial to maintain the operating temperature within limits. Else there is a significant risk of sand-ash reactions which can lead to agglomeration, slagging, and in the worse case scenario complete defluidization. The variability of RDF's composition, and therefore heating value, can lead to the temperature deviating above the boiler's limits for short periods, in the form of hot zones. The latter can increase the propensity of agglomerate formation either through ash melting or the ash coating of sand. Once agglomerates form they reduce the boiler's efficiency because the fluidized median is hindered and requires increasingly more air to properly combust the incoming fuel.

A dynamic model of an RDF fired CFB has been modeled after a 160 MW industrial installation. Bed samples for a one week period have been taken and analyzed for any increase in the bed material particle diameter. The model has proven to be capable of detecting agglomerate formation off-line, showing an increase in the minimum fluidization during a period of time when there was a corresponding significant increase in particle diameter.

2 Literature Review

2.1 Circulating Fluidized Bed Boilers

The schematic illustrated in Figure 1 is that of a CFB. Its a type of boiler that uses sand as the fluidizing median, where a degree of solid reflux is achieved allowing for a more uniform temperature throughout the boiler. Major advantages include stable combustion at low temperatures (750-900°C), uniform temperature distribution, large solid-gas exchange area, ability to handle problematic fuels with a large variability in size, moisture content,
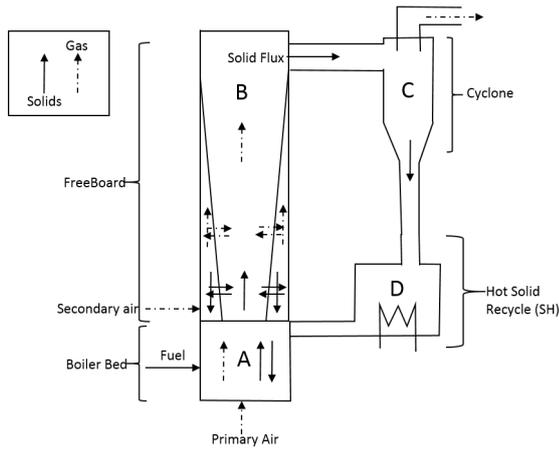
Figure 1. Circulating Fluidized Bed Boiler.

and heating value. They are capable of high heat transfer coefficients between bed and heat exchanger surfaces (Werther, 2007; Scala and Chirone, 2004).

When the fuel enters the boiler it begins to heat, where water is evaporated, volatiles begin to be released through devolatilization, ignition begins, and fragments begin to form. During this process more char becomes available for combustion. Primary air enters the bed of the boiler and entrains the sand and fuel. Above the bed is the freeboard, where secondary air is injected to allow for a higher combustion efficiency and it has been shown to reduce CO concentrations (Hernandez-Atonal et al., 2007). At the top of the boiler the flue gas along with a net solid flux of solids are carried to the cyclone which allows for the flue gas to be utilized in the convective section and separates fly ash from hot solids (sand and ash). The hot solids then pass through a heat exchanger to utilize their high enthalpy content, and then the cooled solids which contain unburnt char are recirculated back into the bed via the loop seal to be fully combusted.

2.2 Characteristics of RDF

RDF is a byproduct of home and industrial waste, but before it can be fired it needs to be sorted and treated. The waste comes into the sorting facility were it is first chopped and shredded into credit card size pieces. Metals are removed by using high power magnets and the remaining mixture passes over a large wind-sifter, which allows for heavier objects such as glass and ceramics to dropout of the mixture. The separated items are sent to recycling, where what is left can be classified as RDF, and is ready for transport into the boiler.

We can characterize what remains in the fuel as either biomass-based (climate neutral) or fossil-based, where the fossil-based constituents are typically plastics and textiles. Due to the sorting process, determining the proportions of biomass vs. fossil based portions through manual sorting is impractical. There are three established methods for determining the biomass-based portion, and therefore the fossil based portions of RDF: The Selective Dissolution

Method, The Balance Method, and the The ^{14}C-Method (Staber et al., 2008). The downside is that these methods are impractical for real-time applications.

2.3 Agglomeration

The development of agglomerates, the binding of bed particles, is highly dependent upon the characteristics of the fuel's ash content, particle-to-particle interactions and the hydrodynamics in the boiler. As the bed material is fluidized ash can melt and bridge bed material together, as illustrated in Figure 2a. Alternatively, ash can lead to a buildup on bed material and create a sticky coating, as illustrated in Figure 2b, which causes more particles to stick together. Therefore, the likelihood of agglomeration formation is dependent upon ash characteristics and has been the topic in many studies looking at biomass and waste fuels (Elled et al., 2013; Lin et al., 2003; Scala and Chirone, 2008; Bajamundi et al., 2015; Ryabov et al., 2003). Proper fluidization is also needed to inhibit the likelihood of agglomeration. If particle mobility and mixing are below optimal it will not only cause a reduction in heat and mass transfer of the bed material (Liu et al., 2012), but the viscous materials can bond together and can lead to permanent bonds depending upon the residence time.

In a study by (Lindberg et al., 2013) they stated that the predominant ash forming elements are K, Na, Ca, Mg, Fe, Al, Si, P, S, Cl, C, H, and O. The main ash characteristics that can lead to agglomeration come from Na and K, alkali metals. When agglomerates form they disrupt the dynamics in the boiler and if the temperature exceeds the melting temperature of the particles for too long the sticky outer layer of bed material can form permanent bonds (sintering), which can lead to slagging or in worst case scenarios complete defluidization. In a study by (Chirone et al., 2006) they report that bed agglomerates begin to form near burning char because of the higher temperatures and this increases the formation of melt, or the particles stickiness. This is especially problematic because it can lead to the formation of eutectics and the escalation of adhesive forces during sintering. Eutectics formed can have melting points as low as 401 $°C$ and 552 $°C$ for $Na_2S_2O_7$ and $Na_3K_2Fe_2(SO_4)_6$ respectively (Dunnu et al., 2010).

(a) Agglomeration from ash melting.

(b) Agglomeration from ash coating.
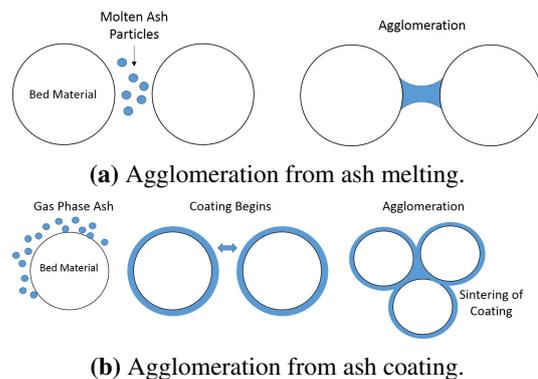
Figure 2. Prominent modes of Agglomeration.

Agglomerates are a common occurrence in fluidized beds, but a well controlled boiler can control the fluidization velocity or temperature well enough to break these clusters apart before sintering takes place. Presented in (Skrifvars et al., 1994; Yan et al., 2003), they discuss how the oxygen concentration in the boiler is linked to the risk of sintering, where regions of higher oxygen content can lead to hot spots. Two mechanisms, flue gas recirculation and air flow, can be used to prevent the likelihood of hot spots. Flue gas recirculation into the boiler bed will help in reducing the oxygen content as well as bed temperature. Maintaining a consistent air flow rate, depending upon the quality of the fuel, for fluidizing the bed material can also help in facilitating a well mixed combustion median in order to reduce hot spots.

A wide range of methods for agglomeration detection, when fired with biomass, have been compared and can be grouped into three categories: on-line detection, experimental methods (controlled agglomeration tests), and theoretical evaluations (fuel ash analysis), (Gatternig, 2015). The last two methods seem reasonable when considering a fuel that is relatively homogeneous, but RDF is a complex and difficult fuel to model and predict melting points, and ash composition because of its composition variability. In most industrial fluidized bed boilers it is routine to take random fuel samples to check for composition consistency. These samples could be used in agglomeration indexes (Visser, 2004; Vamvuka et al., 2008) that look at, among other elements, Na and K in the fuel to determine the likelihood of agglomerate formation. However, this approach assumes that the fuel characteristics will remain the same year after year, but in reality RDF composition is based on the consumers and such an assumption is unrealistic. Also, this method only considers a fraction of the predictability of agglomeration by looking at fuel composition and neglects fuel-ash-bed material interactions, and therefore can give a bit of insight into agglomeration tendencies and should be used cautiously. Another method for agglomeration detection is through advanced multi-component/multiphase thermodynamic modeling (Lindberg et al., 2013), but there is currently a lack of comprehensive thermodynamic databases for ash compounds and the phases formed during combustion.

Therefore, online detection is the most suitable way to predict agglomeration when RDF is used. Current methods used for the early detection of agglomeration have been explored by looking at pressure drops and temperature fluctuations. However, at this point, the probability of defluidization is already prevalent and leaves no options for the operator but to shutdown the plant, and is not a suitable form of early detection. An alternative method, suitable for early detection, of agglomerates on a small-scale in fluidized beds has been proposed by (Nijenhuis et al., 2007). They were able to develop an early agglomeration recognition system that detects very small changes in hydrodynamic multiphase systems, and allow detection of agglomeration up to 60 minutes before occurring.

The method proposed by the authors in this paper for the detection of agglomerates is based on the minimum fluidization needed to fluidize the bed material. As the diameter of the bed material increases so will the amount of air need to fluidized the bed material in order to operate the boiler within the proper temperature limits. Hence modeling the minimum fluidization can be used in early warning detection of minimal to extreme agglomerate formation.

3 Methodology

The dynamic model used has been calibrated and validated using data from a RDF fired CFB, boiler 6, at MälarEnergi, in Västerås, Sweden. It was possible to back calculate the mass flow rate of fuel by conducting a heat balance on the boiler's heat exchangers. By this method it was determined that 16.8 kg/s of RDF are fed into the boiler, taking the thermal efficiency of the boiler into consideration, this corresponds to MälarEnergi's reported value of 30 tonne/hour. The model is designed to allow for the real input of primary air, secondary air, and flue gas recirculate mass flows and corresponding temperatures. It is assumed that the mass flow rate of the fuel and its respective LHV are constant.

3.1 Description of Model

A model has been designed in DYMOLA using Modelica programming language. The reason for having a dynamic model is to be able to capture the transient behavior of RDF through the combustion process. With the end goal of being able to have a model that has the ability to not only monitor agglomeration, but to also be used for emissions tracking, decision support, and fault detection. The Modelica modeling language allows users to build model libraries with ability to reuse component blocks and to easily change parameters to match any complex dynamic system.

Individual component blocks were made for the CFB-loop, also represented in Figure 1, for the boiler bed, free-board, cyclone, and hot cycle recirculate (super heater (SH)) respectively. Multiple functions have been been written in order to accurately represent the thermodynamic properties for all in-coming streams, bottom and fly ash, bed material,and flue gas.

3.2 Mass and Energy Balances

The model is based on mass and energy balances (equations 1 and 2) used for the freeboard and bed of the boiler, cyclone, and superheater following that of a similar approach to that presented in (Basu and Fraser, 2015; Gungor, 2009). Where i represents the control volume in the CFB-loop (A, B, C, D) in Figure 1, m is the mass, H is the enthalpy, α is the percentage of combustion, and $\dot{Q}$ is the heat released during combustion.

$$\frac{d(m_i)}{dt} = \Sigma \dot{m}_{in,i} - \Sigma \dot{m}_{out,i} \qquad (1)$$

$$\frac{d(m_i H_i)}{dt} = \dot{m}_{in,i} H_{in,i} - \dot{m}_{out,i} H_{in,i} + \alpha \dot{Q}_{released,i} \qquad (2)$$

It was possible to calculate the enthalpies of all constituent parts in the energy balance, equation 3, where T_i is the temperature in the control volume and T_{ref} is reference temperature taken at 289.15K.

$$\frac{d(H_i)}{dt} = Cp_i (T_i - T_{ref}) \qquad (3)$$

The fuel composition and flow rate is constantly changing, and in turn so is the boiler bed and flue gas temperature, so a series of functions have been developed to calculate the specific heat for each element in the control volume in the energy balance. In this way, instead of assuming constant values, the model has the capability of more accurately simulating temperature profiles for the bed and freeboard of the boiler. The function developed for calculating the specific heat (Cp) of the gas follows the practices of (Wester, 1987), equation 4.

$$Cp = \frac{1}{T - T_{ref}} \int_{T_{ref}}^{T} \sum_{n=-1}^{n=7} a_c^n \left(\frac{T}{1000} \right)^n \qquad (4)$$

The coefficients for a_c^n represent air, N_2, O_2, CO_2, and water vapor. The gas thermophysical properties and composition were calculated by using flue gas stoichiometric calculations. The flue gas composition is found to primarily be comprised of CO_2, H_2O, O_2, and N_2. Where the model uses the ultimate analysis of the fuel as input, calculates the amount of excess air in the system, and then the flue gas composition can be used to calculate the specific heat, equation 5, as well as viscosity and density at the operating temperature.

$$Cp_{gas} = [N_2] Cp_{N_2} + [O_2] Cp_{O_2} \\ + [CO_2] Cp_{CO_2} + [H_2O] Cp_{H_2O} \qquad (5)$$

The solids contained within each control volume consist of fuel, sand, ash, and char, as shown in equation 6. Where α, β, γ, and δ represent the percentage of fuel, sand, ash, and char respectively that are in the control volume i.

$$Cp_{solids,i} = \alpha \cdot C_{p,fuel} + \beta \cdot C_{p,sand} + \gamma \cdot C_{p,ash} + \delta \cdot C_{p,char} \qquad (6)$$

The functions for fly and bottom ash were developed by using chemical compositions found in (Chang et al., 1997). Where they analyzed the chemical composition and determined the compounds and corresponding percent composition of ash, and found that CaO, SiO_2, Al_2O_3, Fe_2O_3, ZnO, MgO, Cr_2O_3 were the major components (in decreasing order). Specific heat correlations for the compounds were developed from (Abu-Eishah et al., 2004; Karditsas and Baptiste, 1995; Madelung et al., 1999),

therefore temperature dependent ash specific heat values could be estimated, equation 7.

$$C_{p,ash,i} = \Sigma \left(\xi_j \cdot C_{p,j} \right) \qquad (7)$$

where i represents either fly or bottom ash, ξ is the compound percentage in the ash, and j is the compound. With the calculation of Cp_{gases} and Cp_{solids} and corresponding mass flows equations 2 and 3 can be used to determine the boiler temperature.

3.3 Hydrodynamics

CFBs operate at a higher gas velocity and therefore the gas and solids within the boiler act like a fluid. In the bed of a CFB boiler there is a dense emulsion phase, where the gas moves through the inventory as large bubbles. At the top of the bed, where the secondary air input is, the bubbles burst dispersing inventory and unburnt char into the freeboard. The addition of this secondary air, theoretically, allows for a dilute well-mixed phase throughout the freeboard. The freeboard is typically further segregated into a core and annulus. The core is where the gas and solids flow upward, fine particles are carried out of the bed, and coarser particles tend to form clusters and then fall back down in the annulus region as a thin film, where the further up in the freeboard the smaller the annulus region becomes, as shown in Figure 1.

The minimum amount of air velocity required to fluidized the bed material is called the minimum fluidization velocity u_{mf} and is the velocity at which the drag of the fluidized median (sand) is equal to the weight of the bed material. Following the method used in (Kunii and Levenspiel, 2013) the minimum fluidization can be determined, equation 8.

$$\frac{1.75}{\varepsilon_{mf}^3 \phi} \cdot \left(\frac{d_p U_{mf} \rho_g}{\mu_g} \right)^2 + \frac{150(1 - \varepsilon_{mf})}{\varepsilon_{mf}^3 \phi^2} \cdot \frac{d_p U_{mf} \rho_g}{\mu g} = \\ \frac{d_p^3 \rho_g (\rho_p - \rho_g) g}{\mu_g^2} \qquad (8)$$

Where ε_{mf} is the void fraction at minimum fluidizing conditions, ϕ is the sphericity of the sand, d_p is the average diameter of sand particles, ρ is either the density of the fluidizing median or sand, μ_g is the viscosity of the fluidizing median, and g is gravity.

As the amount of air is increased into the boiler the minimum fluidazation velocity of the gas will reach the superficial velocity (U_s) and is affected by the amount of gas, density and size in a given control area. Typically values for industrial CFBs is in the range of 5-10 m/s, (Basu and Fraser, 2015). This velocity carries bed material, ash, and unburnt char up into the freeboard, where a portion of these circulate within the boiler but there is also a net solid flux, G_s that leaves the boiler to be recirculated back through the loop-seal. Where G_s is equal to the amount

of solids going up in the boiler minus the solids circulating within the boiler. A correlation between G_s and operational conditions was presented by (Guan et al., 2010), equation 9, where G_s is in the rang of 200 and 400 kg/m^2, which is within the operating limits of the designed CFB.

$$\frac{G_s d_p}{\mu_g} = 547 Ar^{0.248} \left(\frac{U_s}{\sqrt{gD}}\right)^{0.375} \left(\frac{D}{H}\right)^{0.195} \quad (9)$$

Where Ar is Archimedes number, D is the diameter of the freeboard, and H is the height of the freeboard.

4 Results and Discussion

4.1 Validation

The model has been constructed to predict the performance of a 160 MW CFB boiler. The model has been designed to predict the bed and flue gas temperatures. The validity of the model has been determined by comparing data from boiler 6 at MälarEnergi. Figure 3 illustrates a simulation, for a week, of the flue gas temperature as it exits to the cyclone. The accuracy of the model is quite good initially, less than a few percent. However, it can be seen that when there is sudden increase or decrease the model tends to underestimate, or overestimate, the respective temperature. Since the model is currently designed using a constant fuel mass flow rate and heating value it is reasonable to believe that this is attributing to the deviation in the predicted temperature. The model's profile is able to follow that of the actual profile, but if the quality of the fuel coming into the boiler is poor this would be reflected in a substantial drop in the temperature profile.

4.2 Agglomerate Prediction

There is a lot in the literature about methods used to predict CFB failure from agglomeration, but typically these do not take into account the impact of the combustion environment (Yan et al., 2003) like gas to particle interactions and alkali vapor condensing.

Agglomeration prediction has been studied to a lengthy extent where fossil and biomass fuels are concerned. The standard procedure in industry for predicting agglomeration is determined from pressure drops and temperature changes (Gatternig, 2015), but it has already been mentioned that this is not suitable for early detection. For early detection, using plant process parameters, it is possible to detect agglomeration by looking at the minimum fluidization velocity, where a small increase shows that the diameter of the circulating bed material is increasing.
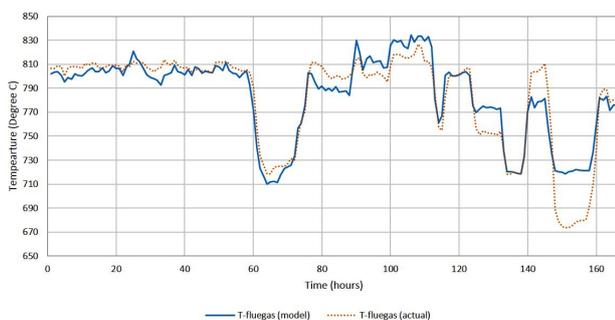
This is because with the onset of agglomerates and then sintering, the minimum fluidization required to fluidized the bed material will slowly increase. Therefore, agglomeration can be monitored by modeling process parameters, while operators can still keep an eye on pressure drops in the boiler bed and temperature fluctuations.

As mentioned the composition of RDF can vary from hour to hour. However, the composition of sand, with an average diameter in the range of $0.40 < d_p < 0.63$, is known and as agglomerates form this will require a higher minimum fluidization. Figure 4 confirms the presence of a relationship between the bed particle size increasing and the required increase in the minimum fluidization. Where the bed material size distribution was obtained from Mälarenergi, daily average, and the minimum fluidization is the model's prediction, taken on a daily average. This method allows for the detection of a a small change in the bed material average diameter with a suitable amount of time for the operator to make the decision to add fresh sand to the boiler before there is a subsequent formation of further agglomeration, slagging, or possibly complete defluidization.

Figure 5 illustrates the main elemental composition in g/kg TS of the bed material samples over the week in question. Because the ash melts are coating the sand particles it is reasonable that the main composition comes from silica, with an average value of 301 g/kg TS. However, a portion of the silica could come from glass fines in the fuel mix, but this value is unknown. It should also be noted that all of these elements, as stated before, are predominant ash forming elements. Therefore, it can be quantified that the agglomeration of the sand has occurred due to either ash melting or ash coating.

Figure 3. Temperature profile of the fluegas during the study period.
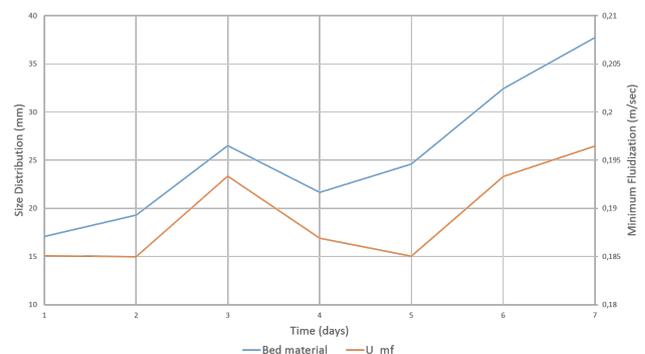
Figure 4. Bed Material Size Distribution $0.4 < d_p < 0.63$ mm Correlates to the Minimum Fluidization.
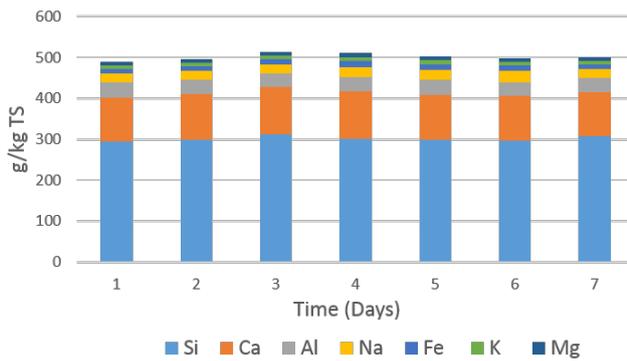
Figure 5. Primary elemental composition of the bed material during the study period.

5 Conclusions

The model presented shows the ability to determine the agglomeration of bed material while off-line. This has been accomplished by building a dynamic model using process parameters as input to model and calculate the minimum fluidization velocity required to maintain a boiler operating temperature within the range of 750 °C and 900 °C. It should be noted that during the seven days there were periods where the fluegas temperature dropped below 750 °C and can be attributed to the possibility of poor fuel. The simulated results show that an increase in minimum fluidization velocity corresponds to an increase in bed material share that is greater than the average diameter of the sand used, $0.40 < d_p < 0.63$. Since agglomeration is prevalent no mater what the fuel source is, it is possible to implement this model as a means for real-time detection of agglomerate formation as a means for decision support to operators.

Compared to other CFB models. The library developed in this study can potentially be reused for any CFB installation through the ease of the drag-and-drop nature of object-oriented programming. The model presented has the ability to handle the transient behavior of RDF, not only for modeling agglomeration, but to also capture the dynamics of the temperature fluctuation in the boiler, hence the possibility for real-time emissions monitoring. Decision support and fault detection can also be implemented by formulating a probabilistic distribution through Bayesian nets. Only one model is needed to monitor multiple aspects of the combustion process in CFBs.

Acknowledgment

Nomenclature

Acronyms

CFB	circulating fluidized bed
RDF	Refuse derived fuel

Greek Symbols

ε_{mf}	Void fraction at minimum fluidization
μ	Viscosity, $\frac{kg}{ms}$
ϕ	Sphericity
ρ	density, $\frac{kg}{m^3}$

Roman Symbols

Ar	Archimedes number, $\frac{\rho_p(\rho_p-\rho_g)g d_p^3}{\mu^2}$
Cp	Specific heat, $\frac{kJ}{kgK}$
d_p	Particle diameter, m
g	Gravity, $\frac{m}{s^2}$
G_s	Net solid flux, $\frac{kg}{m_s^2}$
H	Enthalpy, $\frac{kJ}{kg}$
h	Height of the freeboard, m
m	mass, kg
Q	Heat released, KW
T	Temperature, K
U_{mf}	Minimum fluidization velocity, $\frac{m}{s}$
U_s	Superficial Velocity, $\frac{m}{s}$

Subscripts

g	Gas
i	Corresponding control volume
p	Particle
ref	Reference temperature, ambient

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