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NUMERICAL SIMULATION OF BIOMASS COMBUSTION EFFICIENCY IN CIRCULATING FLUIDIZED BEDS

Afsin Gungor
Nigde University, Faculty of Engineering and Architecture
Department of Mechanical Engineering, 51100 Nigde
Turkey

ABSTRACT
One of the major advantages of circulating fluidized bed (CFB) combustors is their efficiency for the combustion of wide variety of solid fuels. From this point of view, in this study, the combustor efficiency has been defined and investigated for CFB biomass combustor based on the losses using a dynamic 2D model. The model is shown to agree well with the published data. The combustion efficiency of OC changes between 82.25 and 98.66% as the excess air increases from 10 to 116% with the maximum error of about 8.59%. The rice husk combustion efficiency changes between 98.05 and 97.56% as the bed operational velocity increases from 1.2 to 1.5 m/s with the maximum error of about 7.60%.
Keywords: combustion efficiency, emission, biomass combustion, fluidized bed, modeling

1. INTRODUCTION
The circulating fluidized bed (CFB) technology is first used for combustion of coal because of its unique ability to handle low-quality, high-sulphur coals. In forest-rich countries, CFB combustion has increased its market share of biomass combustion during recent years. In particular, biomass fuels provide an increasingly attractive primary energy source, due to their intrinsically renewable nature and potentially limited generation of pollutants. Biomass usually contains negligible sulfur, low nitrogen and heavy metals, and is considered neutral with respect to greenhouse gases. In the recent years, CFB combustion of biomass has received a lot of attention due to its fuel flexibility, high combustion efficiency, high heat transfer, and the potential for low NO_x and SO_2 emissions [1, 2].
Extensive experimental investigation has been carried out to date on the feasibility and performance of different biomass fuels in fluidized bed combustion. Han et al. [3] carried out experiments of cedar pellets combustion in a fluidized bed combustor. They found that the high temperature was improving the combustion efficiency and decrease CO emission, increasing the fluidized velocity suppressed CO formation. Kuprianov and Janvijitsakul [4] reported that the combustion efficiency ranged from 96% to 99.7% for the wood sawdust combustion in a pilot scale fluidized bed combustor. Armesto and Bahillo [5] and Fang and Shi [6] also carried out experiments of rice husk combustion in a bubbling fluidized bed combustor. Combustion efficiencies higher than 97% were achieved. Topal et al. [7] reported that the combustion losses due to hydrocarbons and CO decreases as the excess air increases for the olive cake combustion in a pilot scale CFB combustor.
Mathematical modeling of CFB biomass combustion could improve both their design and operation, reduce any associated problems and facilitate the implantation of this technology. Several review articles summarized the latest development in biomass combustion [8, 9]. Although several different types of models have been developed for CFB biomass combustion systems-kinetic, equilibrium, and other as summarized above, modeling CFB biomass combustion is still at developing stage. From this point of view, in this study, the combustion efficiency of biomass fired CFBs are investigated via previously developed 2D model capable of describing the CFB biomass combustion phenomenon

which integrates and simultaneously predicts the hydrodynamics, heat transfer and combustion aspects. The effects of operational parameters such as bed operational velocity and excess air on combustion efficiency are also investigated by developed model and are also validated with published experimental data in the literature.

2. MODELING

The designing of the CFB is very important because it enables burning biomass with high efficiency and within acceptable levels of gaseous emissions. To simulate and optimize the behavior of a CFB, firstly the mathematical modeling of the hydrodynamic and kinetic characteristics is needed. In the present study, a previously developed 2-D biomass CFB model is used for the simulation [10]. Biomass combustion model calculates the axial and radial distribution of voidage, velocity, particle size distribution, pressure drop, gas emissions and temperature at each time interval for gas and solid phase both for bottom and upper zones.

The main goal of the modeling of CFB combustors is to constitute a system that maximizes combustion efficiency, and minimizes operating and investment costs and air pollutant emissions. The combustion efficiency is calculated considering carbon feed in and carbon losses due to the incomplete combustion which considers both the unburned carbon contained in the riser exit and the losses due to the CO. According to the this assumption the combustion efficiency of CFB combustor can be defined as follows;

$$\eta\ (\%) = \frac{\dot{m}_f X_{c,in} - \dot{m}_{net} X_{c,out} - (\dot{n} y_{CO} / 28)}{\dot{m}_f X_{c,in}} \times 100 \qquad (1)$$

where $\dot{m}_{net}$ is the net mass flow rate discharged from the combustor and $\dot{n}$ is the net gas flow rate discharged from the combustor. The second term in right hand side is the loss due to the unburnt carbon contained in the discharged mass. The third term is the loss due to the unburnt CO in the flue gas.

3. RESULTS AND DISCUSSION

To validate the developed model in terms of combustion efficiency, simulation results are compared with two different size biomass fuel-fired CFB combustors which were published in the literature [13, 30]. In these comparisons, the same input variables are used in the tests as the simulation program input. The effects of operational parameters such as bed operational velocity and excess air on combustion efficiency are also investigated by developed model and are also validated with published experimental data in the literature [7, 11]. Detailed listing of the model input variables are given in Table 1. It must be noted that the model validation is carried out for both industrial and laboratory scale CFBs but combustion efficiency is validated only small scale biomass fuel-fired CFBs due to non-availability of industrial scale biomass fuel-fired CFB combustion efficiency data. For this reason the combustion efficiency analysis is carried out for only available small scale CFBs whereas the model is capable of calculating efficiency for large-scale CFBs as well.

Fig.2a presents the model predictions and experimental results of Topal et al. [7] (bed height: 180 cm, bed diameter: 12.5 cm), showing the effect of excess air on the combustion efficiency. The carbon combustion efficiency increases with increasing excess air as observed in both experimental data and model predictions. This indicates that air staging could improve combustion. An increase of excess air gives an increase in the mean oxygen concentration in the bed. This causes the combustion rate of char to increase by amount of oxygen presence thus increasing the carbon combustion efficiency. If excess air increases further (more than 60%), the combustion efficiency decreases as the combustion losses increase with increasing excess air. Excess air affects combustion efficiency in two ways: one is due to higher heat losses with increasing flue gas flow rates to the ambient. As expected, decreasing the temperature decreases the carbon combustion efficiency due to the decrease in the reaction rates. The other one is bed temperature decreases as the excess air increases and it affects the carbon combustion efficiency due to decrease in the reaction rates and as a result higher carbon content in the mass discharged from the combustor. This phenomenon is also observed in the study of Bhatt [12]. The combustion efficiency changes between 82.25 and 98.66% as the excess air increases from 10 to 116%. The model predictions are in good agreement with the published experimental data. The maximum error observed in combustion efficiency values is about 8.59%.

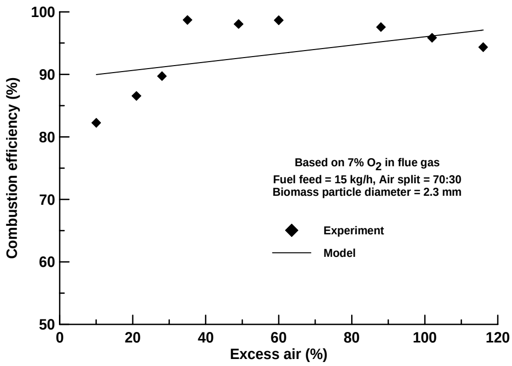

Fig.2a. Comparison of model predictions with Topal et al. [7]'s experimental data with regard to excess air.

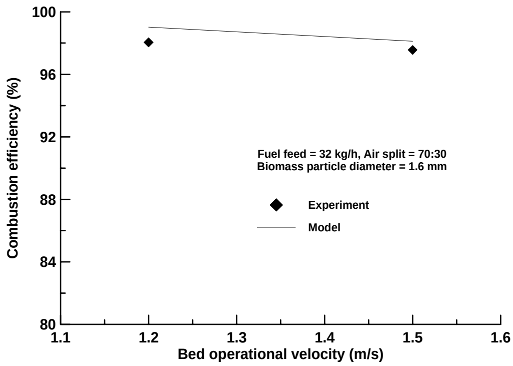

Fig.2b. Comparison of model predictions with Fang et al. [11]'s experimental data with regard to bed operational velocity.

Table 1. Model input variables

Bed diameter (m)	Bed height (m)	Fuel type	Inlet pressure (atm.)	Excess air (%)	Air split	Bed operational velocity (m/s)	Fuel feed rate (kg/h)	Mean fuel particle size (mm)	Mean bed temperature (°C)	Mean bed material particle size (μm)
Topal et al. [7]'s CFB										
0.125	1.8	Olive cake	1.12	10	70:30	1.75	15	2.3	845	71
0.125	1.8	Olive cake	1.12	21	70:30	2.11	15	2.3	845	71
0.125	1.8	Olive cake	1.12	28	70:30	2.24	15	2.3	845	71
0.125	1.8	Olive cake	1.12	35	70:30	2.38	15	2.3	845	71
0.125	1.8	Olive cake	1.12	49	70:30	2.41	15	2.3	845	71
0.125	1.8	Olive cake	1.12	60	70:30	2.50	15	2.3	845	71
0.125	1.8	Olive cake	1.12	88	70:30	2.52	15	2.3	845	71
0.125	1.8	Olive cake	1.12	102	70:30	2.57	15	2.3	845	71
0.125	1.8	Olive cake	1.12	116	70:30	2.61	15	2.3	845	71
Fang et al. [11]'s CFB										
0.2x0.2	6	Rice husk	1.12	25	70:30	1.2	32	1.6	775	71
0.2x0.2	6	Rice husk	1.12	25	70:30	1.5	32	1.6	775	71
0.2x0.2	6	Rice husk	1.12	25	60:40	1.5	32	1.6	775	71

Fig.2b presents the model predictions and experimental results of Fang et al. [11] (bed height: 180 cm, bed cross-section: 20 x 20 cm), showing the effect of excess air on the combustion efficiency. As expected, an increase in the operational bed velocity gives a decrease in carbon combustion efficiency. The reason is that the coal feed increases linearly with operational gas velocity, which tends to reduce the combustion efficiency by increasing the throughput per unit bed area on the system (increases the losses in unburned combustibles). The strong combustion intensity zone moves to the top of the upper zone which is due to the high volatile content of biomass fuels. This causes an increase of the temperature of the bed exit which leads to an increase of the heat losses due to the flue gases to ambient. The combustion efficiency decreases from 98.05 to 97.56% as the bed operational velocity increases from 1.2 to 1.5 m/s. The model predictions are in good agreement with the published experimental data. The maximum error observed in combustion efficiency values is about 7.60%.

4. CONCLUSION

In this study, the combustion efficiency of biomass fired CFBs are investigated. The effects of bed operational velocity and excess air on combustion efficiency are investigated by developed model and are also validated with published experimental data in the literature. As a result of this analysis, it is observed that: The air staging could improve combustion. The carbon combustion efficiency increases with increasing excess air. The bed operational velocity has a reverse effect. These results suggest that biomass fuels can be utilized for effective energy production by using CFBs.

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