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COMBUSTION EFFICIENCY OF A SMALL-SCALE CFB

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ABSTRACT
A well-designed CFB combustor can burn coal with high efficiency and within acceptable levels of gaseous emission. In this study, the combustion efficiency of CFB combustor based on the losses has been defined and effects of operational parameters on combustion efficiency have been investigated by a dynamic 2D model which has been developed in our previous studies. Investigations on combustion efficiency are carried out using the model to examine the effects of different operational parameters and coal properties on bed temperature and the overall CO, NO_x and SO_2 emissions from pilot-scale CFB combustor. Investigations on combustion efficiency are carried out for a pilot-scale CFB combustor. The combustion efficiency changes between 53 and 80% for various excess air ratios used in this study. By increasing excess air ratio, combustion efficiency decreases. Coal particle diameter value has more significant effect on combustion efficiency than to inlet bed pressure value for pilot-scale CFB combustor as excess air ratio increases. The present study also proves that CFB combustion allows clean and efficient combustion of coal.
Keywords: circulating fluidized bed, coal combustion, combustion efficiency

1. INTRODUCTION
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. It is also important to determine the effects of operational parameters in CFB combustors via simulation study instead of expensive and time-consuming experimental studies. However, very few studies on the combustion efficiency of a CFB have been carried out [1-3]. From this point of view, in the present study, effects of operational parameters on combustion efficiency and the pollutants emitted have been investigated by a dynamic 2D model which has been developed in our previous studies [4, 5]. Developed dynamic 2D model for a CFB combustor integrates and simultaneously predicts the hydrodynamics, heat transfer and combustion aspects. Hydrodynamic model considers the bottom zone in turbulent fluidization regime as two-phase flow in detail which constitutes a major difference from most of the previous studies in the literature and the upper zone as having core-annulus solids flow structure [4, 5]. In this investigation, effects of excess air on combustion efficiency and the pollutants emitted are examined for different coal particle diameter and inlet bed pressure values.

2. CFB MODEL
The present CFB combustor model can be divided into three major parts: a sub-model of the gas-solid flow structure; a reaction kinetic model for local combustion and a convection/dispersion model with reaction.

Hydrodynamic model: Hydrodynamic model takes into account the axial and radial distribution of voidage, velocity and pressure drop for gas and solid phase, and solids volume fraction and particle size distribution for solid phase. The model results are compared with and validated against atmospheric cold bed CFB units' experimental data given in the literature for axial and radial distribution of void fraction, solids volume fraction and particle velocity, total pressure drop along the bed height and radial solids flux. Ranges of experimental data used in comparisons are as follows: bed diameter from 0.05-0.418 m, bed height from 5-18 m, mean particle diameter from 67-520 μm, particle density from 1398 to 2620 kg/m^3, mass fluxes from 21.3 to 300 kg/m^{2}s and gas superficial velocities from 2.52-9.1 m/s. The structure and details of the hydrodynamic model are given in previous study [4].

Kinetic Model: Inputs for the model are combustor dimensions and construction specifications (insulation thickness and materials, etc.), primary and secondary air flow rates; coal feed rate and particle size distribution, coal properties, Ca/S ratio, limestone particle size distribution, inlet air pressure and temperature, ambient temperature and the superficial velocity. A continuity condition is used for the gas phase at the top of the cyclone. The cyclone is considered to have 98% collection efficiency. Kinetic 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 dense bed and for riser. The model has been validated against two different size CFB combustors, which use different kinds of Turkish Lignite, the pilot-scale 50 kW CFB combustor at the Gazi University Heat Power Laboratory and an industrial-scale 160 MW CFB combustor at Can Power Plant, obtained during the commissioning period [5, 6]. All reactions and reaction rates used in the model and the structure and details of the kinetic model are given in previous study [5].

3. COMBUSTION EFFICIENCY

The combustion efficiency of CFB combustor based on the losses can be defined as follows;

$$\eta = 1 - \frac{\dot{Q}_{unburnt\ Carbon} + \dot{Q}_{ash} + \dot{Q}_{unburnt\ CO} + \dot{Q}_{flue\ gases} + \dot{Q}_{wall}}{Heating\ value\ of\ fuel} \quad (1)$$

In this model the combustion efficiency is calculated with the following expression according to the losses given in Eq.1;

$$\eta = 1 - \frac{\dot{m}_{net} X_k H_{coal} + \dot{m}_{ash} c_p T_p + \dot{n}_g y_{CO} H_{CO} + \dot{n}_g \overline{c}_{p,gas}\left(T - T_0\right) + UA\left(T - T_0\right)}{\dot{m}_f LHV_{fuel}} \quad (2)$$

where $\dot{m}_{net}$ is the net mass flow rate discharged from the combustor and X_k is the carbon content in the discharged solid particles. The first term in right hand side is the loss due to the unburnt carbon contained in the discharged mass. The second term is the loss due to the ash discharching from the bed. The third term is the heat loss due to the unburnt CO in the flue gas. The fourth term is the loss due to the flue gases to ambient. In the model, it is assumed that the flue gases are discharged into the atmosphere at combustor exit temperature. The last term is the heat loss due to the bed to wall heat transfer.

Table 1. Operating parameters of CFB combustors.

Operating parameters	**Pilot scale combustor [5]**
Coal feed rate (range)	6-7.7 kg/h
Operation velocity (range)	3.60-9.23 m/s
Bed temperature	860-900 °C
Primary/Secondary air ratio	2/3
Bed area	0.0122 m^2
Size of coal feed (range)	0.03-0.9 mm
Mean size of sorbent feed	0.071 mm

The efficiency of coal combustion in the CFB is found to depend on coal size, the operating conditions (such as the temperature in the bed, the residence times of coal particles, excess air values and combustible gases), and the quality of fluidization. In this study, effects of operational parameters on combustion efficiency have been investigated using developed dynamic two-dimensional model for a CFB combustor. Investigations on combustion efficiency are carried out for a pilot-scale CFB combustor. In this investigation, effects of excess air on combustion efficiency are examined for each coal particle diameter and inlet bed pressure values (Figs.1-2). The considered parameters and computation conditions of CFB combustors are given in Table 1.

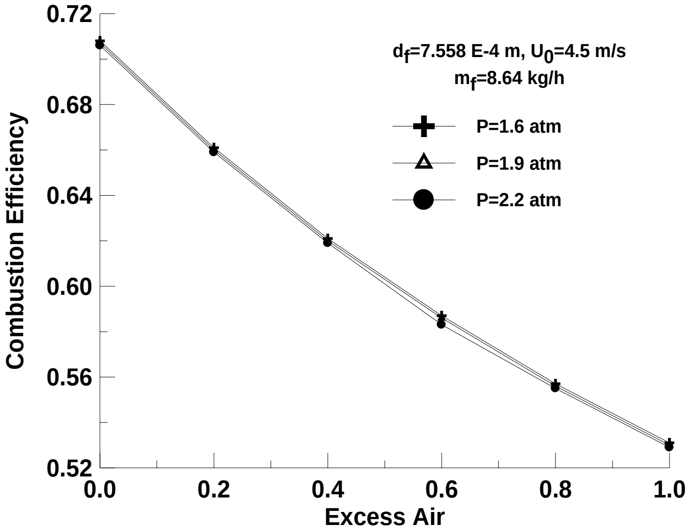

Figure 1. Effects of excess air ratio and coal particle size on combustion efficiency for small-scale CFB

For pilot-scale combustor (12.5 cm i.d., 180 cm tall main column), Fig.1 shows the effects of excess air and coal particle diameter on combustion efficiency in modeling results which plots the predicted model results for three particle diameters (540 μm, 600 μm and 750 μm) and for five excess air ratios (of about 20%, 40%, 60%, 80% and 100%). For this assumption inlet bed pressure is 1.2 atm and coal feed rate is 6.48 kg/h.

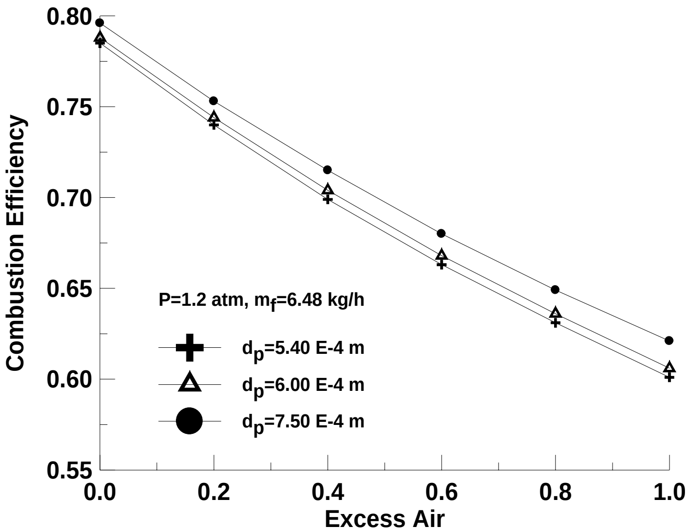

Figure 2. Effects of excess air ratio and inlet bed pressure on combustion efficiency for small-scale CFB.

As mentioned above, the combustion efficiency depends on the combustion losses. It is seen from the Fig.1 that the combustion efficiency decreases as the combustion losses increase with increasing excess air value. Excess air ratio 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 [1]. The other one is bed temperature decreases as the excess air ratio 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.

And Fig.2 shows the effects of excess air and inlet bed pressure value on combustion efficiency in modeling results which plots the predicted model results for three inlet bed pressure values (1.6 atm, 1.9 atm and 2.2 atm) and for five excess air ratios (of about 20%, 40%, 60%, 80% and 100%). For this assumption coal particle diameter is 755.8 μm, bed operational velocity is 4.5 m/s and coal feed rate is 8.64 kg/h.

In these investigations, it is observed that coal particle diameter value has more significant effect on combustion efficiency than to inlet bed pressure value for pilot-scale CFB combustor as excess air ratio increases. It is generally observed that excess air ratio has a negative effect on combustor efficiency in pilot-scale CFB combustor. As pressure increases for constant excess air value, combustion in the bed becomes more effective, causing little distinctive change on pilot scale bed combustor efficiency. The combustion efficiency changes between 53 and 80% for pilot-scale CFB combustor for various excess air ratios used in this study.

4. RESULTS AND CONCLUSION

In this study, the combustion efficiency of CFB combustor based on the losses has been defined and effects of operational parameters on combustion efficiency and the pollutants emitted have been investigated by a dynamic 2D model which has been developed in our previous studies [4, 5]. In this investigation, effects of excess air on combustion efficiency and the pollutants emitted are examined for different coal particle diameter and inlet bed pressure values. It is observed that by increasing excess air ratio, bed temperature decreases and CO emission increases. Coal particle diameter value has more significant effect on CO emission than to bed inlet pressure. Another effect of increasing excess air is the decrease of SO_2 and NO_x emissions. Inlet bed pressure value has positive effect on SO_2 and NO_x emissions. A bigger inlet bed pressure value will result in lower emissions of SO_2 and NO_x if other parameters are kept unchanged.

It is generally observed that excess air ratio has a negative effect on combustor efficiency in pilot-scale CFB combustor. As pressure increases for constant excess air value, combustion in the bed becomes more effective, causing little distinctive change on pilot scale bed combustor efficiency. The present study also proves that CFB combustion allows clean and efficient combustion of coal.

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