Available online at www.sciencedirect.com
ScienceDirect
Journal of the Chinese Institute of Chemical Engineers 39 (2008) 541–556
JOURNAL OF THE CHINESE INSTITUTE OF CHEMICAL ENGINEERS
www.elsevier.com/locate/jcice

# Effects of operational parameters on emission performance and combustion efficiency in small-scale CFBCs

Afsin Gungor [a,*], Nurdil Eskin [b]

[a] Nigde University, Faculty of Engineering and Architecture, Department of Mechanical Engineering, 51100 Nigde, Turkey
[b] Istanbul Technical University, Mechanical Engineering Faculty, Gumussuyu, 34437 Istanbul, Turkey

Received 11 March 2008; received in revised form 15 May 2008; accepted 19 May 2008

## Abstract

A well-designed CFBC can burn coal with high efficiency and within acceptable levels of gaseous emissions. In this theoretical study effects of operational parameters on combustion efficiency and the pollutants emitted have been estimated using a developed dynamic 2D (two-dimensional) model for CFBCs. Model simulations have been carried out to examine the effect of different operational parameters such as excess air and gas inlet pressure and coal particle size on bed temperature, the overall CO, $NO_x$ and $SO_2$ emissions and combustion efficiency from a small-scale CFBC. It has been observed that increasing excess air ratio causes fluidized bed temperature decrease and CO emission increase. Coal particle size has more significant effect on CO emissions than the gas inlet pressure at the entrance to fluidized bed. Increasing excess air ratio leads to decreasing $SO_2$ and $NO_x$ emissions. The gas inlet pressure at the entrance to fluidized bed has a more significant effect on $NO_x$ emission than the coal particle size. Increasing excess air causes decreasing combustion efficiency. The gas inlet pressure has more pronounced effect on combustion efficiency than the coal particle size, particularly at higher excess air ratios. The developed model is also validated in terms of combustion efficiency with experimental literature data obtained from 300 kW laboratory scale test unit. The present theoretical study also confirms that CFB combustion allows clean and efficient combustion of coal.

*Keywords:* Circulating fluidized bed; Modeling; Coal combustion; Combustion efficiency; Emission performance

## 1. Introduction

Fluidized bed combustion allows clean and efficient combustion of coal. Designing of the circulating fluidized bed combustor (CFBC) is very important because of burning coal with high efficiency and within acceptable levels of gaseous emissions. A good understanding of the combustion and pollutant generating processes in the combustor can greatly avoid costly upsets.

Fuel properties play important roles in the technical performance of the power plants. High-ash fuels are suitable for circulating fluidized bed (CFB) applications with no adverse effect, and coal slurries with ash contents up to 53% have been burned together with bituminous coal resulting in a good performance of CFBCs. Sub-bituminous coals have become an important alternative for emissions compliance because of their unique constituents and combustion characteristics, such as reduced $NO_x$ and $SO_2$ emissions because of its low sulphur, nitrogen and ash content and high-volatile matter content. Low ash content in comparison with typical bituminous coals decreases the unburned carbon losses and, as a result, the boiler efficiency increases when sub-bituminous coals are fired (Spitz *et al.*, 2008).

The low-volatile fuels can be also easily burnt in CFBCs. The hot circulating particles provide a large ignition source for low-volatility fuels resulting in excellent flame stability and burning characteristics. The price of these low-quality fuels is very low making CFB technology competitive with other combustion techniques (Nowak, 2003).

The combustion processes are similar in circulating, turbulent or bubbling fluidized beds, but the burning rates of char are different in these beds (Basu and Halder, 1989). The burning rate of char in turbulent fluidized beds is higher than that in bubbling fluidized beds due to higher mass transfer rate in the turbulent bed (Basu and Subbarano, 1986). The direct measurement of burning rate in the riser of a CFB is not as easy

---

* Corresponding author. Tel.: +90 532 397 30 88; fax: +90 388 225 01 12.
*E-mail address:* afsingungor@hotmail.com (A. Gungor).

0368-1653/$ – see front matter © 2008 Taiwan Institute of Chemical Engineers. Published by Elsevier B.V. All rights reserved.
doi:10.1016/j.jcice.2008.05.007

## Nomenclature

| | |
|---|---|
| $A$ | area ($m^2$) |
| $c_p$ | specific heat of solids (kJ/kg K) |
| $\bar{c}_{p,g}$ | specific heat of gas (kJ/kmol K) |
| $C_D$ | drag coefficient |
| $C_{O_2}$ | oxygen concentration ($kmol/m^3$) |
| Ca/S | calcium to sulphur ratio |
| $C$ | gas concentration ($kmol/m^3$) |
| $d_p$ | particle diameter (m) |
| $d_{pi}$ | particle dimension interval (m) |
| $d_{p,new}$ | particle diameter after fragmentation (m) |
| $d_{p,old}$ | particle diameter before fragmentation (m) |
| $D$ | bed diameter (m) |
| $D_b$ | equivalent bubble diameter (m) |
| $D_g$ | diffusivity coefficient for oxygen in nitrogen ($m^2/s$) |
| $G$ | solid stress modulus ($N/m^2$) |
| $h_i$ | height above the distributor (m) |
| $H_b$ | combustor height (m) |
| $H_{bot}$ | height of the bottom zone (m) |
| $H_{coal}$ | reaction enthalpy of coal (kJ/kg) |
| $H_{CO}$ | reaction enthalpy of carbon monoxide (kJ/kg) |
| $\dot{J}$ | mass transfer rate via density difference per unit volume ($kmol/m^3$ s) |
| $k$ | rate constant (m/s) |
| $k_a$ | attrition constant |
| $k_{be}$ | mass transfer coefficient (1/s) |
| $k_c$ | char combustion reaction rate (kg/s) |
| $k_{cr}$ | kinetic rate (1/s) |
| $k_{cd}$ | diffusion rate (1/s) |
| $k_f$ | fragmentation coefficient |
| $k_g$ | gas conduction heat transfer coefficient (W/m K) |
| $k_L$ | reaction rate (1/s) |
| $k_{vL}$ | volumetric reaction rate ($kg/m^2$ s) |
| $LHV_{fuel}$ | lower heating value of fuel (kJ/kg) |
| $\dot{m}$ | mass flow rate (kg/s) |
| $M$ | molecular weight (kg/mol) |
| $\dot{n}$ | gas flow rate (mol/s) |
| $N$ | number of particles in each control volume |
| $P$ | pressure (Pa) |
| $P(d)$ | particle size distribution function |
| $\dot{Q}$ | heat flux (W) |
| $r_{mother}$ | radius of the mother particle (m) |
| $R$ | reaction rate (mol/s) ($mol/cm^3$ s) |
| $\dot{R}$ | mass flow rate generated/consumed from chemical processes per unit volume ($kmol/m^3$ s) |
| $R'''$ | total heat generated/consumed per unit volume ($W/m^3$) |
| $R_a$ | particle attrition rate (kg/s) |
| $R_u$ | universal gas constant (kJ/kmol K) |
| $R_g$ | gas constant (kJ/kmol K) |
| $Re$ | Reynolds number |
| Sc | Schmidt number |
| Sh | Sherwood number |
| $S_g$ | specific surface area of limestone particles ($m^2/kg$) |
| $T$ | temperature (K) |
| $T_0$ | ambient temperature (K) |
| $T_p$ | particle temperature (K) |
| $u$ | gas velocity (m/s) |
| $U$ | overall heat transfer coefficient ($W/m^2$ K) |
| $U_0$ | superficial gas velocity (m/s) |
| $U_{mf}$ | minimum fluidization velocity (m/s) |
| $v$ | particle velocity (m/s) |
| $W_b$ | mass of particle (kg) |
| $x_a$ | weight fraction of particles after attrition at $d_{pi}$ interval |
| $X_k$ | char mass fraction (kg-char/kg-bed material) |
| $y$ | molar fraction of gas species (kmol-gas species/kmol-gas) |

*Subscripts*

| | |
|---|---|
| ash | ash |
| f | feed |
| net | net |
| wall | wall |

*Greek symbols*

| | |
|---|---|
| $\beta$ | gas-solid friction coefficient |
| $\delta$ | thickness of annulus (m) |
| $\varepsilon$ | void fraction |
| $\varepsilon_b$ | bubble volume fraction |
| $\varepsilon_p$ | solids volume fraction |
| $\varepsilon_{mf}$ | minimum fluidization voidage |
| $\Phi$ | mechanism factor |
| $\lambda_s$ | limestone reactivity |
| $\mu$ | gas viscosity (kg/m s) |
| $\rho$ | particle density ($kg/m^3$) |
| $\tau$ | shear stress ($N/m^2$) |

as in a captive fluidized bed like the bubbling or turbulent fluidized bed. However, the burning rate of coarse (3–9 mm) char particles measured in the fast fluidized riser of a CFB was higher than those measured in a bubbling bed in similar thermochemical conditions (Basu and Halder, 1989). The higher degree of mixing in fast and turbulent fluidized beds contributed to the higher burning rates in these regimes (Basu, 1999).

The fragmentation models are necessary if accurate understanding of the paths of burning particles in coal burning plants is needed. The fragmentation behavior differs between coals of different volatile-matter content. The coal rank is believed to be a major factor determining the behavior of particles during fragmentation (Syred *et al.*, 2007). Attrition and fragmentation turned out to be far more extensive in the case of high-volatile fuels. This feature reflects the propensity of such fuels to give rise, upon devolatilization, either to highly porous, friable chars or even to a multitude of fragments of very small size. Combustion efficiency is directly determined by the relative extent of the combustion time scale and of the residence time of char fines in the bed which, in turn, is related to elutriation. Fixed carbon from high-volatile fuels is converted via the