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Simulation model of the mass balance in a supercritical circulating fluidized bed combustor

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ABSTRACT

In the present work, a mass balance allows us to predict operating conditions of coal-fired circulating fluidized bed (CFB) combustor under full load operation. A mass balance model has been developed for the particle size distribution and solids mass fluxes of three granular materials supplied and led out in the 966MW$_{th}$ supercritical circulating fluidized bed boiler. This model emphasizes some important factors, such as feed rates, separator characteristics, drainage and recirculation rates of solids and internal processes. In the simulation model the internal processes such as the combustion process, particle shrinkage, fragmentation and attrition were taken into account, respectively. The model can theoretically predict the PSD and mass balance at different operating loads, ash content and points inside the supercritical CFB combustion system. The results of the simulation indicate that they are in accordance with the experimental data from large-scale supercritical CFB boiler. The results of modeling give an opportunity of studying the impact of changes on the solids particle size distribution (PSD) and solids mass fluxes in operating conditions.

1. Introduction

Hydrodynamics, combustion and heat transfer occurring inside a circulating fluidized bed combustor (CFB) are mainly characterized by particle properties such as the particle size distribution (PSD) [1–3] and the solids concentration [4,5]. The particle size distribution and the solids concentration are key parameters for proper operating of CFB systems, especially the influence to the heat transfer within the furnace chamber. Moreover, the properties of bed inventory have an influence on the hydrodynamics and fuel combustion in the CFB furnace [6–8]. The bed inventory composition in a CFB combustion chamber includes burnout and reactive fuel and an inert material which is a mixture of ashes as well as make-up sand. The sand as additional bed material is fed into combustion chamber during start-up of the boiler and when a coal with low ash content is fired or co-fired with other fuel (i.e. biomass). The behavior and the particle size distribution of granular materials are very difficult to predict in the circulating fluidized bed due to a vigorous movement of particles. A number of population balances in CFB boilers which consider some important fluid dynamic processes [9–11], such as attrition, fragmentation, segregation, particle shrinking, char combustion, and heat transfer [12–14] are presented in the literature. Another key parameter which is very important in the mass balance is the stress history of particles [15]. In order to map all parameters mentioned above in the mass balance model, the CFB furnace chamber is considered for two flow regimes separately. This is due to different particle behavior in the CFB system since there are differences in the gas-solids flow structure between a dense zone at the bottom bed and a dilute zone above the fuel feeding system and secondary air inlets.

The particles transport between furnace chamber and return leg is also taken into account in the mass balance model [16–20]. Basically, the separation efficiency of solids separators is important for proper operation of CFB boilers and plays a significant role in the prediction of the particle size distribution. It is especially important when the loss of circulating material is too high and fuel with low content of ash is fired. Therefore, there is a necessity to recirculate ashes (i.e. fly ash or bottom ash) to the furnace chamber as a new bed material. As a result, it allows to keep mass of solids in the bed inventory. A comprehensive study of the operating parameters with respect to the separation behavior of the cyclone is precisely described by [21].

In this work, the mass balance model for the circulating fluidized bed takes into account the following physical processes (i.e. attrition, segregation, fragmentation, coagulation) and chemical processes (i.e. fuel combustion) that usually occur in the CFB boiler. The parameters used in the mass balance model were optimized from the field test data under full load operation. In this paper, the concept of mass balance modeling at steady-state operation of the boiler was applied. This approach allows to study the sensitivity of state variables due to the character of the particle size distribution, which is not possible to obtain in the classical models based on average balance sheet values of state variables. The model allowed to simulate the steady state operation for a supercritical CFB boiler. Therefore, there was a feasible diagnostics of CFB boiler in a large-scale. The energy balance during combustion is not considered in this paper.

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2. Idea of Mass Balance Model

The principle of creating a mathematical mass balance model in a supercritical CFB boiler under steady-state operation is shown in Fig. 1.

The essence of this approach is balancing of optional parameters by division of particle size distribution into classes. A spherical shape of particles was assumed. The division of particle distribution into classes with respect to their mean size was performed. The span of particles size is characteristic of the each class. The class is represented by the mean particles size, which is located in the middle of the classes. This division is necessary to obtain balance formulae for a given particle class. It should assume, that in each class shrinking core model, i.e. the particles found in the class reduce its own size under the influence of chemical reaction (i.e. fuel combustion) and physical processes (e.g.: attrition, fragmentation, coagulation etc.). It is possible for particles to migrate from the class with greater span to a class with smaller span. Generally an increase of particle size is also possible, i.e. the migration from the classes about smaller span to the classes with larger spans.

All processes occurring in the CFB combustion system can divide in three groups: feeding, internal and external processes respectively. Among external processes and characteristic of external devices following elements can be distinguished: (i) carry away of bed material as a result of air interaction on the bed inventory in the bottom zone of the furnace chamber; (ii) separator characteristic curve, separating device in which coarse particles are recirculated to the combustion chamber; (iii) ash remover characteristic curve (i.e. drainage constant), drainage system of bottom ash; (iv) characteristic of return leg which circulatingbed material feeding into the furnace chamber; (v) characteristic of fly ash recirculation system which fine particles as additional bed material are feeding into the combustion chamber. Moreover, the internal processes connected with the migration of particles between classes can be distinguished: (i) fuel combustion; (ii) fragmentation i.e. size reduction of particle classes; (iii) abrasion i.e. the migration of particles from the classes having larger diameters to the classes with smaller diameters. Additionally, the accumulation of fine particles about sizes less than 50 microns was assumed.

An example of a general scheme of the mass balance of the "*k*"-th particle class is shown in Fig. 2.

According to the above idea the mass balance equation of general mass flow for the particle classes (*k-1…N*) is proposed in the following form Eq. (1):

$$\dot{m}f_l(d_k) + \sum_{j=1}^{NI}\dot{m}i_{lj}(d_k) + \sum_{j=1}^{NE}\dot{m}e_{lj}(d_k) = 0, \tag{1}$$

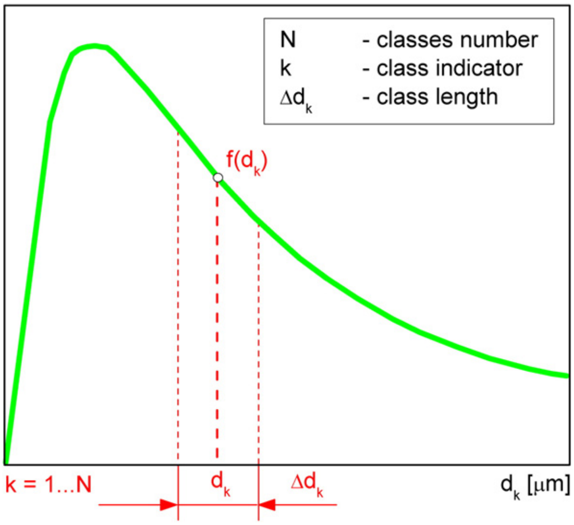

Fig. 1. Idea of mass balance — division of particle distributions into classes.

where $\dot{m}f_l(d_k)$, $\dot{m}i_l(d_k)$, $\dot{m}e_{lj}(d_k)$,denote mass flow functions of feeding, internal and external processes, respectively. Subscript *l* denotes a number of granular materials. Subscript *k* is a number of particle class and subscript *j* denotes number for both external and internal processes. The upper limit of internal processes is equal to *NI* and for external processes equaled *NE*. The unknown distribution function occurs inside mass flow balance of external and internal processes. As an example, the mass flow of an internal processes could calculate according to the following formula Eq. (2):

$$\dot{m}i_{lj}(d_k) = X_l\cdot m\cdot K_{lj}(d_k)\cdot f_{Ul}(d_k)\cdot \Delta d_k, \tag{2}$$

where X_l is a share of "*l*"-th granular material in total mass in the system, *m* denotes a total mass of mixture of granular materials, $K_{lj}(d_k)$ is a characteristic function of some internal process, $f_{Ul}(d_k)$ is an unknown particle distribution of "*l*"-th granular material and "Δd_k "denotes the length of"*k*"-th particle class.

Based on knowledge about physical and chemical processes Eq. (1), it is possible to determine an unknown particle size distribution for different granular materials in the CFB furnace. Final particle size distribution is connected with the mass ratios of granular materials Eq. (3), which are fed to the furnace chamber.

$$\sum_{l=1}^{nm} X_l = 1, \tag{3}$$

where X_l denotes share of "*l*"-th granular material in the fluidized bed and *nm* is a total number of granular materials considered in the CFB combustion system.

2.1. Definition of the Mass Balance Model

Schematic diagram of the supercritical CFB boiler with capacity 966MW$_{th}$utilized to formulate of mass balance was presented in Fig. 3. Three granular materials i.e. bituminous coal as main fuel, ash obtained from burned coal and limestone as sorbent utilized to desulphurization process of flue gases are taken into account in the mass balance. Three granular material particle distributions were assumed in order to examine the behavior of a supercritical CFB boiler. The input particle distributions are determined by sieve analysis of granular materials which are fed into the boiler.

The equations of mass balance for *k*-th particles class and every one of granular materials are determined by the following formulas, respectively:

$$\dot{m}^a_{feed}(d_k) - \dot{m}^a_{elut}(d_k) + \dot{m}^a_{down}(d_k) - \dot{m}^a_{bott}(d_k) + \dot{m}^a_{refl}(d_k) + \dot{m}^a_{rebod}(d_k) + \frac{d\dot{m}^a_{frag}(d_k)}{dd_k}\cdot\Delta d_k + \frac{d\dot{m}^a_{attr}(d_k)}{dd_k}\cdot\Delta d_k = 0, \tag{4}$$

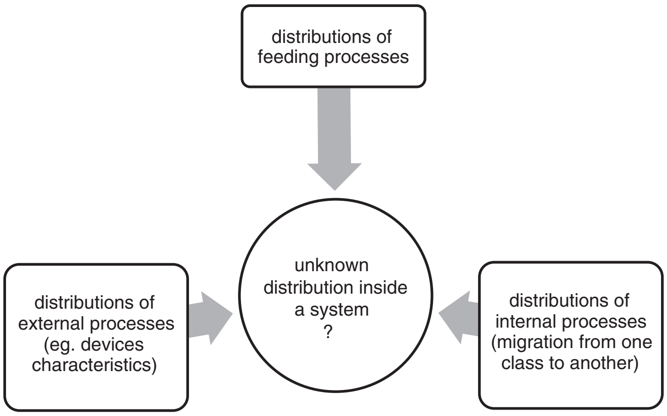

Fig. 2. Division of processes for the particles class.