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Review

Development and application of the design principle of fluidization state specification in CFB coal combustion

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A B S T R A C T

In this paper, the design principle of Fluidization State Specification (FSS) is reviewed and its applications in CFB boiler are introduced. In the early 2000s, FSS design principle was proposed to determine the fluidization state in the upper furnace as the basis of engineering design. The principle was initially adopted by engineers to select a proper superficial gas velocity to prevent the severe erosion on water walls. It was used in many CFB furnace designs including the world's largest 600 MW supercritical one in China. Later, FSS design principle was extended to reduce the pressure head of the draft fan to save energy consumption. Industrial application showed that by changing the amount of bed inventory, CFB boilers could operate at a re-constructed fast bed state, not only saving ~30% power of the draft fans, but also further reducing the erosion on water walls and improving combustion efficiency. Recently, FSS design principle was further improved and applied to achieve ultra-low NOx and SO_2 emission. A third coordinate with improved bed quality, i.e., size distribution of bed material was proposed to add on the original two-dimensional fluidization state diagram defined by the superficial gas velocity and the solid circulation rate. Industrial practices showed that under the guideline of the improved FSS design principle, it was possible for CFB boilers to reach over 99% desulfurization efficiency with limestone injected into furnace, and less than 50 mg/Nm^3 (at 6% O_2) NOx emission at the furnace exit. FSS design principle promotes the booming of ultra-low emission CFB boilers in China.

1. Introduction

Circulating fluidized bed (CFB) combustion technology has been developed for more than three decades. Due to its merits in fuel flexibility, low NOx formation, cost-effective in-furnace desulfurization, low turn down ratio and excellent scalability [1–5], the technology is widely accepted by industries. So far, ~8000 CFB boilers, most burning coals, have been put in operation around the world.

The furnace of a coal-fired CFB boiler is a place not only for coal particle burning, but also for heat exchanges between the two-phase flow and surrounding heating surfaces, and the formation and removal of NOx and SO_2 [2]. Therefore, designing the furnace is the base to implement the CFB coal combustion technology.

In the early development stage, CFB furnace design was rather empirical. It was mostly based on the experience of the bubbling fluidized bed (BFB) boiler design, and the heat transfer coefficients and overall coal combustion behavior obtained in pilot-scale CFB combustors or small-scale CFB boilers. However, those limited experimental data and empirical formula could not meet the design requirements of a CFB furnace as the dimension increased. As a result, many CFB boilers designed in the early years could not reach the rated load, and caused overheat of heating surfaces and severe erosion on water walls. Such problems were very prominent in China in 1990s when a large number of CFB boilers were made based on the principles featured with a high fluidization velocity [3,6].

In the early 2000s, Chinese researchers and engineers realized that the main cause for the above problems was that the fluidization state in the CFB furnace, specified by two parameters, i.e., the superficial gas velocity u_f and the solid circulation rate G_s, was set improperly. Consequently, a design principle named as Fluidization State Specification (FSS) was proposed [3], which will be explained in more detail in next section. Under the guidelines of the principle, Chinese engineers re-selected a fluidization state as a new base, in subsequent CFB boiler design. They also adopted it in the design of the world's largest 600 MW supercritical CFB boiler, which was successfully put into operation in China in 2014 [6]. The new designs significantly increased the availability and economic performance.

In the middle 2000s, a number of large capacity CFB boilers were

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Nomenclature

Ar	Archimedes number $\left(=\frac{d_p^3\rho_f g(\rho_p-\rho_f)}{\mu_f^2}\right)$, –
d_p	particle size, m
D_t	riser diameter, m
F	fly ash flow rate, kg/s
Fr	Froude number $\left(=\frac{u_f}{(gd_p)^{0.5}}\right)$, –
g	gravitational acceleration, m/s^2
G_{in}	feedstock flow rate, kg/s
G_{out}	discharging flow rate, kg/s
G_s	solid circulation rate, kg/(m^2·s)
$G_s{}^*$	saturated carrying capacity, kg/(m^2·s)
i	a certain size cut, –
I_v	bed material inventory in the bed of furnace, kg
u_{ch}	choking velocity, m/s
u_f	fluidization velocity, m/s
u_t	terminal velocity, m/s
u_{tr}	transport velocity, m/s
η	overall separation efficiency, –
η_d	discharging efficiency, –
η_s	separator's collection efficiency, –
μ_f	gas viscosity, Pa·s
ρ_f	gas density, kg/m^3
ρ_p	particle density, kg/m^3

developed to meet the demand of the power generation industry. However, it was found that their auxiliary power consumption was often more than 3% higher than that of a pulverized coal fired boiler. This disadvantage made a CFB boiler to be less competitive [7]. Thus, FSS design principle was re-examined. Researchers found that by changing the amount of bed inventory, a CFB boiler could operate at a re-constructed fast bed state, not only saving ~30% power of the draft fans, but also further reducing the erosion on water walls and improving combustion efficiency. In addition, SO_2 and NOx concentrations at the furnace exit could be controlled under 200 mg/Nm^3 (@ 6% O_2).

More recently, CFB combustion technology encountered a new challenge as Chinese government announced a so-called ultra-low emission requirements to the coal-fired power plants. As required, SO_2 and NOx concentrations in the flue gas emitted from the chimney should be kept below 35 mg/Nm^3 and 50 mg/Nm^3 (@ 6% O_2) respectively [8,9]. Provided CFB boilers are forced to install the selective catalytic reduction (SCR) and wet flue gas desulfurization (FGD) devices to meet the ultra-low NOx and SO_2 emission requirements, the investment and operation cost of a CFB boiler would significantly increase [10]. As a result, CFB combustion technology will lose its advantage in economical emission control and thereby the competitiveness against the pulverized coal-firing technology. Therefore, it is urgent to investigate if FSS design principle could be still valid to further reduce the NOx and SO_2 emission from a CFB furnace to meet or nearly meet the ultra-low emission requirements.

The paper briefly reviews the FSS design principle and discusses the fluidization state in a CFB boiler. Then it introduces the development and applications of the FSS design principle in China, especially on the ultra-low NOx and SO_2 emission control.

2. FSS design principle

Due to the wide size distribution of the bed inventory, the flow pattern in a CFB furnace is often regarded to a combination of a bubbling bed or a turbulent bed formed by coarse particles in the bottom furnace and a dilute phase bed formed by fine particles in the upper furnace [1,2].

FSS design principle suggests that the first priority for a CFB boiler design is to select a specified fluidization state (u_f and G_s) for the dilute upper furnace. Only after the state is selected, other boiler parameters, e.g., heat transfer coefficient and the primary/secondary air flow ratio can be properly determined. To select a proper state, the material balance in a CFB furnace should be understood first.

2.1. Material balance in a CFB boiler

The conventional gas-solid fluidization theory, including the fluidization regime classification, was developed for the chemical reactors [e.g., [11–13]]. For a chemical CFB reactor, the solid particles are mostly expensive feedstock, such as catalysts, and they are with uniform size or narrow cut size. In order to avoid the loss of the expensive feedstock, the solid circulation loop is closed.

Differing from a CFB reactor, a CFB boiler is the open system for the solid phase, with continuous solid input and output [3,14]. Simply, as shown in Fig. 1, it is regarded as a one-inlet and two-outlet open system with multi-sized particles feedstock. The inlet refers to solid input of coal, limestone and inert sands for bed material make-up. Two outlets refer to the two exits for solids to leave the furnace: one is for the bottom ash drained from the ash discharging port, and the other is for the fly ash entrained by the flue gas from the cyclone exit.

The mass balance of solid particles can be mathematically described by Eq. (1):

$$G_{in}(i) = G_{out}(i) + F(i) \tag{1}$$

where $G_{in}(i)$ is the flow rate of feedstock ash; $G_{out}(i)$ is the discharging flow rate and $F(i)$ is the fly ash flow rate.

At a pseudo steady state, solid particles within a certain size range

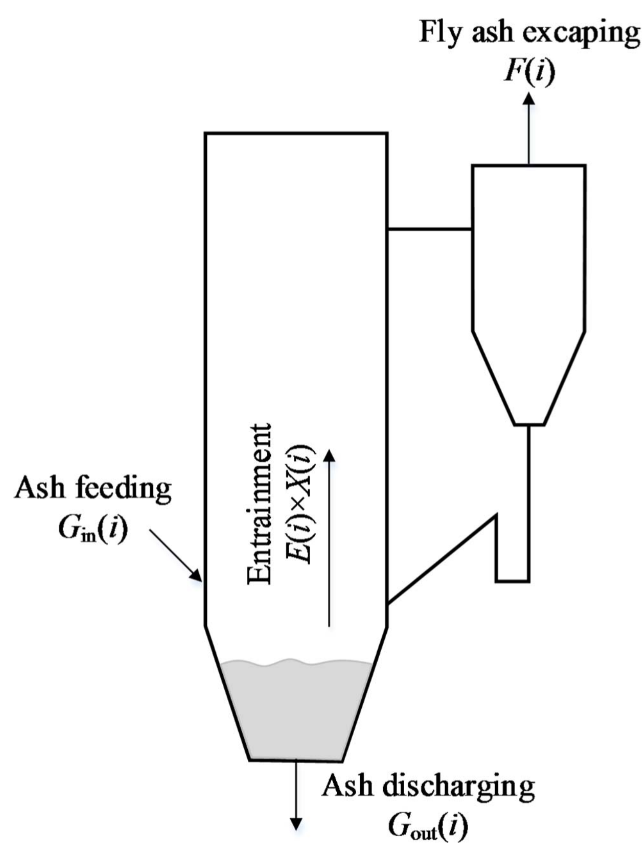

Fig. 1. Schematic diagram of material balance in CFB boilers.