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Review

Research Progress on the Dynamic Characteristics of Circulating Fluidized Bed Boilers While Processing Rapid Variable Loads

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Abstract: In order to achieve the "dual-carbon" goal, China's energy sector is rapidly evolving towards a green and low-carbon future, with the integration of large-scale new energy into the power grid. However, due to the fluctuating characteristics of new energy generation, the difficulty of grid peaking has gradually increased. Consequently, enhancing flexibility and achieving wide and rapid peak shaving have emerged as the primary development directions for thermal power units. Circulating fluidized bed (CFB) boilers have been widely developed due to their excellent coal adaptability, large load regulation range, and low-cost pollutant removal ability. However, the flexibility of load variations in most CFB units is not high, limited by the substantial inertia of the furnace side and fluctuating pollutant emissions. This review is conducted with respect to the boiler side to analyze inertia sources and effects on the system while processing rapid variable loads, including gas–solid flow inertia, fuel combustion inertia, and heat transfer inertia. It discusses the development of numerical simulation models for CFB boilers and points out corresponding applications and limitations in simulating dynamic characteristics during load changes. Through experimental bench tests and numerical simulation, it investigates the dynamic characteristics of pivotal parameters in the variable load process. Moreover, the pivotal elements influencing the variable load performance and viable regulatory techniques are revealed, thereby furnishing theoretical guidance for enhancing the unit flexibility and peak shifting rates of China's CFB boilers.

Keywords: circulating fluidized bed; rapid variable load; dynamic characteristics; flow inertia; combustion inertia; heat transfer inertia; numerical simulation

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1. Introduction

In order to promote the realization of the "carbon peak, carbon neutral" goal, the "14th Five-Year Plan" of modern energy systems pointed out that China's renewable energy will enter a new stage consisting of a spike in high-quality development [1]. In contrast with the randomness, intermittency, and volatility of renewable energy power generation [2], coal power generation has high stability and flexible load regulation capability. In the current complex and changing international political and economic context, coal still plays an important role in ensuring China's energy security. Coal's importance is so great that it is difficult to replace with other energy sources in the short term, as can be seen from Figure 1. Therefore, when the proportion of new energy generation increases to a certain extent, the difficulty of grid peaking increases. Enhancing the operational flexibility of coal power units is not only the main development direction of coal power units but also one of the key measures for realizing the large-scale, safe, and efficient utilization of new energy power.

Circulating fluidized bed (CFB) boilers have received worldwide attention for their high-efficiency, high-flexibility, and low-pollution combustion technology [3,4]. The primary components of a CFB boiler are a furnace, a separator, and a loop seal, co-creating an extremely effective main circulation loop. Large quantities of bed material and coal particles are fluidized in the furnace and returned to the furnace through the separator and loop seal to achieve recirculating combustion and rapid heat transfer. Due to CFB boilers' excellent gas–solid mixing and recirculating combustion of fly ash, their combustion efficiency is usually between 95% and 99%. Thus, a CFB boiler can adapt to various fuels (such as low-quality coal and biomass) and flexibly adjust the heat load. Above all, CFB boiler combustion technology is an effective tool for promoting sustainable energy development and reducing carbon emissions.

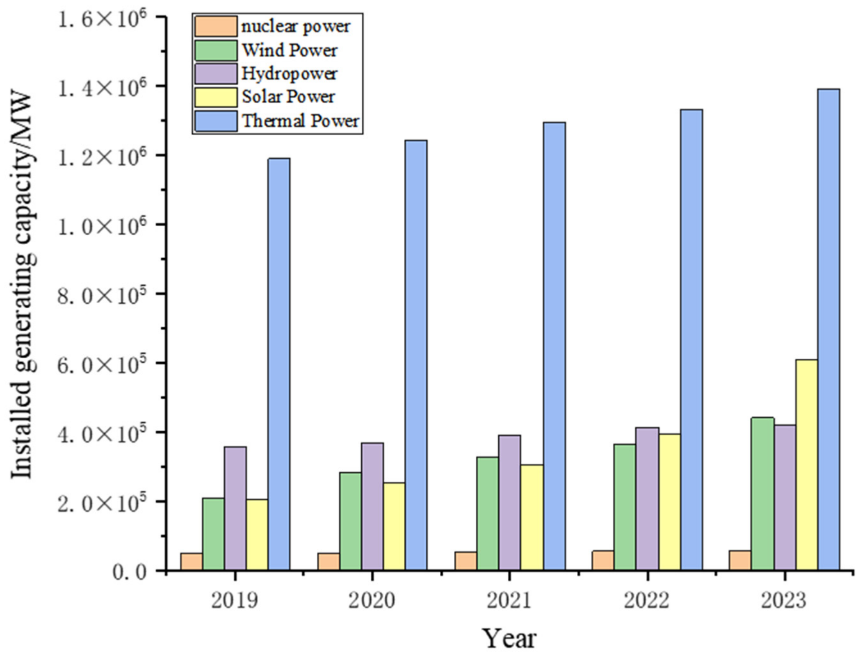

Figure 1. Statistical data on China's electric power industry in the past five years.

As one of the clean coal combustion technologies, another outstanding advantage of CFB combustion is its ability to achieve low-cost pollutant control [5]. In a CFB boiler's combustion process, adding appropriately sized limestone particles to the furnace can effectively initiate the sulfur fixation reaction, thereby removing over 90% of the SO_2 in the flue gas and achieving a desulfurization efficiency of more than 90%. At the same time, CFB boilers have a natural advantage regarding low NO_x emissions due to their moderate combustion temperature (850–950 °C) and the uniform temperature distribution in the furnace. With reasonable bed temperature design and oxygen adjustment, the NO_x raw emissions can be maintained at 200 mg/m^3. However, when CFB boilers are involved in power system peak shaving, gases tend to be distributed unevenly due to the variable combustion state and drastic bed temperature changes in the furnace. As a result, the production and removal characteristics of sulfur and nitrogen pollutants change with the gas and temperature distribution, which may lead to problems such as large fluctuations in pollutant emissions, a high tendency to exceed standards, and high energy consumption, which, in turn, limit the improvement of the unit's peak regulation rate.

Flexibility retrofits for coal-fired units center on increasing the depth and unit variable load rate [6]. The load range for deep peaking approaches the minimum stable combustion load of the boiler; thus, the minimum stable combustion load is a key factor in constraining the unit's deep peaking ability. For CFB boiler units, heat release in the furnace is mainly generated by the combustion of a large amount of instantaneous char, which cannot be completely burned in a single pass, but it still maintains high reactivity and can quickly complete the combustion process under appropriate conditions. The high heat storage capacity of the residual ash also makes the combustion of CFB boilers more stable than that of pulverized coal boilers, with the lowest stable combustion load reaching less than 30%, which can be further reduced to 20% by using flue gas recirculation technology.

In terms of variable load rate, the pulverized coal (PC) furnace recirculation loop involves a small amount of material. Small fuel particles allow for rapid combustion. Their flow and combustion inertia are low and response to load changes is fast. The maximum load variation rate of PC boiler units around the world can reach about 7%/min. CFB units have a slight disadvantage compared to pulverized coal units, but there is still much room for improvement. The recirculation loop exhibits a high degree of system inertia, which is influenced by a number of factors, including the mm-scale feed coal particle size, the substantial quantity of bed material in the furnace, and the rapidly changing flow regime. In comparison to PC boilers, CFB boilers typically exhibit a relatively low variable load rate. Currently, the maximum variable load rate reported in Chinese CFB unit studies is around 2–3%/min [7–9], which is a definite gap from the international realistic optimal level of 4%/min [10,11] and the simulated optimal level of around 6%/min [12]. As shown in Figure 2, there are currently many ways to achieve variable load rates in CFB boilers through experimentation and simulation. Determining how to effectively improve the variable load rate and promote low-cost flexibility modification of CFB boiler units has undoubtedly become one of the main difficulties of researching CFB combustion technology.

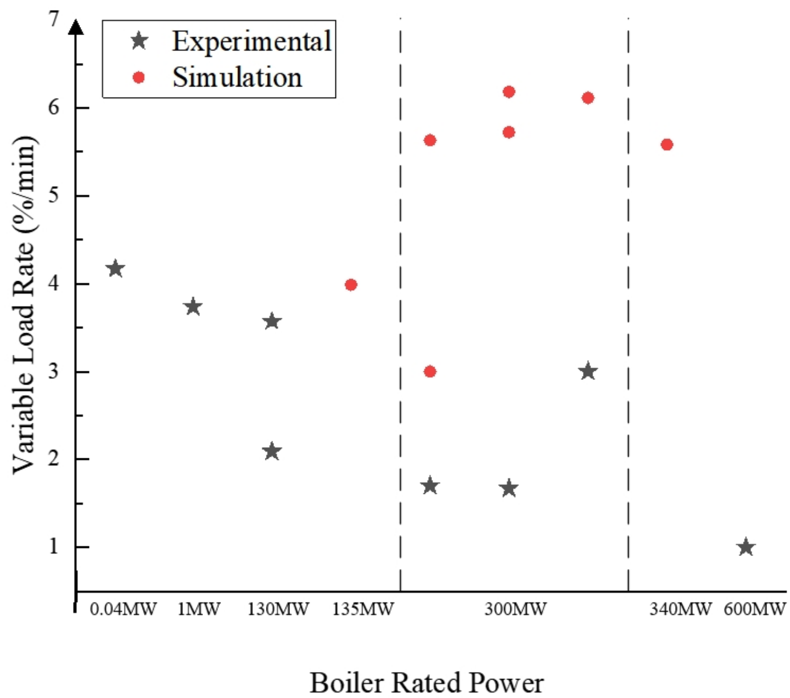

Figure 2. Different load rates of CFB boilers have been achieved in experiments and simulations.

CFB boiler units are characterized by strong nonlinearity and multi-inertia and multi-parameter coupling. The study of CFB variable load capability should not be limited to analyzing the steady-state condition of a boiler before and after processing a variable load. The focus must also be on the analysis of dynamic characteristics exhibited during the variable load process. Therefore, it is crucial to monitor the long-term changes in parameters related to transient flow, combustion, and the heat transfer process during load changes so as to analyze the mechanism as well as the key factors limiting the variable load rate of CFB boilers.

2. Inertia Sources in Circulating Fluidized Bed Boilers While Processing Rapid Variable Loads

In accordance with the generating mechanism, the inertias of a CFB boiler system can be divided into the combustion inertia of the fuel system, the thermal inertia of the heat transfer process, and the flow inertia of the gas–solid two-phase flow in the main circulation loop, as shown in Figure 3. These three inertias produce strong coupling in the system through parameters such as bed temperature, work material temperature, flue gas temperature, void ratio, and circulation flow rate. On the whole, these three inertias all constrain the variable load rate of a CFB unit. The impact of these three inertia factors on the variable load rate cannot simply be added up [13]. The flow inertia affects combustion and heat transfer through the distribution of logistics concentration [14], serving as these processes' boundary conditions. In general, the time delay of flow inertia is quite large [15]. So, compared to combustion and heat transfer inertia, flow inertia is more important. The inertia of boiler systems is complex and diverse, and there are long inertia delay times. Moreover, the effect of inertia on the boiler side is relatively greater than that on the steam turbine system. Thus, in this article, we mainly focus on analyzing the impact of boiler-side inertia on the variable load of CFB boilers.

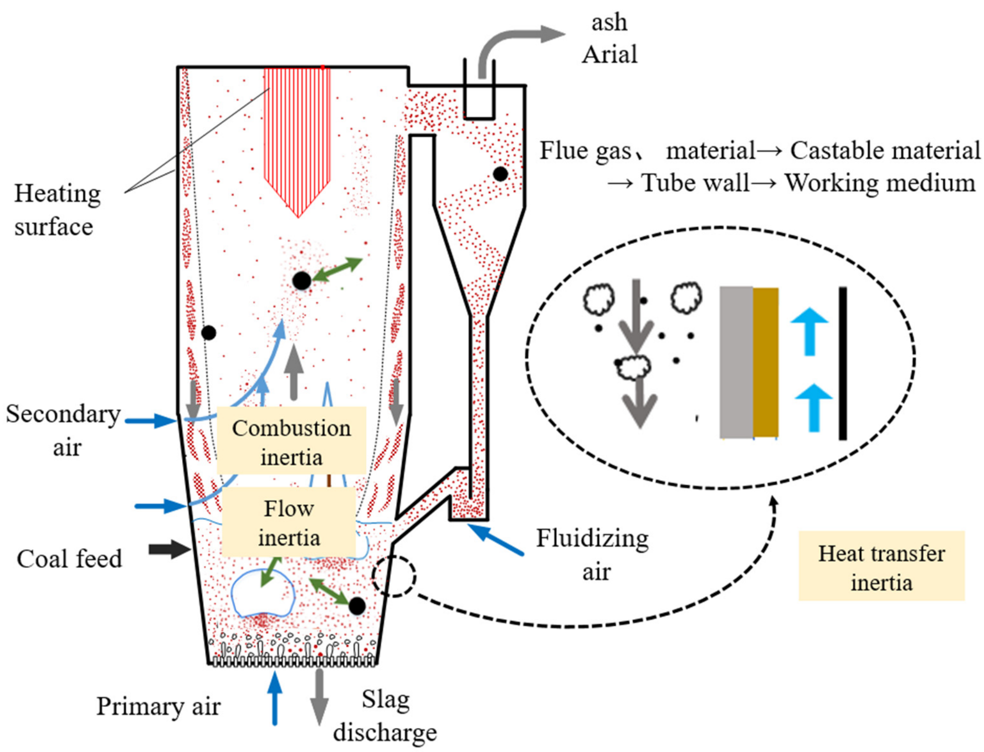

Figure 3. Distribution of inertia in CFB units.

2.1. Flow Inertia

Flow inertia refers to the inertial properties of solid particles and gases generated by motion state changes. During the operation of a CFB boiler, the material within undergoes multiple cycles in the recirculation loop, enhancing the stability of the boiler. However, when the load (the operating parameter) of the boiler is changed, the material stored in the system, the particle flow rate, and the particle concentration in the circuit do not respond immediately. Rather, they will initially remain in the previous state of motion, exhibiting obvious hysteresis. This delay is caused by the flow inertia of the material and gases.

In the current CFB boiler flow model, the quasi-steady-state flow model is usually used to determine the flow state both before and after a load change. This model predicts an exponential distribution of a void fraction along the furnace's height [15]. Its distribution pattern is calculated from parameters such as the void fraction in the dense phase region and the void fraction above the transported disengagement height (TDH).

$$\varepsilon_i(h) = \varepsilon_{\infty,i} + (\varepsilon_{den,i} - \varepsilon_{\infty,i})e^{-\alpha_i(h-H_{den})} \quad (1)$$

The void fraction is shown in Equation (1), where $\varepsilon_i(h)$ refers to the void fraction of the *i*-th-level-particle-size particle at a height of h, $\varepsilon_{den,i}$ represents the void fraction in the dense-phase region of the *i*-th-level-particle-size particle; $\varepsilon_{\infty,i}$ represents the void fraction in the zone above the TDH of the *i*-th-level-particle-size particle; α_i represents the exponential decay coefficient of the *i*-th-level-particle-size particle, and H_{den} indicates the height of the dense-phase region, given in m.

However, in the actual dynamic flow process, which is affected by flow inertia, the flow state changes in the dense-phase region and above the TDH provoke a certain time delay when affecting the flow in the intermediate-height region. This means that the adjustments of the flow state at all heights do not occur instantly and there is an obvious dynamic response process.

At present, research on the gas–solid flow characteristics of CFB boilers mainly focuses on the optimization of the flow state and improvements of the main structural components [16]. Regarding the former [15], it can be concluded that by changing the ratios of primary to secondary air flow, coal particle size to initial bed material height, etc., the fluidizing air velocity can be changed to control the gas–solid flow mixing efficiency and solid residence time. As for the latter [17–19], the interaction between the gas and solid phases results in different density distributions in different components. By optimizing key parts of a CFB boiler such as the air distribution panel, air chamber, riser, separator, and returning device, the overall gas–solid flow and circulation of the boiler can be adjusted to accommodate the special requirements of variable loads.

2.2. Combustion Inertia

Combustion inertia is a key factor in the operation of a CFB boiler, affecting the combustion rate of coal particles and the ratios of reactants during load changes. From a macroscopic view, combustion inertia directly affects the response speed and efficiency of the boiler with respect to load changes. In the combustion process, the time delay caused by the coal-particle-crushing-and-combustion process as well as the heating rate influenced by the changing furnace temperature codetermine the dynamic characteristics of the coal combustion process. When adjusting the amount of coal used or air supply, due to the presence of residual carbon heat, the combustion state in the furnace does not change immediately; rather, there exists a certain time delay.

Similar to the combustion process for coal pellets in a pulverized coal furnace, the particle size of coal pellets changes when they are burned in a high-temperature CFB boiler [20]. When coal is added to a combustion furnace, the water and volatile matter in the coal rapidly separate. And the combustion of char also requires a long process, including elements such as primary rupture, char combustion, secondary rupture, abrasion, etc. The volatile fraction has a shorter combustion time compared with that of char. When the volatile content is high, the high combustion rate consumes a lot of oxygen and in turn limits the reaction of the char. As shown in Figure 4, the whole process of pellet crushing and combustion takes a certain amount of time. It is possible to reduce the size of coal particles to decrease the time required for coal crushing, thereby accelerating the combustion process.

The burn-out time of coal particles consists of two parts: one is the time required to pre-heat the coal particles after they enter the furnace and before they start to ignite; the other is the amount of time required for the coal particles to burn out completely after ignition [21]. Compared with PC boilers, CFB boilers produce lower temperatures in the furnace, which affects the preheating and burnout time of the coal pellets. As soon as the dried and preheated new pellets are added to the combustion furnace, they are quickly surrounded by a large amount of high-temperature bed material and heated to nearly bed temperature, so pellets with large particle sizes are heated more slowly. In addition, the large-size coal pellets in the CFB boiler cycle several times in the recirculation loop before they are completely burned out, further increasing the time delay. Some scholars [22–25] have preheated coal to the ignition temperature before placing it in the furnace. From the perspective of particle size, a number of scholars [21,26,27] reported that fine-sized particles had a rapid combustion response, and they accelerated the combustion rate by decreasing the coal particle size, aiming to increase the load change rate. The reduction in the burning time of coal particles in a CFB boiler will result in rapid heat release, which can meet the variable demands of the boiler.

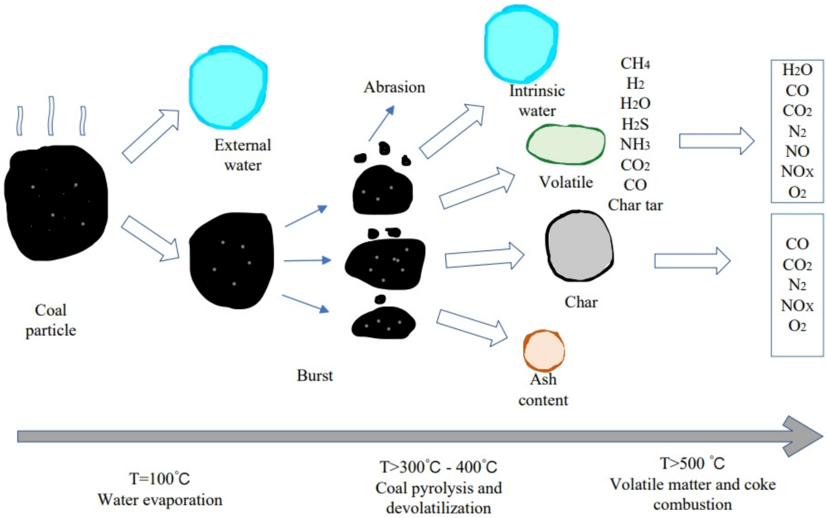

Figure 4. Modeling of coal particle crushing and combustion.

Furthermore, the coal combustion process is also influenced by furnace temperature. During the variable load process of a CFB boiler, the bed temperature changes with the load, which has an obvious effect on the coal combustion rate. As shown in Figure 5, at higher furnace temperatures, coal particles can be ignited and burn more rapidly. In contrast, a decrease in furnace temperature leads to an increase in heating time and an elongation of the tail of the combustion curve, indicating a deceleration of the combustion process. Consequently, by means of flexible bed temperature control, the inertia in the combustion process can be effectively reduced, which, in turn, improves the boiler's responsiveness to load changes.

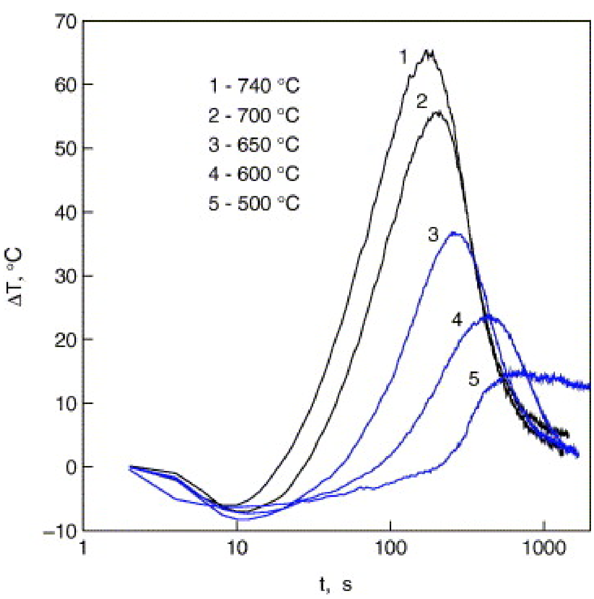

Figure 5. Variation in furnace temperature for the same type of coal at different bed temperatures [28].

2.3. Heat Transfer Inertia

The heat transfer process in the furnace of a CFB boiler is a complex phenomenon involving multiple mechanisms [29], as shown in Figure 6. Firstly, particles in the bed near the wall transfer heat to the wall through direct thermal conductivity, thereby forming a temperature boundary layer with a temperature gradient between the central region and the particles in the vicinity of the wall. Secondly, the thickness of the gas boundary layer formed when the gas–solid two-phase flow is in contact with the wall has a significant impact on the heat transfer effect. The movement and collision of particles will alter the thickness of the gas boundary layer, which, in turn, affects the convective heat transfer in the gas phase. Finally, radiant heat transfer is the primary way in which heat transfer occurs between the high-temperature bed and the wall. The efficiency of this radiant heat transfer increases with the bed temperature. However, there is a difference between the upper and lower parts of the bed due to the difference in hydrodynamic properties, which leads to a difference in their radiant heat transfer characteristics. These heat transfer mechanisms codetermine the thermal efficiency and combustion stability of a CFB boiler.

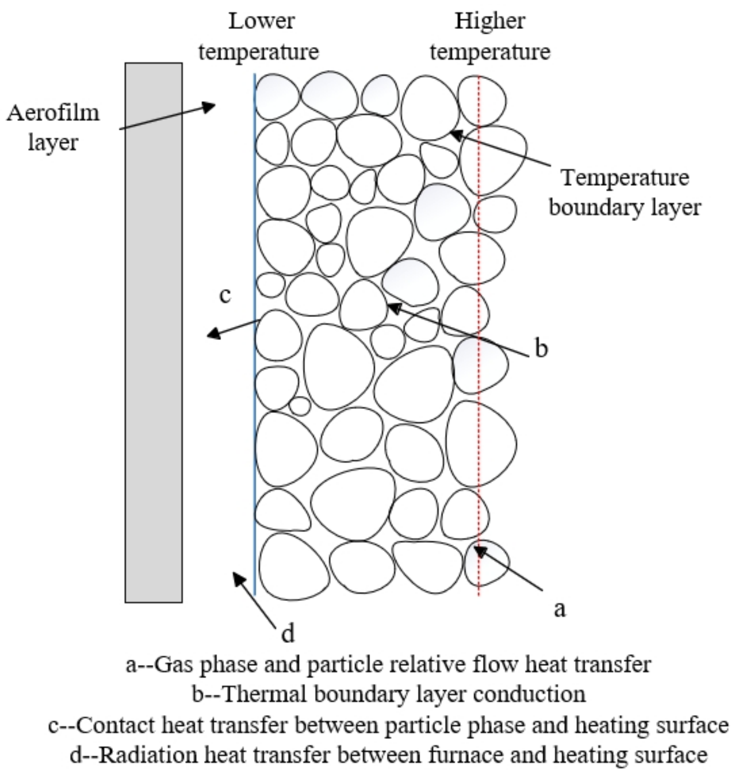

Figure 6. Gas phase and particle relative flow heat transfer in a CFB furnace.

In the CFB boiler system, the hysteresis of heat transfer is primarily reflected in the thermal response characteristics of refractories. When the furnace temperature changes, it takes a prolonged time for the refractory material in the furnace and external circulating system to reach thermal equilibrium with the furnace. This lag in heat transfer response is influenced by the thermal resistance and thickness of the refractories [30]. In the external circulation circuit, CFB boilers use different cyclones to adapt to different operating conditions and requirements. CFB boilers are equipped with refractory cyclones. In addition, as shown in Figure 7, the thermal inertia ratios of inventory, refractory, metal, flue gas, and working fluid change significantly in different variable load operation ranges. However, the refractory thermal inertia always dominates [31]. The thermal inertia of refractory materials for the cyclone and water wall section is the largest, contributing to roughly 80% of the total thermal inertia of the boiler. In light of the high thermal inertia and easy replacement of refractory material, some scholars have endeavored to reduce the heat transfer inertia of boilers by changing refractory materials [31,32]. It has been demonstrated that replacing traditional refractory material with metal grids can reduce thermal inertia by 30–35%.

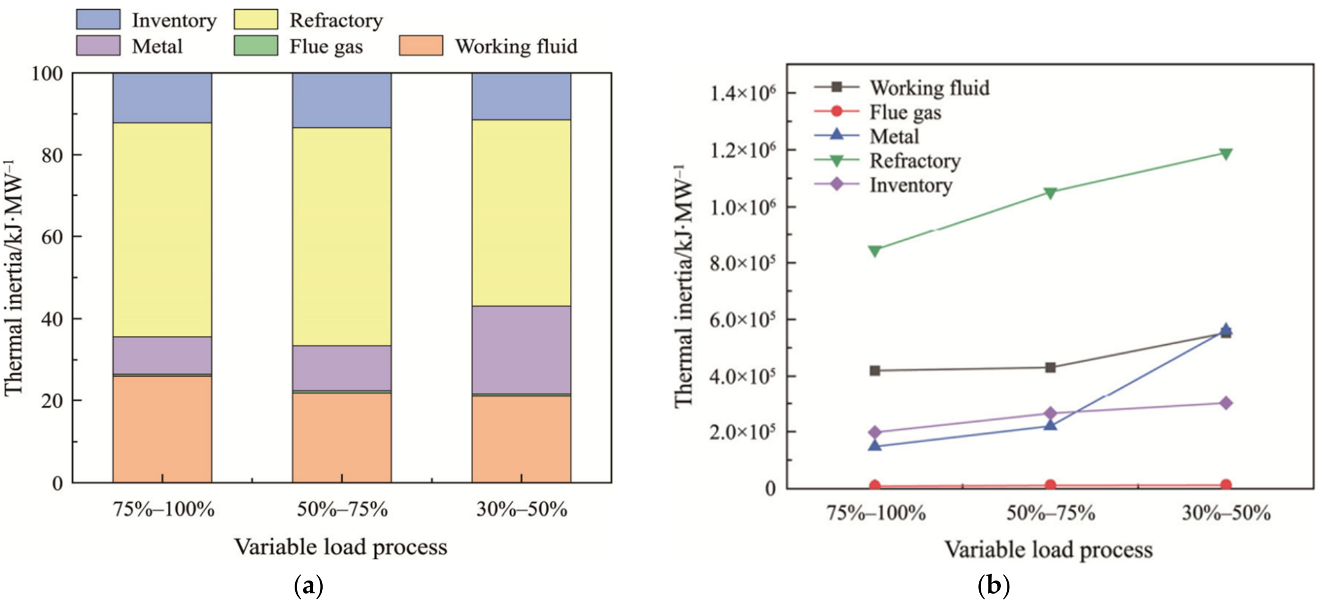

Figure 7. (**a**) The thermal inertia proportions of heat accumulators in a 330 MW CFB boiler; (**b**) thermal inertia of heat accumulators in 330 MW CFB boilers with different loads [31].

3. Experimental Study and Analysis of Dynamic Characteristics of Circulating Fluidized Bed Boilers While Processing Rapid Variable Loads

3.1. Experimental Study and Analysis of Flow Characteristics

The cold state concerns the flow characteristics and material circulation within a boiler. The circulation rate of solids and the gas velocity jointly determine the fluidization state in a CFB boiler [33], including the residence and mixing degree of the material employed. By adjusting the operating parameters and optimizing the boiler structure through cold-state experiments, the flow dead zone can be reduced, thereby improving material circulation efficiency and reducing flow inertia. Concurrently, severe ash accumulation problems emerge in the flow dead zone, resulting in elevated heat transfer inertia and the potential for complications such as furnace shutdowns [34].

The substantial inertia of CFB boilers is primarily attributed to the gas–solid two-phase flow, and the hydrodynamic characteristics, including the distribution of solids concentrations, have great influence on the combustion and heat transfer processes as well [35]. The average particle size is a crucial parameter for the distribution of solid concentrations. A reduction in the average particle size allows a greater number of particles transported by the gas flow to enter the upper part of the furnace [27]. The fuel particle size distribution in a CFB boiler can be described using the Rosin–Rammler distribution function, shown in Equation (2):

$$y_x = 1 - \exp\left(-\left(\frac{x}{x_p}\right)^{\alpha}\right) \quad (2)$$

where y_x refers to the cumulative mass distribution of particle size x; α is the uniformity index, representing the dispersion of particle size distribution; and x_p indicates the characteristic particle size, μm (the larger the x_p, the greater the overall granularity). In a CFB furnace with finer bed material, the gas–solid flow state is more uniform [36], and the solids circulation rate is more sensitive to the air velocity ratio under the same operating conditions. Fine bed material enhances the degree of gas–solid mixing in the furnace, improving the load-changing rate.

Air staging enhances the uniformity of the axial solids concentration [37], and varying the proportion of secondary air also affects the solids circulation rate. These two factors have a combined effect on the variable load capacity. Deng [38,39] conducted variable load experiments on a 4.6 m high experimental bench with the objective of comparing the hydrodynamic properties of fluidized air speed at different change rates (0.05, 0.08, and 0.11 m/s^2). As shown in Figure 8, as the change rate of air speed increases, both the change in pressure drop across the riser and the time required to stabilize the solids mass flow rate at the outlet of the riser decrease. However, the results regarding the final steady state achieved are identical, indicating that the change rate of air velocity merely speeds up the time it takes for the gas–solid flow to stabilize in the recirculation loop but does not alter the final steady state that is achieved.

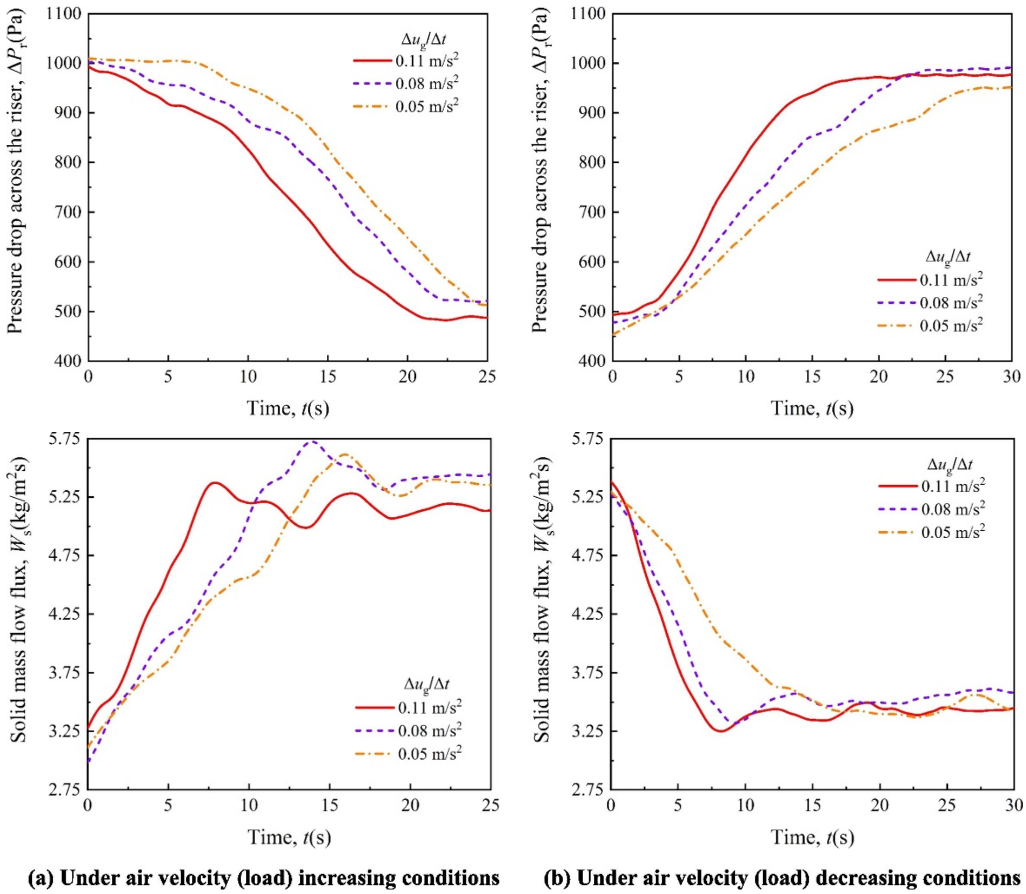

Figure 8. The change in pressure drops across the riser and the change in solid-mass flow flux at the outlet of the riser for different rates of change in the "load" of a 4.6 m experimental bench [38].

3.2. Experimental Study and Analysis of Combustion Characteristics

Fuel combustion generates heat and gases that affect the homogeneity of the gas–solid flow. Consequently, regarding flow inertia, cold-state experiment studies are very limited due to the above-mentioned strong coupling relationship. In the context of thermal state experiments, it is essential to consider the impact of combustion efficiency, temperature distribution, and other factors on the boiler's rapid variable load capacity. The optimization of combustion parameters and the implementation of dynamic combined combustion technology can effectively enhance the peaking capacity of a CFB boiler.

The load change rate is significantly influenced by various operating parameters, including primary air, secondary air, fuel characteristics, and other factors [40]. Tang [26,41] conducted a study on the process of changing the load from 50% to 75% and 100% for a 0.1 MW CFB experimental platform. The results indicated that the load change rates were only 0.69%/min and 0.81%/min. He posited that the larger fuel particle size results in a slower combustion process, which required multiple cycles to complete. This hypothesis is supported by the findings reported in [21,22,26,27]. So, scholars have tried to regulate load variation by increasing the bed material volume and decreasing the fuel particle size. It was demonstrated that the heat storage capacity of a CFB boiler increased when the bed static height was elevated from 200 mm to 400 mm. Furthermore, the rate of change in load increased from 0.78%/min to 1.14%/min when the load change rate of combustion-side load was increased from 50% to 75%. A reduction in fuel particle size from 0–1 mm to 0–0.12 mm resulted in a decrease in ignition temperature and an increase in combustion rate. The rate of load change increased from 0.78% per minute to 1.09% per minute for boilers with the same starting range of load change. These results demonstrate the impact of bed material volume and fuel particle size on the variable load rate of CFB combustion.

The dynamic combined combustion process reduces fuel particle size. This allows coal to burn more quickly and release heat more effectively. Liu [42] proposed a method for the dynamic co-firing of CFB coal particles and pulverized coal by feeding pulverized coal through secondary air pipes or coal feed pipes in a 240 t/h CFB boiler. The results indicated that both feeding pulverized coal from secondary air pipes and using higher calorific pulverized coal increased the variable load rate. When pulverized coal was fed from the secondary air pipes and the total quantity of coal calories was step-increased by more than 20%, regardless of whether the original calorific value was high, the CFB boiler was capable of variable load rates of 2.09%/min and even 3.58%/min.

In fuel preheating, an external heat source is used to heat coal before it is placed in a furnace, a process believed to facilitate the combustion process and enhance combustion efficiency. Zhu [23] converted preheated pulverized coal into preheated gas with high calorific value and preheated char with high physical sensible heat and a sufficient porous structure, thereby achieving low-load ignition and improving combustion stability. This method can lead to a maximum load variation of up to 3.75%/min in a 1 MW combustion chamber. Hui [25] investigated the depth and flexible load regulation characteristics of pulverized coal preheat combustion in a 40 kW CFB boiler. Their study examined the variables that influence preheating and combustion in a range of varying load conditions. During preheating, the rising load has a long residence time regarding solid fuel at the low-load stage (13–25%). The fuel is more completely mixed with the primary air, which promotes the gasification reaction of pulverized coal and accelerates the variable load rate. The variable load rate in the case of a decreasing load is influenced by the combination of the combustion rate and thermal inertia. During combustion, the load increase rate is primarily determined by the pulverized coal reaction rate and reaction intensity. A high load step (>25%) will result in a rapid increase in fuel and air volume at the initial stage of combustion. This is because the combustion rate is dependent on the reaction rate and furnace temperature. The limited volumetric thermal intensity of the combustion chamber and the reduced radiative and convective heat transfer from hot flue gases to the pulverized coal particles will result in prolonged ignition and combustion processes. At a loading step of 25%, the maximum variable load rate reaches 4.17%/min and 3.13%/min for the preheating and combustion processes, respectively.

The research on combustion characteristics during rapid load change in a CFB bed is now focuses on small and medium-sized test benches, providing a reference regarding the variable load regulation of large boilers. However, the application of these methods to large boilers still requires further development.

3.3. Experimental Study and Analysis of Heat Transfer Characteristics

In practice, the boilers used in the field of CFB contain a significant quantity of refractory materials. The inertia of the refractory material serves to enhance the heat storage capacity of a CFB [41]. Sun [31] discovered that over 50% of the total thermal inertia of CFB boilers is attributable to refractory material. During the load increase process, the heat stored in the heat accumulator within the CFB boiler is reduced, and the reduced heat is then stored in the medium. Consequently, the cited authors proposed a solution based on this concept, whereby existing refractory material would be replaced with metal grids. This scheme improves heat transfer in the furnace and reduces the furnace temperature, in turn affecting the thermal inertia of each heat accumulator in the boiler during a load change.

However, Dong [32] found that merely increasing refractories' thermal conductivity (that is, replacing them with a high-thermal-conductivity material) is ineffective. As the thermal conductivity of a refractory increases to a certain level, the time required to reach thermal equilibrium becomes greater. Therefore, heat transfer can be accelerated by a reduction in the thickness of the heat-resistant material. The refractory material of a 300 MW subcritical CFB boiler was modified to improve the average load increase rate from 0.48%/min to 0.53%/min during a 50–90% load increase, constituting a relative improvement of approximately 10.42%. Although this increase in the variable load rate of the CFB boiler generated by refractory material change was not high, the variable load rate can be further increased by refractory material change in combination with other boiler variable load techniques.

3.4. Experimental Study and Analysis of Pollutant Emissions

The NO_x and SO_2 emissions from a CFB boiler are closely related to the combustion conditions during the variable load operation of a boiler. The oxygen concentration distribution in the furnace affects NO production [43]. NO_x emissions from fluidized bed combustion are affected by the combustion temperature and uniformity, excess air coefficient, and staged combustion [44]. Desulfurization efficiency is mainly influenced by parameters such as limestone particle size, bed temperature, and calcium–sulfur molar ratio.

Zhang [45] investigated the changes in pollutant emissions generated by increasing the load from 50% to 100% for a 350 MW supercritical CFB unit. The increase in the coal feed rate caused a sharp increase in the mass concentration of SO_2 in the furnace. Subsequently, the bed temperature rose, the desulfurization reaction entered the optimum operating temperature range, and efficiency is improved. As a result, the SO_2 mass concentration at the outlet of the furnace increased rapidly and then decreased slowly. In addition, the increase in bed temperature also led to an increase in NO_x emissions from 80 mg/m^3 to 160 mg/m^3. Primary airflow reduction was limited when the load was reduced to the point where minimum fluidizing air velocity must be maintained. So, the benefits of graded air distribution could not be fully utilized, resulting in a weakly reducing atmosphere in the dense-phase region and increased NO_x emissions.

Tang [26,41] investigated the dynamic emission characteristics of pollutants as the load was increased from 50% to 100% in a 0.1 MW CFB experiment. As shown in Figure 9, when the load is increased by adding air first and then coal, the rise in oxygen content will result in a sharp increase in the instantaneous emission of NO_x. Subsequently, as the oxygen content decreases, the instantaneous emission of NO_x will also decrease. In order to prevent transient surges in NO_x emissions during load changes, it is necessary to adjust the fuel/air ratio in a rational range in order to maintain a suitable combustion atmosphere and control NO_x emissions. An increase in load will increase average NO_x emissions. When the load is increased from 50% to 75%, the average NO_x emissions increase from 276 mg/m^3 to 296 mg/m^3. When the load is increased from 75% to 100%, the average NO_x emissions increase from 296 mg/m^3 to 334 mg/m^3. The quantity of bed material and the size of coal particles affect emissions of pollutants during the load change. An increase in bed material quantity is beneficial for improving the combustion-side load change rate but it has no significant effect on NO_x emission concentrations. Reducing fuel particle size facilitates the formation of reducing components such as HCN and NH_3, which can effectively reduce NO_x emissions.

Both dynamic co-firing and fuel preheating can enhance the variable load rates of CFB units. However, it is essential to monitor and mitigate the pollutants associated with this technology. In the dynamic co-firing of pulverized coal and coarse coal particles [42], the heat released from the rapid combustion of pulverized coal increases the temperature of the entire boiler by approximately 30 °C. The critical fluidizing air velocity in the dense zone decreases when a coal pipe feed is employed. This phenomenon is accompanied by an increase in the number of gas bubbles that pass through the bed [27]. The increased rigidity of the bubble jet leads to a longer transit time for the oxygen-enhanced gas within the bubbles. This results in a greater reduction in the atmosphere. The concentration of NO_x emissions increases by approximately 40 mg/m^3 as a consequence of the elevated temperature and the reductive atmosphere. Hui [25] analyzed the effect of preheating on pollutant emissions. As the load increases, there is a gradual increase in the emission of NO, which is mainly due to the increased input of fuel-N and the oxidation of char-N. Furthermore, due to the lower combustion temperature (below 950 °C), NO_x emissions are higher in the low-load range (25% to 50%) than in the high-load range.

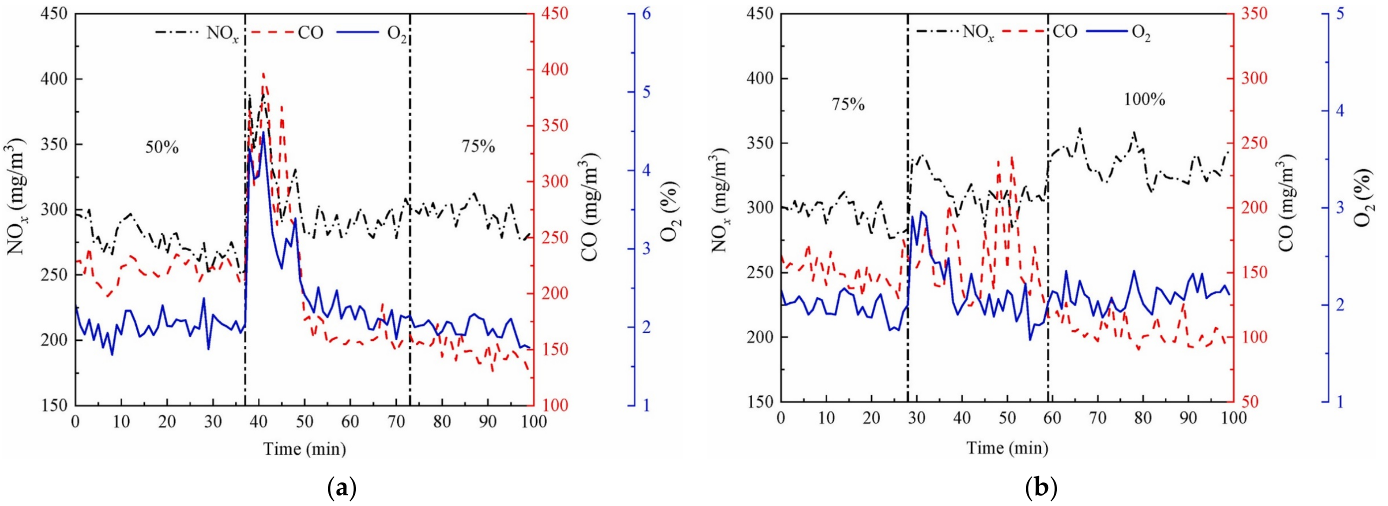

Figure 9. (**a**) Changes in pollutant emissions from a 0.1 MW test bed when loads are changed from 50 to 75%; (**b**) changes in pollutant emissions from a 0.1 MW test bed when loads are changed from 75 to 100% [26,41].

4. Development of a Numerical Model for the Dynamic Characteristics of Circulating Fluidized Bed Boilers While Processing Rapid Variable Loads

In order to accurately depict the variable load dynamic characteristics of a CFB boiler, scholars usually construct corresponding dynamic models for research purposes. According to various methods for describing gas–solid two-phase flow behavior, the dynamic model of the furnace side of the CFB boiler can be summarized as a mathematical model based on the fluidization model (FM), computational fluid dynamics (CFD) model [46], and computational particle fluid dynamics (CPFD) model. The FM can accurately reflect a real CFB boiler's flow state while also decreasing the calculation time and difficulty. Consequently, the majority of scholars currently employ one-dimensional models or core–annulus models in FM to simulate the variable load dynamic characteristics of CFB boilers. Although CFD and CPFD models offer significant advantages in terms of simulation accuracy and analytical capability, they usually require more computational resources and more-complex data processing.

In addition to these models, there are dynamic models involving machine learning algorithms and control techniques. The traditional coordinated control system for a CFB is similar to the coordinated control system for coal powder boilers. At present, the more-advanced CFB boiler coordinated control systems include advanced energy balance control and fast load response control. Machine learning algorithms and control techniques are usually classified within the category of parameter identification in mathematical models [47,48]. Unlike modeling methods based on physical process mechanisms, data-driven modeling approaches do not rely on an understanding of process mechanisms. Therefore, in this paper, we focus on exploring three inertial mechanisms and do not discuss mathematical modeling approaches in depth.

4.1. Fluidization Model

In the FM, the CFB boiler is divided into regions based on different flow behaviors (such as flow patterns), which are called cells [49]. As shown in Figure 10, considering the mass and heat exchange between cells, the mass and energy conservation equations for the gas and particle phases are developed separately for each cell. Rather than solving the momentum conservation equation directly, the FM employs a strategy of closing the original set of equations by estimating key flow parameters (such as particle concentration distribution and the flow rate of solids) through simplified methods (such as sub-models or semi-empirical formulations).

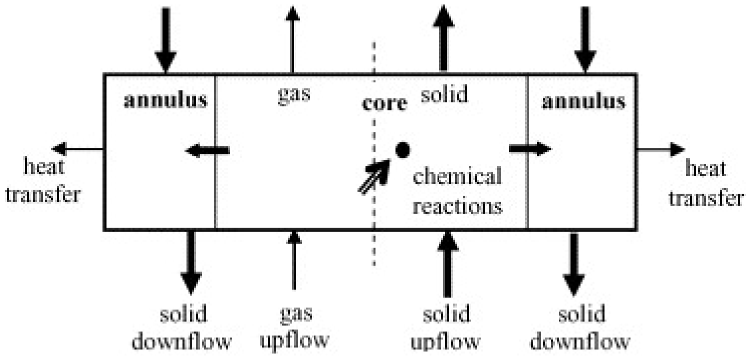

Figure 10. Typical cell configuration [49].

The advantage of the FM is that it does not require one to solve highly nonlinear momentum conservation equations. The sub-models or semi-empirical formulas used are mostly derived or generalized based on extensive experimental data, which are accurate and widely applicable. This approach enables the FM to achieve the desired prediction accuracy with minimal computational resource consumption. Based on these advantages, the FM is particularly suitable for modeling industry-scale CFB boilers. Consequently, it has been widely used in the prediction and analysis of CFB boiler variable-load dynamic characteristics.

4.1.1. Zero-Dimensional Model

The zero-dimensional (0-D) model treats the simulated object as a single and uniform system. The 0-D model is designed to assess this system's performance and output. It does not consider the internal spatial distribution and gradient variations, and it considers the physical parameters inside the model to be uniformly distributed. In the context of modeling a CFB boiler using the 0-D model, it is customary to divide the entire boiler system into several major sections. These include the furnace, separator, standpipe, and loop seal, which are typically considered four separate cells [50,51]. Saastamoinen [50] conducted a simplified study of the combustion kinetics of a CFB boiler. He considered the fuel particle size distribution and combustion state in order to derive simplified equations for estimating the combustion rate and the response of fuel stock to supply changes. The constructed 0-D semi-empirical combustion model is able to predict the dynamic combustion characteristics in response to fuel supply perturbations (such as impulses, steps, linear increases, and cyclic changes) or variable loads.

4.1.2. One-Dimensional Model

The one-dimensional (1-D) model considers the variation of physical parameters in the vertical direction, assuming a uniform distribution of physical parameters across the boiler's cross-section. As shown in Figure 11, the 1-D model divides the flow field vertically into a number of cells, assuming that the physical parameters in each cell are the same. The primary component of this model is the mass and energy balance sub-model that introduces empirical correlations to establish mass and energy balance equations for each cell. Additionally, it incorporates equations for mass and energy exchange between cells.

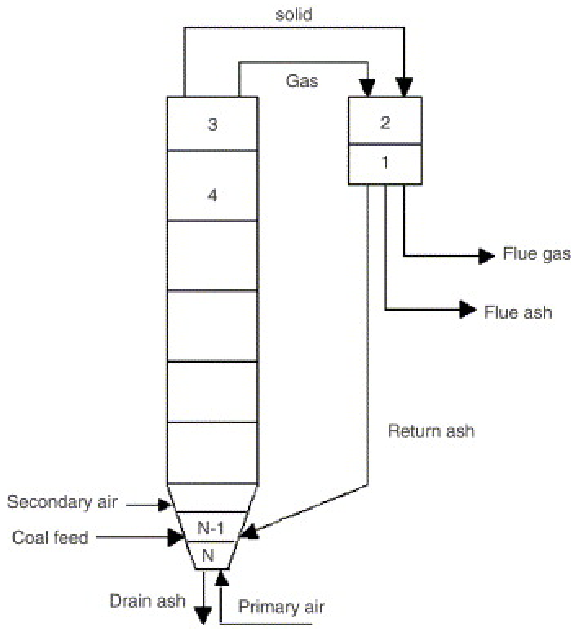

Figure 11. Cell structure of the 1-D CFB model [15].

The 1-D model is capable of accurately representing the fundamental characteristics of gas–solid flow in CFB boilers at a relatively low computational cost, rendering it particularly well-suited for the simulation and analysis of industrial-scale CFB boilers. Weiss [52] was the first to introduce the concept of 1-D modeling to CFBs. He divided the CFB system into three subsystems: a reactor, a separator, and a heat exchanger. He then linked the subsystems and divided them into multiple chambers. In addition to the mass and energy exchanges between neighboring chambers, the relationship between each chamber and chambers that are not directly adjacent was also considered in order to simulate the operation of the CFB reactor under both steady- and unsteady-state conditions. Li [53] proposed an empirical formula for the height of the dense-phase bed based on Weiss's work, and it was used to develop a 1-D kinetic model for a large-scale CFB boiler with a capacity of 220 t/h. This approach made the model adaptable to the calculation of variable operating conditions and dynamic characteristics and enabled the prediction of the dynamic response of the CFB boiler when the boiler coal feed was decreased from 100% to 90%.

In order to enhance the precision and applicability of the dynamic models of CFB boilers, scholars have integrated and expanded upon the 1-D model from various vantage points. Deng [54] posited that the solid storage capacity of the outer circuit of CFB boilers is substantial and greater emphasis should be placed on the flow dynamic characteristics of the outer circuit. Subsequently, he devised a 1-D kinetic model of the 350 MW industrial-grade CFB boiler based on mass and pressure balances. Hu [55] developed a 1-D full-loop dynamic model of the furnace, taking the flow inertia and coupling effects of the components within the entire loop into account. He validated the model's accuracy under variable load conditions, providing a robust foundation for investigating the dynamic response of the entire loop at the furnace-side CFB when processing variable loads. There is no embedding model designed for CFB boilers in the commercial software product Aspen 8.4 Dynamics. Therefore, in contrast to PC boilers, the principal challenge in modeling the dynamic behavior of CFB boilers is the accurate reflection of the influence of the flow region. As shown in Figure 12, Zhu [56] borrowed the cell model idea and embedded the heat transfer coefficient sub-model reflecting the influence of flow regime in a 1-D model. She extended the steady-state model to a dynamic model and developed a dynamic process model for a 350 MW CFB boiler.

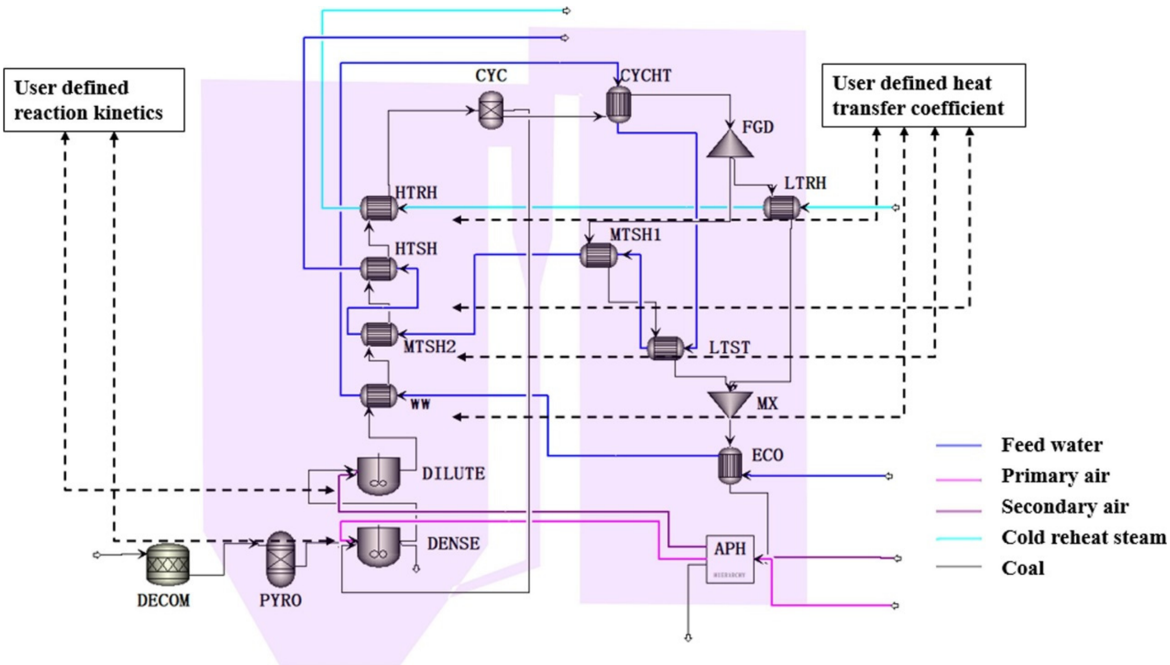

Figure 12. 1-D modeling of a 350 MW CFB boiler in Aspen [56].

4.1.3. Core–Annulus Model

In an actual CFB, the complexity of the gas–solid flow results in an uneven distribution of solids, especially between the center of the bed and the area near the boiler wall. In order to model this phenomenon more accurately, the core–annulus model (1.5-D) was extended from the traditional 1-D model. As shown in Figure 13, the core–annulus model divides the boiler furnace radially into the annular zone and the core zone [49] to characterize the gas–solid flow behavior in the two zones and construct a sub-model describing the mass exchange rate between the two zones, respectively. Due to the turbulence effect and collision of particles in the gas–solid flow, the concentration of solid particles in the center region is relatively low, and the gas rises faster. The area near the wall has a higher concentration of solid particles and a slower rate of gas rise. This uneven distribution results in a flow lag and affects the combustion efficiency of the particles.

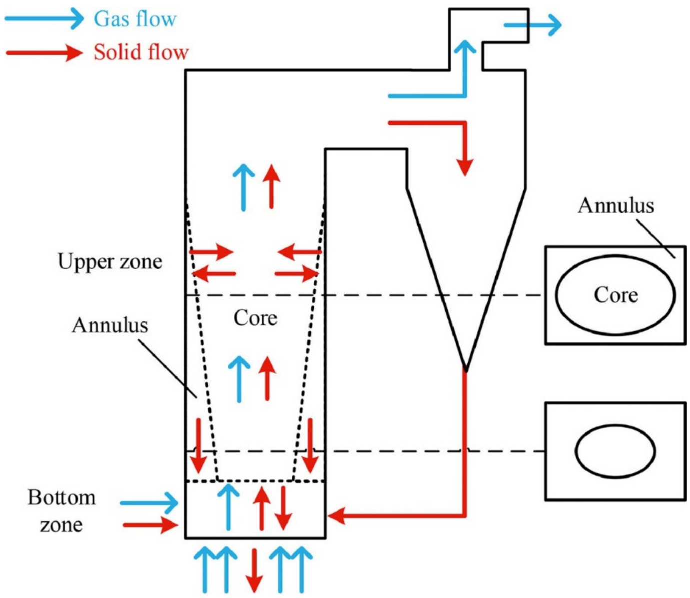

Figure 13. Typical schematic of the core–annulus model for CFB boilers [57].

The core–annulus model has been favored by researchers for its ability to more accurately capture the flow characteristics in different regions. Park [58] constructed a simplified model of the flow in a 1.5-D 0.3 MW coal-fired CFB boiler by considering the differences in flow conditions in the center and side wall zones of the furnace as well as the thermal inertia of the circulating castables. The accuracy of the model's predictions of furnace temperature, char, and oxygen content after a step change in coal feed was verified by comparison with real furnace test data. Subsequently, Chen [49] considered the effect of bed material and fuel particle size distribution on fluid dynamics, combustion, and heat transfer based on Park's work [58]. He used a modular modeling approach to simulate the steady-state and dynamic processes of a 410 t/h CFB, and the simulated data were in good agreement with the measured data. Kim [59] then used a selection of models for other physical phenomena in fluidized beds. In their study, they simulated the characteristics of the behavior of solids, such as the mass distribution of local solids and the flow of solids in the furnace and of circulating solids under various operating conditions. Based on a 1.5-D model using advanced process simulation (APROS) software, Peters [60] and Zhang [61] simulated the combustion characteristics of a 1 MW CFB boiler with different fuels, blending ratios, and loads and the hot and cold startup process of a 660 MW ultra-supercritical CFB boiler under 0–50% turbine heat acceptance (THA) conditions, respectively. These studies have shown that the core–annulus model can predict the dynamic behavior of CFB boilers and is a powerful tool for rapid variable load studies of CFB boilers.

4.1.4. Two-Dimensional Model

The two-dimensional (2-D) model provides a more detailed spatial division in the simulation of a CFB boiler, not only taking into account the variation in physical parameters with respect to the height of the boiler chamber but also carefully distinguishing the radial distribution of the differences [62,63]. Li [64] performed a dynamic simulation of a 660 MW ultra-supercritical CFB boiler. This simulation divided the furnace into four parallel subcircuits in the radial distribution of the cells according to the specific arrangement of the separators in the boiler system and took into account the mass exchange between these circuits. The advantage of the 2-D cell model is its ability to accurately reflect the lateral distribution of the operating parameters in the furnace, an essential facet for understanding and optimizing the performance of CFB boilers. However, comparing the two-dimensional model constructed using the cell model with the CFD/CPFD model revealed that the former not only fails to reduce computational resources but also has much worse computational accuracy than the latter. Therefore, few researchers have simulated the variable loads of a CFB boiler using the two-dimensional model.

4.2. Computational Fluid Dynamics Model

The computational fluid dynamics (CFD) model establishes the mass, momentum, and energy conservation equations for the gas and particle phases, respectively, and introduces appropriate assumptions to complete the set of equations describing the flow behavior in the furnace in detail. In order to solve the system of equations, the flow field is divided into a number of spaces with specific dimensions, called meshes, according to the accuracy demand of a study. The original set of continuous equations is then discretized using a different method to obtain complete flow field parameters, including pressure, flow velocity, and particle concentration.

Nowadays, most scholars use CFD models to carry out the steady-state simulation of the flow, combustion, and other characteristics of CFB boilers [65], but research on the variable load process in CFBs is still immature. Huttunen [66] used a detailed CFD simulation approach for a 76 MW bubbling fluidized bed (BFB) boiler and a 90 MW CFB boiler. A comparison demonstrated that the greater thermal capacity of CFB boilers resulted in a slightly slower load change rate than that of BFB boilers. Additionally, the substantial quantity of material affected the temperature distribution in the furnace during load changes. Wang [67] employed a 3-D CFD model to simulate the chemical chain gasification process of lignite in a CFB. This approach enabled the capture of the axial and radial velocities of transient particles, providing a comprehensive characterization of the process.

4.3. Computational Particle Fluid Dynamics Model

The computational particle fluid dynamics (CPFD) model meticulously simulates the behavior of the particle phase and its interaction with the fluid phase. This is achieved by individually tracking and calculating the trajectory and interactions of each particle, including particle motion, collisions, and agglomeration phenomena. The difference between CFD models and CPFD models is that CFD models usually employ single-phase or multiphase flow models for particles, whereas CPFD models are more precise in their representation of particle phase behavior. Both CFD and CPFD models involve the use of Navier–Stokes equations to characterize the fluid phase. However, CPFD is specifically designed to optimize the representation of particle–fluid interactions.

The primary reason for CPFD's computational efficacy is the concept of "computational particles", "Computational particles" are an extension of the concept of "fluid micro-clusters" within the Lagrangian method, which is applied to the particle phase to form "particle micro-clusters". Each computational particle is composed of multiple real particles with identical physical properties, kinematics, and chemical characteristics. This not only enhances computational efficiency but also facilitates the addressal of particle flow characteristics. The utilization of CPFD models in the commercial software product Barracuda 17.4.0™ is more appropriate for the simulation of large CFB boilers.

As with the CFD model, the CPFD model has been extensively validated in terms of its accuracy in simulating large CFB boilers. However, the majority of studies to date have focused on steady-state simulation [68–70], which involves the comparison of results before and after variable loads. There is a paucity of research on the dynamic characteristics of the variable load process. Zhang [71] constructed a 20 MW CFB boiler model based on CPFD and subsequently simulated the dynamic results from the startup to steady-state operation. The results accurately predicted the location of wear and verified the accuracy of the CPFD simulation.

In order to gain insight into the mass balance of the recirculation loop under load regulation, Deng [38,39] employed a CPFD model to simulate the dynamic behavior of the CFB cold test bed under varying rates of change of the "load" (characterized by the primary air velocity). Shen [72–74] constructed a comprehensive thermal model of a CFB boiler using the CPFD method to simulate the gas–solid flow and pollutant emission characteristics of a 350 MW coal-fired CFB boiler under variable loads, thermal start-up, and banked-fire conditions. This study was conducted to analyze the dynamic characteristics of pollutant emissions from CFB boilers under banked-fire and thermal start-up conditions. The results of all simulations conducted demonstrated that the dynamic characteristics of the CFB boiler variable load process simulated by the CPFD model exhibited a high degree of accuracy.

5. Numerical Simulation Study on the Dynamic Characteristics of a Circulating Fluidized Bed Boiler While Processing Rapid Variable Load Conditions

5.1. Simulation Study and Analysis of Flow Characteristics

Flow inertia determines material redistribution and stabilization in the variable load process. The solid particle quantity not only affects the thermal inertia of the bed material but also influences the gas–solid reaction rate, which, in turn, determines the combustion inertia. Consequently, flow inertia represents a crucial factor limiting a CFB unit's variable load rate. Furthermore, the heat and gases generated during combustion exert a direct influence on the state of particle motion and flow characteristics.

The difference in airflow rate affects the time required for a boiler to stabilize in operation. For full-load operation, the airflow rate is higher, resulting in a shorter stabilization time than for partial-load operation [75]. The airflow rate is determined by operating parameters, including the primary and secondary air flow rates. It has been observed that changes in parameters such as bed pressure and the mass flow rate of solids exhibit hysteresis with respect to the operating parameters. Rapid changes in operating coefficients will cause greater hysteresis and more pronounced fluctuations in the CFB loop, which are detrimental to operational safety. Therefore, it is of practical importance to elucidate the mechanism of how operating parameters influence flow inertia.

However, the majority of studies on CFB boilers focus on the stable flow characteristics, with only a few considering the full boiler circuit flow dynamic characteristics [76–78]. Some scholars [38,39,54,79] have posited that the flow inertia resulting from the substantial solid storage capacity within the outer circuit of a CFB boiler should not be overlooked, and further investigation into the outer circuit is required. Deng [38,39,54] created a 1-D kinetic model for the full-loop of a 135 MW CFB boiler based on mass and pressure balances. Subsequently, he constructed a CPFD model for a 4.6 m full-loop experimental table. The results indicated that compared with adjusting the slag discharge, changing operating parameters, separator efficiency, castable material thermal conductivity, and thickness; reducing operating bed pressure; and adding circulating ash have a more significant impact on the variable load of a CFB boiler. The findings revealed the influence of these adjustments on the variable load characteristics of a CFB boiler. By reducing the initial bed pressure in the furnace to 5.5 kPa, reducing the castable material thickness to 0.06 m, and setting the applied/discharged circulating ash flow rate to 6 kg/s, it was possible to increase the maximum variable load rate to approximately 4%/min.

As the boiler load increases, the volume fraction of particles in the dense-phase region increases, while the flow field distribution in the dilute-phase region becomes more uniform. Conversely, as the boiler load decreases, the circulating material stock decreases, and the particle volume fractions in both the dense- and dilute-phase zones also decrease [80]. In the context of dynamic load change, using a reasonable amount of residual carbon ensures that the boiler can change loads quickly. The addition or removal of circulating ash can rapidly modify the bed material quantity in a CFB boiler, which can consequently influence the suspended particle distribution at all heights, decrease flow inertia, and effectively enhance the boiler's variable load rate. Hu [79] developed a 1-D model of the full circuit of a 135 MW CFB boiler, taking the gas–solid flow coupled effects, heat transfer, and combustion processes into account. As the load decreases, the bed pressure increases with decreasing particle of the bed material. This phenomenon indicates that the load rate is reduced by the solids-induced flow inertia. In order to enhance the rate of load reduction in the boiler, the circulating ash can be discharged from the loop and subsequently stored in a silo; conversely, during the load-increasing process, the stored ash can be added back to the boiler to increase the heating rate. This methodology enables the boiler to achieve a variable load rate of 4%/min. Stefanitsis [81,82] developed a 300 MW CFB boiler transient/dynamic 1-D model using the commercial software APROS and investigated the influence of thermal energy storage on power consumption. The results of the simulation of a 100–60–100% load change indicated that thermal storage can significantly enhance the load change rate. Compared to the non-thermal storage method, the rates of increase or decrease in loads increased from 5.09/5.06%/min to 5.64/5.73%/min with the use of solids inventory thermal storage or the removal of 20%, respectively. As the percentage of solids in the inventory increased to 40%, the variable load rate reached 6.19/6.12%/min.

5.2. Simulation Study and Analysis of Combustion and Heat Transfer Characteristics

When the load changes, the corresponding high combustion inertia leads to a less adaptable combustion rate, which may lead to incomplete combustion. The heat transfer inertia is influenced by the material properties and the heat storage capacity, resulting in a delay in temperature and pressure changes. CFB boilers are complex and difficult to regulate because of their multi-parameter characteristics. The combustion rate in the furnace will be affected when the load changes, such as when primary air, secondary air, and coal flow rates are changed. Furthermore, the heat released by uneven combustion will also affect furnace temperature changes.

The increase or decrease in loads is affected by different inertia factors. Castilla [75] developed a 1.5-D model for a 80 MW CFB. It was found that the load reaches a new steady-state more easily when it increases than when it decreases. Furthermore, the differing heat capacities between the top and bottom of the furnace have a significant effect on the stabilization time. It has been observed that heat transfer hysteresis is greater than combustion hysteresis. As the load increases, the fuel combustion inertia becomes the primary influencing factor, while as the load decreases, the heat transfer inertia dominates. The lower-bed region has the slowest load change rate because it has a substantial heat capacity and minimal oxygen. In contrast, the upper furnace region responds more rapidly to temperature changes and is able to reach a new steady-state more quickly. Furthermore, this region is also more sensitive to load changes and fuel regulation.

Different operating parameters have different effects on load change. Alobaid [83] used APROS software to apply a 1-D model to a 1 MW experimental furnace with low-rank coal. This process examined how combustion changed when the load increased from 63% to 100%. In order to further analyze the effects of primary airflow, secondary airflow, and coal feed on combustion, Yang [84] employed the SIMULINK model predictive control (MPC) method to investigate the influence of primary and secondary airflow ratios during variable load on a 350 MW supercritical CFB boiler. He concluded that the primary and secondary airflows exert distinct effects on the CFB combustion system. An increase in the primary airflow elevated the overall oxygen level in the furnace, which enhanced the instantaneous char combustion rate. But the change in secondary airflow only directly affected the oxygen content in the dense-phase zone. These results are also in agreement with the results simulated by Zhu [56]: the secondary air flow rate changes have a lesser effect on the CFB boiler system than the primary air flow rate. At variable loads, rapid changes in the primary and secondary air can facilitate stored energy release or suppression on the combustion side, overcoming the significant delay and inertia caused by the fuel quantity. By regulating the primary and secondary air, it is possible to maintain the unit's variable load rate within the range of 1%/min to 1.14%/min.

5.3. Simulation Study and Analysis of Pollutant Emissions

From the perspective of the gas medium, stronger gas streams exert a pronounced influence on the reducing atmosphere within the boiler because of their capacity for significant penetration. Zhang [85] divided a furnace into 11 cells in the height dimension and modeled the dynamics. Zhang's model simulated the SO_2 and NO_x emissions from a 350 MW CFB boiler during the variable load process. Increasing the bed temperature at the load increased NO_x emissions and decreased SO_2 emissions. It is possible to reduce the combustion rate in the dense zone by keeping the total air flow constant and reducing the primary and secondary air flows. This reduction in bed temperature reduces the formation of volatile nitrogen and lowers NO_x emissions. Every 0.29% reduction in the primary air ratio or 1.36% increase in the upper and lower secondary air ratios will reduce emissions by 1 mg/Nm^3 NO_x. On the contrary, lowering the bed temperature during load reduction makes NO_x emissions decrease and SO_2 emissions increase. The increase in the molar ratio of calcium to sulfur can reduce SO_2 emissions. Every 0.23% increase in the molar ratio of calcium to sulfur leads to a 1 mg/Nm^3 SO_2 reduction in emissions.

From a solid standpoint, smaller particle sizes can change the solid concentration in the furnace, affecting the penetration of the airflow into the boiler. Ke [44,86] developed 1-D/1.5-D CFB overall combustion mathematical models for SH-135MW and SC-350MW and discussed their NO_x emission characteristics over a wide load range. As shown in Figures 14 and 15, both increasing cyclone efficiency and decreasing coal particle size can affect pollutant emissions. This is because both measures reduce the particle size of bed material, which decreases the minimum fluidization velocity and alters the gas–solid flow behavior in a CFB boiler. This improvement allows for a greater quantity of oxygen-rich gas to ascend as bubbles through the lower dense-phase region. The acceleration of the bubble rise velocity enhances the bubble jet's initial momentum, allowing bubbles to break gradually in the splash zone and mix slowly with the particles. These behaviors lead to the formation or enhancement of a reducing atmosphere, which effectively suppresses NO_x production.

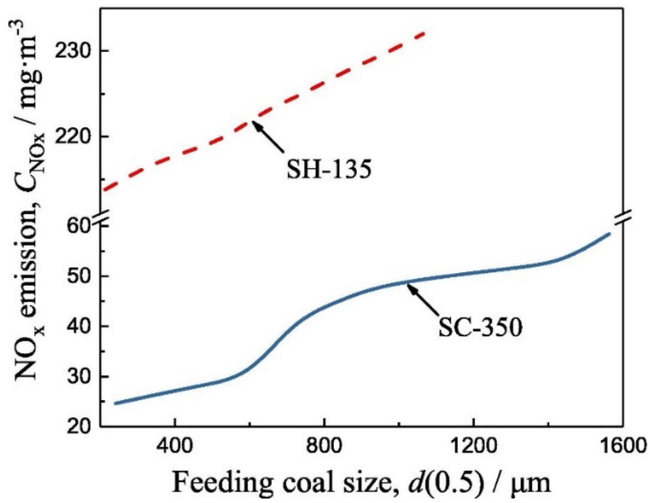

Figure 14. Effect of feeding coal size on NOx emissions in SH-135MW and SC-350MW CFB boilers [44,86].

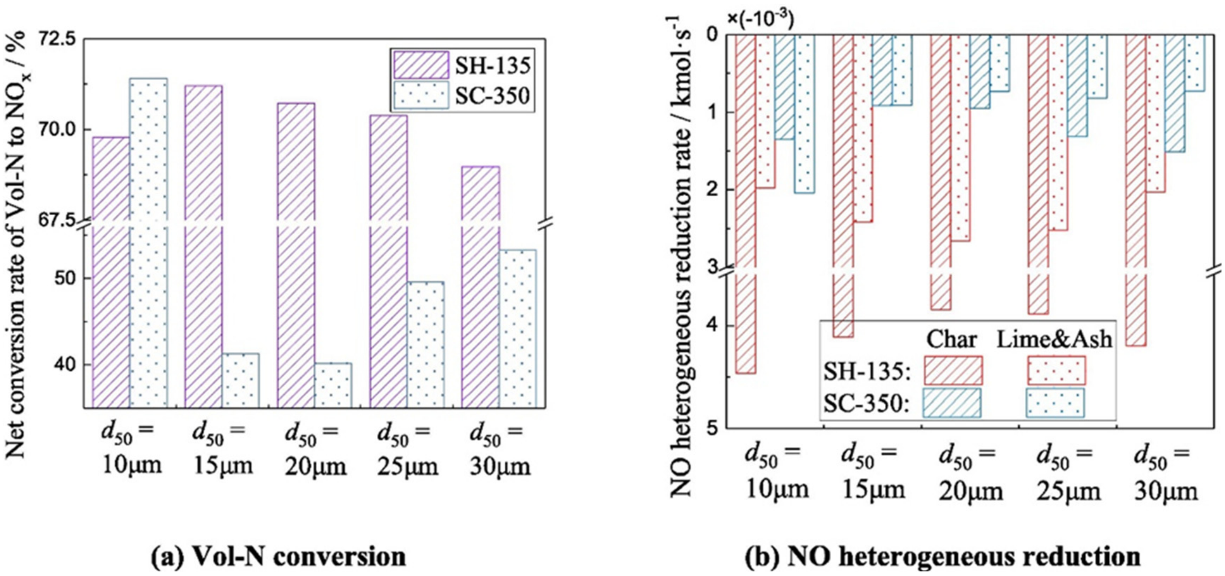

Figure 15. Comparison of NO_x formation/reduction rates for different cyclone efficiencies (for the whole furnace) in SH-135MW and SC-350MW CFB boilers [44,86].

When studying pollutant emissions from CFB boilers during load changes, it is insufficient to focus on the effects of gases or solids in isolation. Rather, we must simultaneously consider the effects of changes in multiple parameters on pollutant emissions during load changes. Liu [87] developed a mathematical model of a 300 MW subcritical CFB boiler and used it to conduct step change tests on the coal feed, air supply, and urea flow rate, and all parameters changed simultaneously. When the coal feed rate was elevated by 5%, an initial increase in NO_x emissions occurred because of the rapid evolution of volatiles from the fuel. Subsequently, the increase in the combustion of carbon-based reducing medium resulted in a decrease in NO_x emissions. When the air supply was increased by 5%, the O_2 concentration in the furnace rose, prompting a NO_x emission increase. With a 5% increase in urea flow rate, rising NH_3 production in a selective non-catalytic reduction (SNCR) reactor increased the ammonia-to-nitrogen ratio. This accelerated the denitrification reaction rate and thus reduced NO_x emissions. When the coal feed and air supply were simultaneously increased by 5%, the NO_x emission mass concentration increased rapidly at first and then decreased gradually. Eventually, it reached an equilibrium point higher than the initial value. This phenomenon can be attributed to the inherent inertia of the coal combustion process. When the supply of air to the furnace combustion was increased at a faster rate than the coal feed, the oxidizing atmosphere was initially enhanced and subsequently weakened. During the 200 MW variable load process, the bed temperature and furnace outlet temperature decreased. And lowering the furnace temperature slowed chemical reaction rates and combustion atmosphere changes. These phenomena resulted in reducing NO_x primary production and the denitrification rate.

As previously stated, the majority of scholars have employed flow simplification modeling to simulate a CFB boiler. Furthermore, Shen [73,74] utilized a CPFD model to investigate the pollutant emission characteristics of dynamic processes in a CFB boiler. As shown in Figure 16, during the hot start-up process of a 350 MW CFB boiler [74], the concentrations of NO and CO increased, while the concentration of O_2 decreased. Following the stabilization of the boiler, there were fluctuations in the production of NO, CO, and O_2. The concentration of SO_2 initially increased, then declined sharply, and finally exhibited dynamic fluctuations. The main reason for this behavior is that sufficient oxygen during the start-up process leads to a rapid increase in both NO_x and SO_2 in the furnace and a gradual decrease in NO_x content as oxygen decreases. When the furnace temperature is higher than 1120 K, the limestone calcination reaction reaches its maximum efficiency, and the desulfurization reaction causes SO_2 concentrations to decrease. The regulation induced by the hot start-up process is similar to the load-increasing process in a 0.1 CFB test bed observed by Tang [26,41]: the O_2 concentration greatly affected the reducing atmosphere in the furnace. On the other hand, the initial bed material and furnace temperature also influence the pollutants. During the initial stages of boiler operation, an increase in initial bed height results in augmented suspension particle concentrations in the dense-phase zone, so the capacity for secondary air infiltration diminishes, thereby impeding the mixing of gases and solids in the dilute-phase zone of the furnace, resulting in an increase in the oxygen-deficient zone in the furnace, inhibiting NO_x generation. When the initial furnace temperature rises, the HCN and NH_3 concentrations generated from the volatile fraction in the furnace dense-phase region increase. This ultimately weakens the reduction in NO in the atmosphere and increases NO_x emissions. Nevertheless, the increase in the initial bed height and furnace temperature lead to an increase in desulfurization efficiency and a decrease in SO_2 concentration.

From the hydrodynamic standpoint, various techniques have been employed to optimize this process, whether by means of gases (e.g., decreasing the excess air coefficient, reducing the primary air fraction, and delaying the mixing of the secondary air) or solids (e.g., increasing the initial bed height). The primary objective is to elevate the particle concentration in the gas–solid flow, thus generating a reducing atmosphere and reducing original NO_x emissions in the CFB furnace. Nevertheless, inadequate gas–solid mixing in specific zones will decrease coal combustion efficiency. Consequently, there is a trade-off between enhanced operational flexibility and the regulation of pollutant control. In order to achieve the optimal ultra-low emission control of sulfur and nitrogen pollutants in CFB boilers, it is essential to develop a comprehensive pollutant emission model during the variable load process of CFB boilers. The model can provide guidance for pollutant emission control and further reduce pollutant control costs.

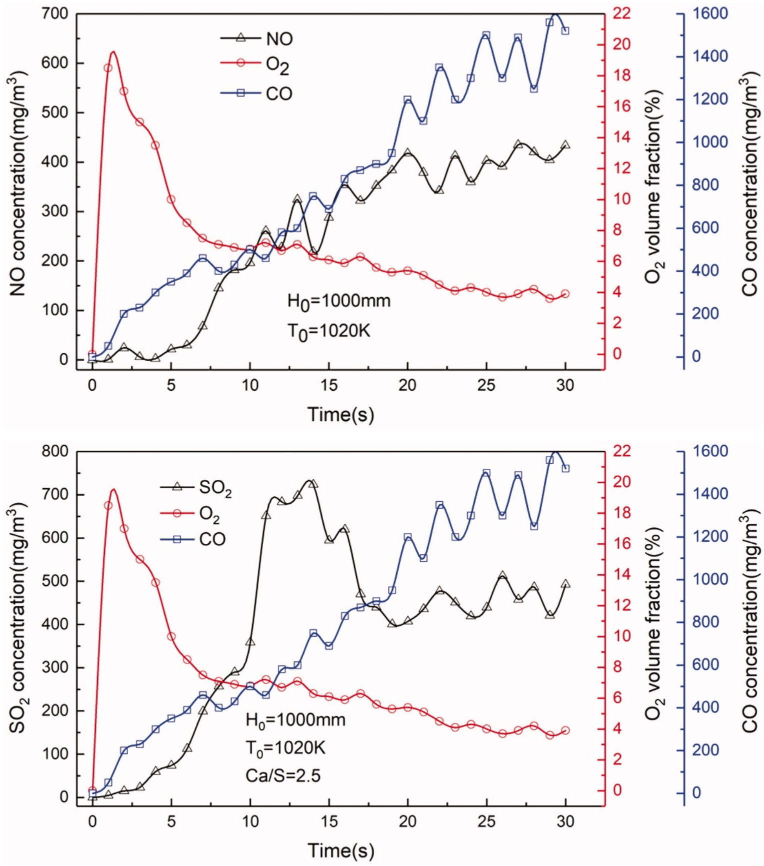

Figure 16. Dynamic changes in NO and SO_2 concentrations in the furnace chamber during hot startup of a 350 MW CFB boiler [74].

6. Conclusions

Due to the complex inertia and pollutant emissions, the unit flexibility transformation has become a difficult task regarding CFB combustion technology. This paper analyzes the CFB boiler variable load dynamic characteristics in experiments and numerical simulations, identifies the key factors affecting boiler variable load, and discusses methods to increase the variable load in a CFB boiler. The following conclusions may be drawn:

(a) The dynamic model can accurately portray the dynamic and transient behavior of a CFB boiler in regard to the variable load characteristics. The current research on the CFB variable load capacity is limited to steady-state analysis before and after the variable load. There is less research on the dynamic characteristics exhibited during the variable load process. Most of these phenomena are investigated based on the fluidization model. With the improvement of computational capabilities, using complex and accurate CFD/CPFD models to simulate the dynamic characteristics in a CFB boiler during rapid variable loads will become an important development direction.

(b) The particles generate considerable flow inertia in the full loop of a CFB. Changing the concentration of solid particles in the furnace can reduce the circulating material quantity and heat storage capacity, in turn reducing the flow and heat transfer inertia. The solid content in the circuit can be controlled by modifying the bed material particle size, enhancing cyclone efficiency, and storing the circulating ash. These modifications can be employed to enhance a boiler's variable load rate. These methods can yield a variable load rate of up to 6%/min in numerical simulations. However, their application to actual CFB units requires further investigation.

(c) Changing coal particle size as well as applying dynamic combined combustion and coal-preheating techniques are intended to increase the combustion rate to decrease the burn-out time. The addition of pulverized coal in the dynamic combined combustion process intrinsically reduces the feed coal particle size. Smaller pieces of coal burn out more quickly to release heat than larger pieces. Coal-preheating technology reduces the preheating time, allowing the coal to reach the ignition temperature before it enters the boiler. These technologies can increase the variable load rate to 2–4%/min. However, research on these technologies has been limited in regard to small and medium-sized test benches. Therefore, it remains to be seen whether these technologies can be applied to large boilers.

(d) As the load is increased, the concentration of SO_2 initially rises and then gradually decreases. An increase in the amount of air (oxygen) results in an increase in NO_x emissions. Subsequently, NO_x emissions gradually decrease when oxygen content decreases. As the load decreases, the reduction in bed temperature results in a decrease in NO_x emissions but also an increase in SO_2 emissions. During variable load operations, it is possible to reduce NO_x emissions by improving the combustion process, including via reducing the excess air coefficient, reducing the primary air ratio, delaying the mixing of secondary air, and increasing the initial bed height. With the growing emphasis on energy saving and emission reduction for thermal power units, the flexible operation control of CFB units should not only consider the load regulation performance but also achieve ultra-low emission standards.

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