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A review on research and development of CFB combustion technology in China

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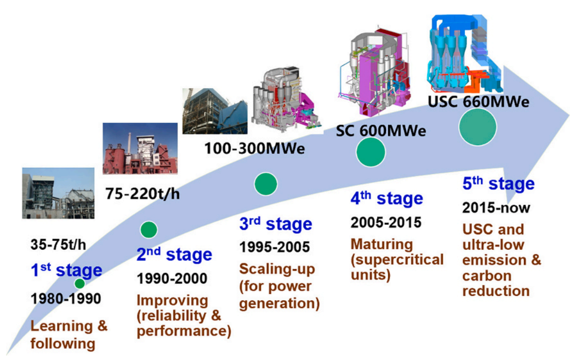
HIGHLIGHTS

- Present status of circulating fluidized bed combustion (CFBC) technology in China is reported.
- CFBC technology development history in China is introduced by five stages.
- Major engineering applications of CFBC technology in each stage are reviewed.
- Typical fundamental research and achievements on CFBC technology in China are introduced.
- The prospects of CFBC technology for carbon neutralization are discussed.

GRAPHICAL ABSTRACT



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ABSTRACT

The development history and present status of the circulating fluidized bed combustion (CFBC) technology in China are reviewed. This technology has been developed for nearly 40 years since the early 1980s in China, and its development history can be divided into five stages, including a learning stage, an improvement stage, a scale-up stage, a maturing stage, and an ultra-low emission and ultra-supercritical stage. There are currently >3500 units of CFB boilers operating in the country, with unit capacities covering the range of 35–2000 t/h in steam output, mainly used for coal firing. Among the units, the world's first 600 MW supercritical CFB boiler was successfully demonstrated in 2014 and was regarded as a milestone of CFBC technology in the world. CFB boilers are playing an important role in thermal and power generation in China. Several achievements in engineering application and fundamental research are achieved. The reviewed history and achievements could be used as references for researchers and engineers in future CFBC technology development. At the end of the paper, the prospects of CFBC technology in the area of carbon neutralization are discussed. Though the application in coal combustion is shrinking, CFBC technology will play an important role in CO_2 reduction and carbon neutralization.

Abbreviations: BFB, Bubbling fluidized bed; BFBC, BFB combustion; CFB, Circulating fluidized bed; CFBC, CFB combustion; CHP, Combined heat and power; CLC, Chemical looping combustion; FBC, Fluidized bed combustion; FSS, Fluidization state specification; FGD, Flue gas desulfurization; HTC, Heat transfer coefficient; PC, Pulverized coal; SCR, Selective catalytic reduction; SC, Supercritical; USC, Ultra supercritical.

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Symbols

G_s	Solid circulating rate (kg/m^{2}s)
I_v	Bed inventory in mass or height
t	Time (s)
T	Temperature (K)
u_f	Fluidizing air velocity (m/s)

Greek symbols

α	Burnt-out ratio (−)
ρ	Density (kg/m^3)
ε	Mass fraction (−)
η	Efficiency (%)

Subscripts

b	bulk
c	critical
e	electric
s	solid

1. Introduction

Fluidized bed is a chemical reactor where a bed of particles is completely supported by the drag force imposed by the fluid. The flow pattern of these particles is described by the term "fluidization", as it has the appearance and many properties of a true liquid or fluid [1,2]. Circulating fluidized bed (CFB) is a subset of fluidized bed where solid particles are mostly entrained out of and then recirculated back to the same bed [1–4].

Nowadays fluidized bed technology has been widely applied in many industrial processes, including catalytic cracking and synthesis, hydrocarbon processes, roasting and calcination, metallurgical processes, biochemical and environmental processes, pharmaceutical and food processes, and non-reacting physical processes. In the area of energy conversion, it is massively adopted to coal combustion, gasification, and incineration [3–5]. Correspondingly, the technologies are referred as (coal-fired) fluidized bed combustion (FBC) or circulating fluidized bed combustion (CFBC) technologies.

Conventionally, in a fluidized bed combustor, the average size of feedstock and bed material was rather large (5–10 mm) and the fluidizing air velocity (1.2–3 m/s) was rather low [3–7], and thereby the fluidization regime mainly belonged to bubbling fluidized bed (BFB). Correspondingly, the technology was called bubbling fluidized bed combustion (BFBC). In a coal-fired BFB combustor, coal particles with a certain size range are fed into the bottom bed. The combination of coal particles and inert particles is called the bed material. Bed material is fluidized by the fluidizing gas (normally air). The fuel input only counts 1% - 3% in mass of the bed material [5–7]. The inert particles provide a great thermal inertia to stabilize the combustion, and to introduce the intensive interactions among the particles and between the gas-solid flow and the heat transfer surfaces.

During the combustion, coal particles experience a series of processes including heating, fragmentation, attrition, volatile matter release and burning, and char burning. At the same time, the size of coal particles gradually decreases. The small-size particles, no matter whether they are fuel or inert bed material, are entrained out of the combustor by the gas, while large-size ones are kept in the lower bed except some of them that are drained out from the bottom. Most large particles can remain in the combustor for a rather long time to reach a relatively high combustion efficiency. Part of the heating surfaces are immersed in the lower dense bed or arranged surrounding the upper dilute bed to take out the heat generated by combustion, such that the combustor can operate at a design temperature, normally in the range of 750 to 900 °C [3–5].

Coal-fired BFB technology processes many advantages, including [3–7]:

- Ease to maintain a uniform bed temperature, in favor of fuel ignitability and combustion stability.
- Excellent fuel flexibility, suitable for coals with high ash content, high water content, high sulfur content, low volatile content, and low heating value.
- Simple fuel processing, as the feedstock of the fuel could have a wide size range, e.g., 0–50 mm;
- High heat transfer rate due to large interfacial surface area between fluid and particles and high fluid-particle contact efficiency, facilitating fuel ignition and combustion, and less heating surface.
- Remarkably higher combustion efficiency than that of stoker-fired fixed bed combustion.
- Wide range of turndown ratio, in which the BFB combustor could maintain at a high temperature for a long period and then quickly resume to a desired operational load.
- Low NOx emission, with no thermal NOx formed at the BFBC temperature, and fuel NOx formation greatly suppressed by the local reducing atmosphere.
- Cost-effective SO_2 emission control, suitable for in-situ capture of SO_2 with low-cost limestone.
- Low heavy metal emission, with most heavy metals exist in the form of non- hazardous salts and drained out from the bottom of the bed [8].

China started the development of coal-fired BFB boilers in the mid 1960s. By 1980, there were >3000 domestic-designed coal-fired BFB boilers installed in China, with the largest unit steam output of 130 t/h [9,10]. More details will be introduced in the later section. The massive amount of practices showed BFBC technology is a relatively excellent combustion technology, but at the same time, it has three significant limitations.

The first is low combustion efficiency [10–14]. Though the efficiency of BFB combustion is higher than that of stoker-fired fixed bed combustion, it is still very unsatisfactory, compared with that of a pulverized-coal fired combustion. In general, a BFB boiler is of small capacity and has a rather short furnace. Thus, the fine particles elutriated from the bottom dense bed will leave the furnace in a short time. Moreover, above the dense bed, due to the low solid concentration and small amount of fuel burnt there, the temperature is rather low. As a result, the unburnt carbon content in the fly ash is normally high. In addition, since fuel feedstock is of large size, the fuel could not be completely burned resulting in high unburnt carbon content in the bottom ash.

The second is the high erosion rate of heating surfaces [9,10,13,14]. In a BFB boiler, to maintain the combustion temperature, a certain amount of heating surfaces must be immersed in the bottom dense bed. The dense and relatively coarse solid particles move cross over the tubes, causing severe erosion on the surfaces and reducing the availability of the boiler.

The third is the difficulty to scale up in capacity [3,10–15]. Since BFB boilers operate in the bubbling regime with low fluidizing velocities and high temperature zone is mainly limited to the dense bed, a tremendously large bed area is needed for the installation of heating surfaces as the boiler capacity increases. The large bed area not only costs extra land for the boiler construction, but also causes bad quality in fluidization which leads to bed material aggregation and even slagging during combustion. As a result, BFB boilers are limited to small capacities and BFBC technology is deemed impractical for power generation.

CFB boilers inherit many above-mentioned advantages of BFB boilers. At the same time, they possess merits in higher combustion and de-SOx efficiencies and more intensive heat transfer throughout the furnace. In addition, CFB boilers operate at higher fluidizing velocities such that finely grained solid particles with a much higher mass flow rate are entrained out and recycled back to the bed. Therefore, CFB

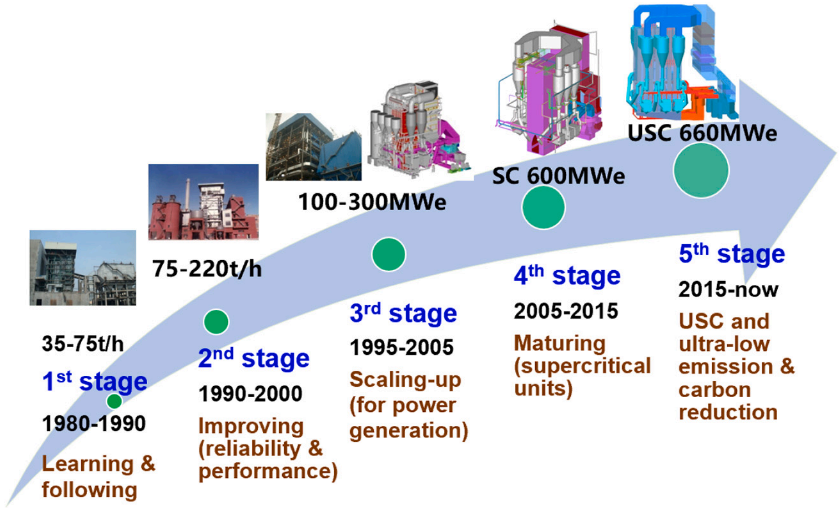

Fig. 1. The development history of the CFBC technology in China.

boilers obviously increased the capacity in handling particles thereby showing excellent scalability (higher cross section load) compared to BFB boilers [2,3,7,13–15].

CFBC technology was introduced to China in the early 1980s. For nearly four decades, it has been a hot research and development (R&D) topic in combustion. Almost all Chinese engineering universities and thermal research institutes were involved in BFBC and CFBC research, including Tsinghua University (THU), Xi'an Jiaotong University (XJTU), Southeast University (SEU), Zhejiang University (ZJU), Huazhong Science and Technology University (HUST), Harbin Institute of Technology (HIT), Chongqing University (CQU), Institute of Process Engineering (former the Institute of Chemical Metallurgy), Chinese Academy of Sciences (IPE-CAS), Institute of Engineering Thermophysics, Chinese Academy of Sciences (IET-CAS), and Xi'an Thermal Power Research Institute Co. Ltd. (TPRI). Among them, THU and IET-CAS continuously played a leading role in national CFB combustion research projects and made a great contribution in developing CFB boiler design theory. XJTU focused on the hydrodynamic of working medium in the tubes. SEU, ZJU, HUST, CQU and HIT studied almost every fundamental issue on the combustion side. IET-CAS developed several patented CFB boilers. IPE-CAS contributed a lot to mathematical modeling and numerical simulation of the two-phase reacting flow in the CFB furnace. TPRI resolved many engineering problems during the commercialization of CFB boilers.

Currently, there are >3500 CFB boilers operating in China, accounting for >80% in unit number or total capacity in the world. Most of them are still with small steam output, including ~500 units of 35–50 t/h, ~1800 units of 60–90 t/h, and ~ 800 units of 120–320 t/h [15]. When steam output is >400 t/h, the unit can be used for electricity generation, and its capacity is often expressed in MWe of electricity output. Currently, there are >400 ones with electricity output of 100–135 MWe (steam output of 400–460 t/h), >50 supercritical ones with electricity output of 350 MWe (steam output ~1100 t/h) and three units with capacities of 600–660 MWe (steam output 1900–2000 t/h) [16,17]. The total installation capacity is >100,000 MWe, generating ~10% of the total electricity in China.

The CFB boilers with capacity of 300 MWe and above are manufactured by the Big-three boiler companies, i.e., Harbin Boiler Company (HBC) in Harbin, Heilongjiang Province, Dongfang Boiler Company (DBC) in Chengdu, Sichuan Province, and Shanghai Boiler Company (SBC) in Shanghai City. All of them have produced several supercritical CFB boilers, mostly with capacity of 350 MWe. The CFB boilers with smaller capacities are mostly made by Taiyuan Boiler Company at Taiyuan city in Shanxi Province (TYBC), Jinan Boiler Company at Jinan city in Shandong Province (JNBC), Huaguang Boiler Company at Wuxi city in Jiangsu Province (HGBC), Sichuan Boiler Company at Zigong city in Sichuan Province (SCBC), Hanzhou Boiler Company, at Hanzhou city in Zhejiang Province (HZBC) and Babcock and Wilcox Boiler Company in Beijing city (BWBC). In recent years, TYBC dominates the market of small coal-fired CFB boilers while HGBC dominates the market of municipal waste-fired CFB boilers.

In the past 40 years, CFBC technology was developed from null to a major solid fuel combustion technology in China. In a few aspects, Chinese researchers and engineers also made their own contributions to improve CFBC technology. Nowadays, China is a dominate user and manufacturer of the CFB boilers in the world. The development history of CFBC technology and the main achievements in engineering application and fundamental research in China could be a reference for the future study. As coal is limited to use for carbon neutralization, discussion on the prospects of CFBC technology in the future is also desired.

2. The engineering application of CFBC technology in China

The engineering application of CFB technology in China can be divided into the five stages, as shown in Fig. 1. The first four stages, the learning stage, the improvement stage, the scale-up stage, the maturing stage were reviewed by the authors before [17,18]. In this paper, more details will be given. The last one, called the ultra-low emission and ultra-supercritical (ULE and USC) stage happened recently, from 2015 to present. In the first two stages, Chinese CFB technologies lagged behind foreign ones. In the end of the third stage, Chinese researchers and engineers gradually caught up with the foreigners in the design, manufacturing and operation of CFB boilers. In the last two stages, they independently developed CFB technologies with ultra-low emission performance and ultra-high steam parameters.

2.1. Stage 1: Learning stage

The first stage was a learning stage, occurring in the period of 1980–1990 [17,18]. From the mid 1960, about two decades before CFBC technology was introduced into China, major Chinese engineering universities and thermal research institutes had worked on the BFBC technology, mainly for burning low rank coals and coal gangue, including fuels of high ash content and low heating value, and/or high sulfur content. The research was independently conducted from scratch as China was not open to the West at that time. The research topics covered the hydrodynamics and combustion of the bubbling bed, heat transfer between the fluidizing medium and immersed tube and tube

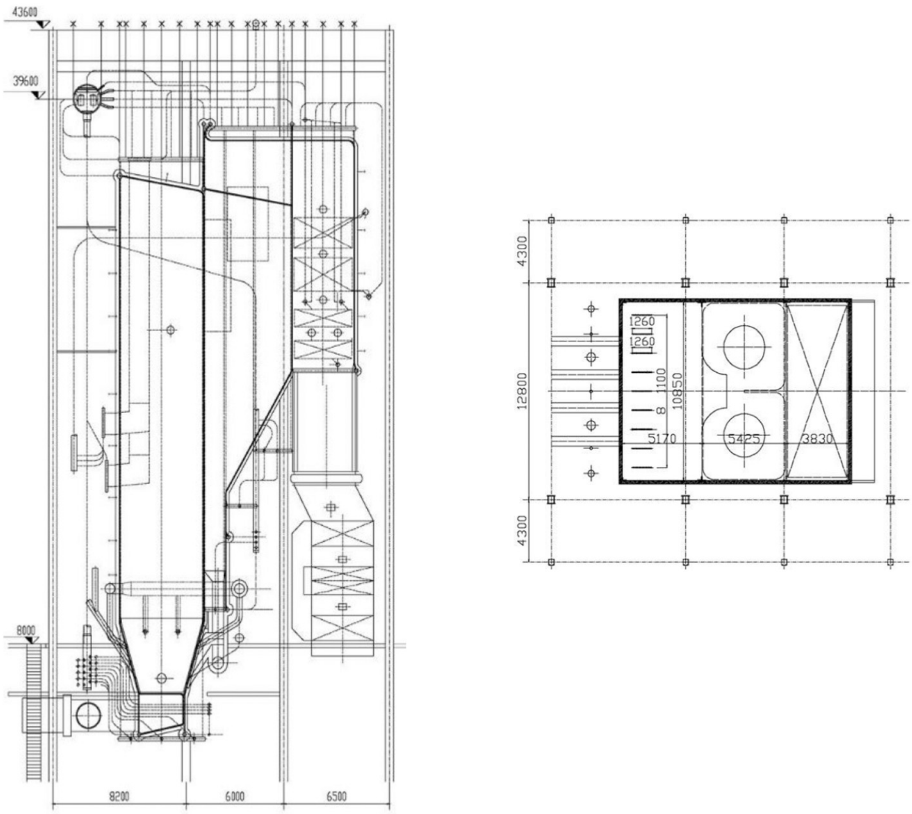

Fig. 2. The layout of a 220 t/h CFB boiler with a water-cooled square cyclone [38].

bundles, heat transfer and combustion in freeboard, and coal fragmentation in the bed etc. By the end of the 1980s, there were >3000 units BFB boilers operating in China [19], counting for three quarters of BFB boilers in the world. Most of them were of small capacities in the range of 4–35 t/h, mainly used for hot water or low parameter steam generation [19]. The largest two were in steam output of 130 t/h, one established in Jixi, Heilongjiang Province and the other built in Shaoguan, Guangdong Province [20]. In the 1980s, the largest BFB boiler in the world was in capacity of 220 t/h, developed by the Foster Wheeler Corporation (FWC) and installed in Black Dog Power Plant in USA [21]. The associated BFBC technology was licensed to Dongfang Boiler Company (DBC) in the middle 1980s. However, DBC only applied the licensed technology to retrofit an FWC-made BFB boiler in Pakistan. Therefore, all BFB boilers installed in China were made by domestic technologies.

Though the Chinese accumulated great experiences in BFB boiler design and operation, they were struggling to resolve three main limitations, i.e., low combustion efficiency, high erosion rate, and difficulties in scale-up as introduced in the previous section. Naturally, the successful demonstration of the first commercial CFB boiler with a capacity of 270 t/h, developed by the Lurgi company in Germany in the early 1980s [11] greatly caught their attention. Right after, the Chinese researchers and engineers unanimously recognized CFBC was the technical breakthrough of FBC. All the engineering universities and institutes that used to work on BFBC technology turned to work on CFBC technology.

Supported by the government, Chinese boiler manufacturers collaborated with foreign companies, including Ahlstrom Company, Finland and Foster Wheeler Corporation, USA [21,22] to import or license the corresponding CFBC technologies. At the same time, many universities and thermal institutes initiated associated research activities, closely following their foreign counterparties. Thus, the first stage was called the learning or following stage [17,18].

In this stage, the Chinese combined the new knowledge learned from the foreigners with previous experiences on BFB boilers. They retrofitted or replaced many BFB boilers with CFB ones, often with much larger capacities. The largest CFB boiler developed by Chinese technologies was 75 t/h [23], while in the same period, the largest CFB units operating in China made by foreign technologies was 220 t/h.

Since coal-fired CFBC technology was new, its applications in the learning stage encountered various problems, even for boilers designed by the licensed foreign technologies. A common one was severe erosion on the heating surfaces of the water membrane wall and superheaters hanged in the top furnace, resulting in frequent unscheduled shutdowns, and thereby low reliability [24]. The continuous operation time of a CFB boiler was usually <500 h, with a maximum of 2000 h [25]. In addition, to keep the compact design of the boilers, researchers and engineers used two-dimensional (2-D) solid-gas separators rather than 3-D cyclones. Those solid-gas separators could not effectively capture fine particles, resulting in a poor material balance and heat transfer in the top furnace. Therefore, the newly installed CFB boilers were often incapable of reaching the rated output, especially when relatively low ash coal was burnt [24–26].

By the end of this stage, quite a few boiler companies produced domestic-designed CFB boilers including Sichuang Boiler Company in Sichuan Province (SCBC), Jiangxi Boiler Company in Jiangxi Province (JXBC), Jinan Boiler Company in Shandong Province (JNBC), Hanzhou Boiler Company in Zhejiagn Province (HZBC), Beijing Boiler Company (BBC) and Tanshan Boiler Company in Hebei Province (TSBC). Besides these middle-scale boiler companies, many small boiler companies used to make BFB boilers also actively cooperated with the research institutes to develop small CFB boilers. However, the big boiler companies, which were mostly dedicated to the power generation units barely involved themselves in the development of the emerging CFBC technology.

The main Chinese universities and institutes working on CFBC technology research and development included: Tsinghua University in

Beijing (THU) led by Professors Xuyi Zhang, Bolin Cao, Qiayu Zheng, Yong Jin, and Junkai Feng, Huazhong University of Science and Technology in Wuhan, Hubei Province (HUST) led by Professor Dechang Liu, Zhejiang University in Hanzhou, Zhejiang Province (ZJU) led by Professors Kefa Cen and Zhongyang Luo, Southeast University in Nanjing, Jiangsu Province (SEU) led by Professors Changsui Zhao, Xianglin Shen and Yiqian Xu; Harbin Institute of Technology in Harbin, Helongjiang Province (HIT) led by Professors Lidan Yang and Yukun Qin, Shanghai Jiaotong University in Shanghai (SJTU) led by Professor Xiuming Jiang, Xi'an Jiaotong University in Xi'an Shaanxi Province (XJTU) led by Professor Jun Li, Institute of Engineering Thermophysics, Chinese Academy of Sciences in Beijing (IET-CAS), led by Professor Dasan Wang, and Institute of Process Engineering, Chinese Academy of Sciences in Beijing (IPE-CAS) led by Professors Mooson Kwauk and Youchu Li.

Cooperated with JNBC, IET-CAS developed the first domestic 10 t/h and 35 t/h CFB boilers [27,28]. Cooperated with SCBC, THU developed the first domestic 75 t/h CFB boiler in compact design with 2-D S-shaped separators [10,29,30]. Cooperated with BBC, THU developed a 10 t/h CFB boiler with an internal horizontal cyclone separator placed in the top of the furnace [31]. SJTU and HIT also patented CFB boilers with internal separators. Cooperated with HZBC, ZJU designed a 35 t/h CFB boiler with a downward-exit mid-temperature cyclone to burn coal gangue [32]. SUE designed 4 units of 35 t/h CFB boilers with fly ash recycle to burn the blend of anthracite and coal gangue [33]. At the time, they also conducted the research on pressurized CFB combustion technology [34]. XJTU designed a 50 MW CFB boiler with mid-temperature water-cooled cyclones to burn high sulfur coal [35]. At the same time, a wide range of fundamental studies were conducted [36].

2.2. Stage 2: Improvement stage

The second stage was an improvement stage, occurring in the period of 1990–2000 [17,18]. The main task was to improve the reliability and performance of CFB boilers. Based on a vast amount of operation experiences and great efforts in research, the researchers found that the erosion problem was mainly due to the employment of high gas fluidizing velocity, the large size of circulation ash, and insufficient protection of heating surfaces. It was also found that the output issue was caused by the low solid circulating rate (G_s), and the heat transfer coefficient in the upper furnace was lower than expected [24–27]. By the end of the 1990s, with the adoption of various anti-erosion countermeasures, continuous operation hours significantly increased, and the reliability problem was basically resolved. With the adoption of highly efficient cyclones and finer feedstocks, the bed material balance was significantly improved such that most boilers could reach the rated output [26].

In this stage, the large CFB boilers were still made by foreign technologies [37]. Meanwhile, based on the accumulated design experiences, several CFB boilers were also domestically designed. Fig. 2 shows a layout of the first Chinese 220 t/h CFB boiler with a water-cooled square cyclone with a curved inlet patented by Tsinghua University [38]. The performance of this boiler was satisfactory. With improved performance, CFBC technology was widely accepted by the thermal power industry.

However, in this stage, CFB technology was mainly limited to industrial boilers rather than power generation ones and Chinese CFBC technology was still far behind the international leading ones. Nevertheless, the application of the CFB boilers became more and more popular and many BFB boilers were also retrofitted in CFBC boilers [9,24]. The fundamental and engineering studies were wider and deeper. IET-CAS, THU, and ZJU kept leading in technology development, and Professor Yue Guangxi became one of the leaders of THU research group. Professor Jinghai Li became the leader of IPE-CAS research group. As the boiler capacities increased, the internal cyclone separators were abandoned. At the same time, the big boiler companies such as HBC, DBC, and SBC became major manufacturers of the large CFB boilers.

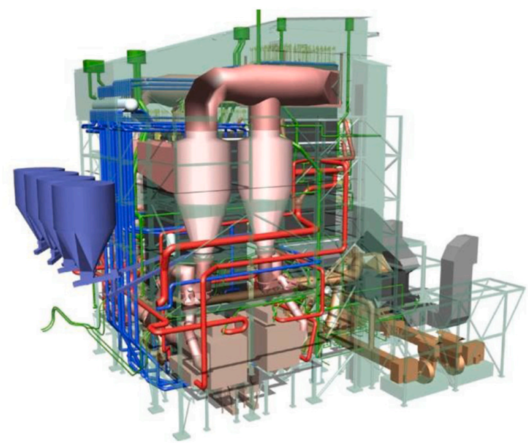

Fig. 3. Layout of a Baima 300 MW CFB boiler designed by Alstom [39].

2.3. Stage 3: Scale-up stage

The third stage was a scale-up stage, occurring in the period of the mid 1990s to the mid 2000s [17,18]. In those years, the Chinese economy was under fast development. CFBC technology, which had shown excellent performance in burning low-rank coals and had achieved great success in the thermal industry, received attention from the power generation industry. To meet the needs of the power sector, the major Chinese boiler companies signed a license agreement with USA's CE company and Germany's EVT company to make utility CFB boilers with reheat systems [26]. The imported technologies covered 50–200 MW CFB boilers with or without steam reheating. Supported by the Chinese National Development and Reform Commission (NDRC), the major Chinese boiler companies also obtained the license of 300 MW subcritical CFBC technology from Alstom, France [39].

Fig. 3 shows the layout of the 300 MW CFB boiler, which was demonstrated in Baima, Sichuan Province. The boiler was featured by a pant-leg furnace, equipped with four cyclones and four external heat exchangers (EHEs). It was conceptually designed by Alstom and made by DBC [39].

Meanwhile, the application of CFBC technologies promoted fundamental studies. Applications showed the licensed CFBC technologies were often unable to reach the designated performance in burning the local fuel feedstock and the employment of EHE caused an extra 5 kPa pressure drop and extra system complexity [39]. Therefore, a series of research was conducted to deeply understand the physiochemical processes in a CFB boiler. Experiments were conducted not only in laboratories but also on the operating boilers, covering fluid mechanics [40,41], heat transfer [42,43], combustion [44,45], and emission control [46,47]. Based on the studies, the fluidization state specification (FSS) design principle [24] was proposed by Tsinghua University. This design principle distinguished a CFB boiler from a conventional chemical CFB reactor and a BFB boiler [18,24], and guided Chinese engineers to design and operate the CFB boiler at a proper fluidization state [24]. More details about the FSS design principles are to be introduced in the latter section.

By the end of this stage, Chinese boiler companies grasped the manufacturing technologies of various kinds of CFB boilers. The CFBC became a main combustion technology for the thermal industry and an emerging technology for the power generation industry in China. It was in the end of this stage that Chinese CFBC technology caught up with the foreign ones.

In this stage, the big boiler companies played a dominate role in CFB boiler manufacturing and retrofitted for the units with large capacities. HBC, DBC, ZJU, THU finished the government-supported research

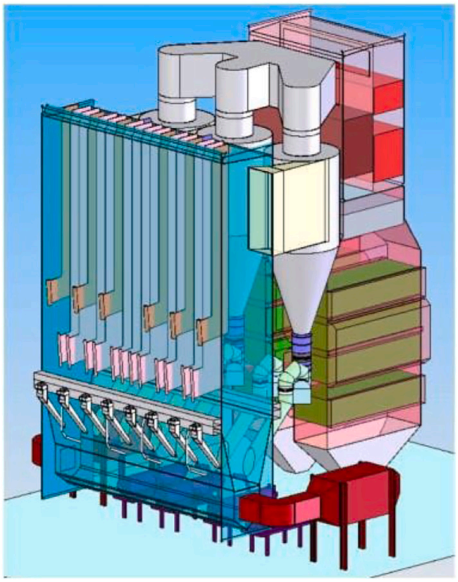

Fig. 4. Layout of a 300 MWe CFB subcritical boiler developed by DBC [22].

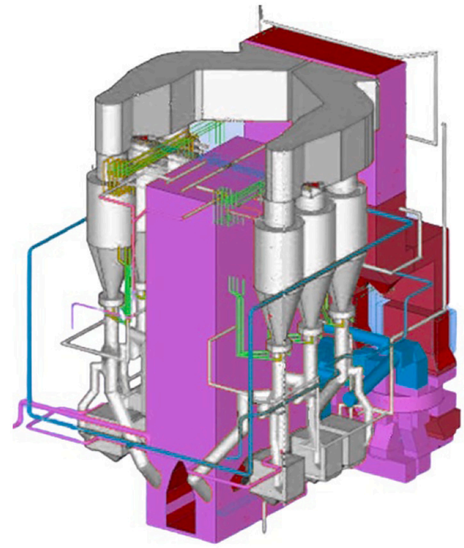

Fig. 5. Layout of the first 600 MW SC-CFB boiler designed by DBC [51].

project to develop a 100 MW CFBC boiler by the end of 2004 [48]. In this stage, Xi'an Thermal Power Research Institute (TPRI), the largest thermal power research institute in China, was heavily involved CFBC technology research and development. Based on the adsorption of foreign technologies, TPRI and HBC developed the first domestic 100 MWe CFB boiler and successfully put it into commercial operation in 2003 [49].

By the end of this stage, since other leading professors retired, Professor Guangxi Yue became a chief leader of THU research group and Professor Qinggang Lyu became the chief leader of the IET-CAS research group. Many young researchers including Professors Junfu Lyu, Yanguo Zhang, Zhen Li, Hairui Yang at THU, Professors Zhongyang Luo, Leming Cheng and Mengxiang Fang at ZJU, Professor Hanping Chen at HUST, Professors Xiaoping Chen, Laihong Shen and Lunbo Duan at SEU, Professors Defu Che and Houchang Tan, Professor Shaohua Wu at HIT, Professor Chunyuan Ma at Shandong University, Professors Wei Wang and Weigang Lin at IPE-CAS, and Dr. Minhua Jiang, Dr. Xianbin Xiao, Dr. Huai'an Lyu and Dr. Ping Xiao at TPRI became the key contributors for Chinese CFBC technology research and development.

2.4. Stage 4: Maturing stage

The fourth stage is a maturing stage, occurring in the period of 2005–2015 [17,18]. With experiences accumulated in the previous stages, the domestic design, manufacturing, and operation of CFB boilers became more and more mature. The features of excellent fuel flexibility and cost-effective emission control were widely recognized. By the end of 2009, CFB boilers with unit capacities of <300 MWe were mostly made by using domestic technologies, and >60 units of subcritical 300 MWe CFB boilers have been built, including 22 units made by licensed foreign technologies and 47 units made by domestic design [16].

The first Chinese 300 MWe CFB, independently developed by DBC, was put into operation in 2008 at Baolihua Power Plant, Guangdong Province, China [44]. As shown in Fig. 4, different from the ones made by the licensed technologies, the boiler had relatively simple structure, characterized by a single furnace with three cyclones without any EHEs. Application showed the boiler was easy to operate, with rather slight erosion on water walls and excellent fuel flexibility. The reliability of the domestic CFB boilers was satisfactory, with a maximum continuous operation time of 434 days [16]. In 2009, the first 330 MW CFB boiler with 8 cyclones co-developed by HBC and TPRI was put into commercial operation [50].

Increasing the capacity and stream parameters has been regarded as the most common way to improve the unit efficiency for a steam power plant. Consequently, in 2005, the Chinese government supported a demonstration project to develop the first 600 MW supercritical CFB (SC- CFB) coal-fired unit [51]. With a great effort, the unit was successfully put into operation at Baima Power Plant, Sichuan Province, China in May 2013 [52]. The boiler was designed and manufactured by DBC.

Shown in Fig. 5, the boiler had an H-shaped single furnace, equipped with two air distributors, six steam-cooled cyclones of I.D. 9 m and six compact EHEs. The full furnace size was 15.0 m × 27.9 m × 55.0 m, divided by a partition wall, as shown in Fig. 6.

The water-steam loop is illustrated in Fig. 7. The final-stage superheaters were installed in the furnace, while the first stage superheaters and final stage reheaters were installed in the EHEs. The membrane water-wall consisted of vertical Benson tubes designed with low mass-flow rate, such that the self-compensating function of the flow rate of the working medium varies with the heat flux. The main steam temperature was controlled by three-stage attemperators. The reheat steam temperature was controlled by the EHE and an emergency water-spray attemperator. The operation results showed that the hydrodynamic safety exceeded expectations. The maximum temperature deviation among the water wall outlet tubes was <17.0 °C and that of the partition wall was <28.0 °C. The low mass flow Benson design is very successful. The performance data can be seen in Table 1 [52,53].

The performance met or even surpassed the designation [53,54]. At full load, the load furnace temperature was 890 °C which was exactly same as the design value. It indicated the Chinese researchers offered reliable data to the boiler designer about the material balance and heat transfer. Compared with the FW-made 460 MW SC-CFB installed in Lagisza, Poland, the DBC-made 600 MW SC-CFB boiler has high boiler efficiency and lower emission. Although it burned a low-grade fuel, the boiler had lower carbon content in the bottom and fly ashes. With the same SO2 emission, the limestone consumption was 20% less, and NOx emission was 40% less [52].

The success of the 600 MW SC-CFB project was regarded as a milestone in the global CFBC technology development by the International Energy Agency (IEA) [54]. It was also regarded as an indication that Chinese CFB technology reached the world leading level [53]. Since 2013, SC-CFB technology has undergone rapid development in China. Fig. 8 shows the landmark of CFB boiler development, including the supercritical ones. After the success of the demonstration project, the

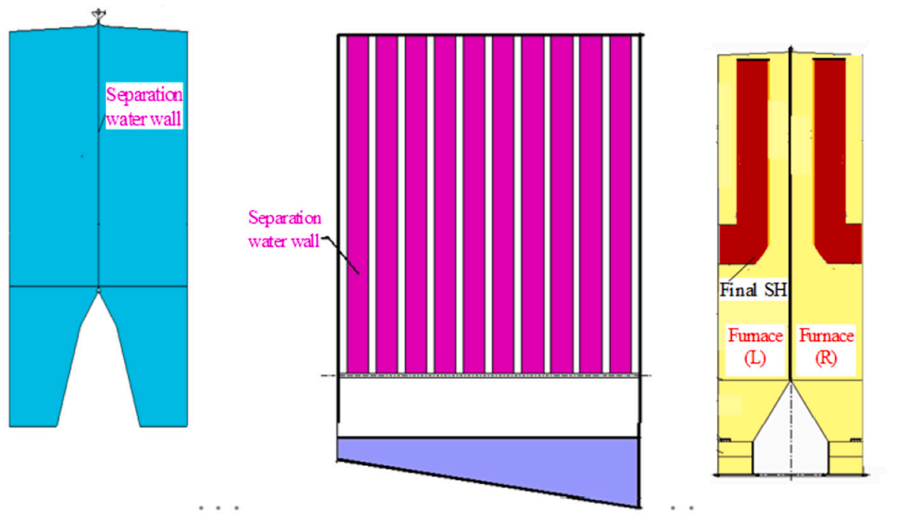

Fig. 6. Furnace and partition wall of 600 MW SC-CFB developed by DBC [51].

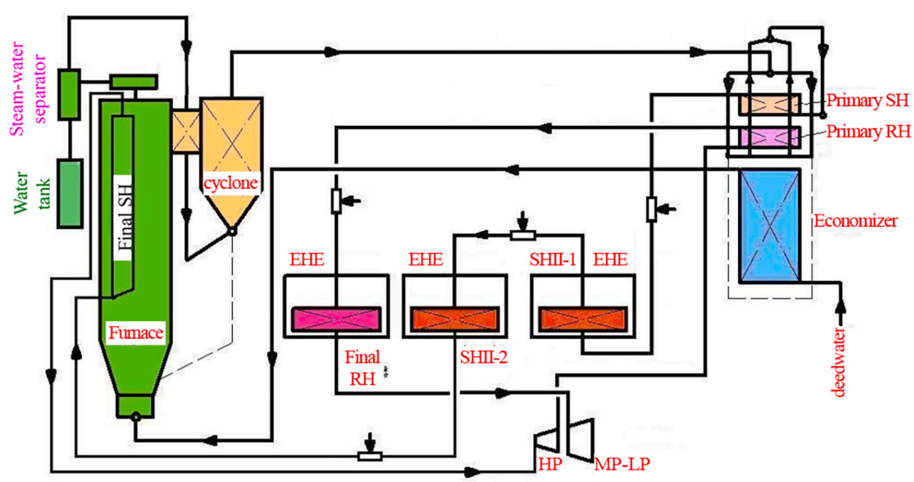

Fig. 7. Water and steam flow diagram of 600 MW SC-CFB developed by DBC [51].

Table 1
Main performance data of the first Chinese 600 MW SC-CFB.

Parameter	Unit	Designated	Measured
Power Load	MW	600	601
Main Steam Pressure	MPa	25.39	24.81
Main Steam Temperature	°C	571	570
Main Steam Flow Rate	t/h	1819.1	1748.0
Reheated Steam Pressure	MPa	4.15	4.04
Reheated Steam Temperature	°C	569	567
Attemperator Water Flow Rate	t/h	142.0	109.2
Furnace Temperature	°C	890	890
Boiler Efficiency	%	>91.01	91.52
SOx Emission	mg/Nm^3	<380.0	192.0
Ca/S Molar Ratio	mol/mol	2.1	2.1
De-SOx Efficiency	%	96.7	97.1
NOx Emission	mg/Nm^3	<160.0	111.9
Particulate Matter Emission	mg/Nm^3	30.0	9.3

Big-three boiler companies in China quickly developed 350 MW SC-CFB boilers to meet the market requirements. They all adopted a simplified design of a single furnace without EHE. The final superheater and reheater were hanged in the front of the upper furnace. Three steam-cooled cyclones were located between the furnace and the convective pass. The main differences among the designs were the mass flux value of the working medium in the water wall and the connection style, in parallel or in series, used between the partition wall and the water wall. By the end of 2021, over 80 units of SC-CFB boilers, two of 660 MW and the rest of 350 MW were installed, among which near 50 units have already been put in operation in China [16,53,54].

Another major improvement of the unit efficiency of a CFB boiler was done on saving the auxiliary power consumption. Compared with a pulverized coal-fired boiler, auxiliary power consumption of a CFB boiler usually is three percentage points higher because a high-pressure-head draft fan is needed to suspend the bed inventory [55]. Guided by the FSS design principle, the fluidization state in the CFB combustor was reconstructed [56,57], by reducing the number of coarse particles in the bed inventory while keeping the number of fine particles nearly the same to reduce the overall bed inventory. Such a manipulation kept the heat transfer coefficient nearly unchanged, while alleviating water wall erosion by reducing the average size of the bed material, and even slightly enhanced combustion efficiency by increasing the residence time of the fine fuel particles in the furnace [56–58]. Fig. 9 compares the service power between the CFB boilers employing the fluidization state reconstruction with the conventional CFB boilers reported in literature. With the fluidization state reconstruction, CFB boilers could have a low

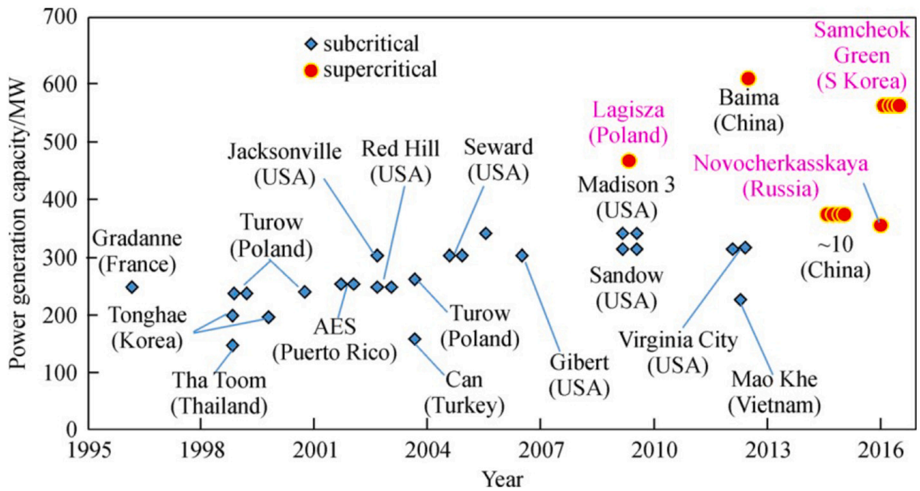

Fig. 8. The landmarks of CFB boiler development [53].

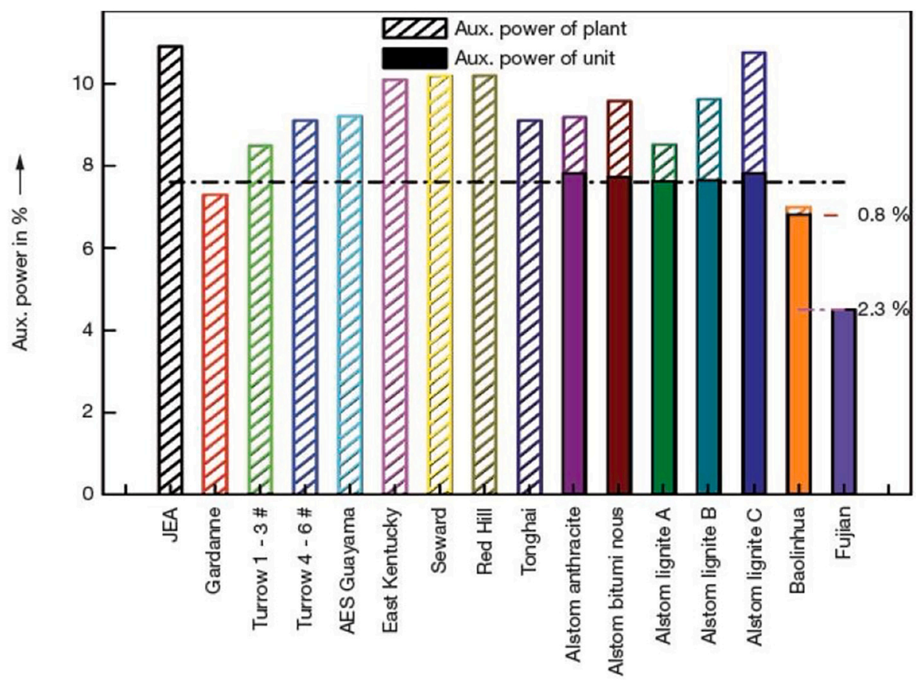

Fig. 9. Comparison of the service power assumption between the fluidization state reconstructed CFB boiler with other CFB boilers [57].

service power (4% -7%), which is compatible to the pulverized coal-fired (PC) ones [55]. So far, this energy-saving technology has been adopted in hundreds of CFB boilers in China [56–60].

By the end of the fourth stage, Chinese CFBC technology became comparable or even prevailing over international ones [57].

In this maturing stage, the main companies making SC-CFB boilers were DBC, HBC and SBC. Cooperated with THU, Taiyuan Boiler Company at Taiyuan City of Shanxi Province (TYBC) became the first company in the world in developing the above energy-saving CFB boilers. It quickly grew and owned a big market share of the new industrial boiler orders. Due to his contributions in the 600 MW SC-CFB design and other CFB researches, together with Professor Guangxi Yue, Professor Junfu Lyu was recognized as a new leader in the CFBC area. The research team by Professor Dong Yang at XJTU conducted heavy studies on water-side hydrodynamics for the SC-CFB boilers. Besides the universities mentioned before, close to the demonstration power plant of 600 MWe SC-CFB project, Chongqing University (CQU) led by Professor Xiao Lu conducted a series of research and on-site measurements of the boiler. At the same time, Taiyuan University of Technology at Taiyuan, Shanxi Province (TUT) by Professor Suxia Ma became active in CFBC studies.

2.5. Stage 5: Ultra-low emission and ultra-supercritical stage

The fifth stage, starting in the mid 2010s, was called the ultra-low emission and ultra-supercritical (ULE and USC) stage. The main task in this stage was to meet the latest strict emission requirements via the in-furnace combustion organization and to develop the ultra-supercritical CFB boiler with further improved efficiency.

Although CFB boilers naturally have the merits of low NOx and SO_2 emission, they normally only reach the level of 100–200 mg/Nm^3 (@6% O_2, the same thereafter) [7,14,18,61]. When the so-called ultra-low emission requirements, which required the dust, NOx and SO_2 emission from coal-fired boilers including the CFB ones to be <10 mg/Nm^3, 50 mg/Nm^3 and 35 mg/Nm^3, respectively, were issued by the Chinese

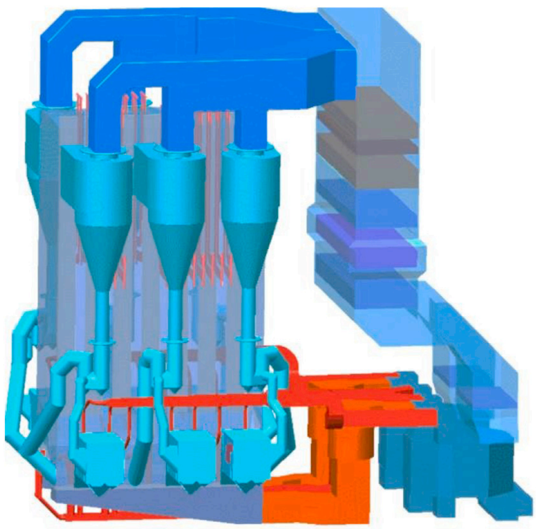

Fig. 10. Layout of the first 660 MW USC-CFB boiler designed by DBC [64].

government in 2013 [62], the CFBC technology faced a great challenge. If a CFBC unit needed to be equipped with FGD (flue-gas desulfurization) and SCR (selective catalytic reduction) to meet the ultra-low emission requirements as a pulverized coal-fired unit, it would lose the economic advantages in pollution control. To resolve this problem, guided by the FSS design principle, Chinese researchers and engineers further optimized the fluidization state, featuring a finer particle size of the bed material (bed quality) and a larger solids circulation rate [57]. A novel CFB combustion technology was developed, such that ultra-low NOx and SO_2 emission could be cost-effectively realized in the furnace. In about five years, this technology had been adopted by hundreds of CFB units in China. It is regarded as a breakthrough in CFBC development [62].

To further increase the unit efficiency, USC-CFB boilers are also under development in China. Fig. 10 shows the layout of the 660 MW USC-CFB newly designed by DBC [63]. The boiler features a single furnace, 6 cyclones with EHE [63,64]. The boiler is now under construction and is going to be established in Binzhou City, Shanxi Province, China in the end of 2022. The main steam pressure is 29.4 MPa, and the superheated and reheated steam temperatures are 605 °C and 623 °C respectively. The design fuel is a mixture of 25% high-calorific coal with 75% coal slime and gangue. The deign boiler efficiency is 93.5%.

Though the demonstration USC-CFB boiler was made by DBC, HBC and SBC also finished their own design. The ultra-low emission technology, firstly developed by THU and TYBC, was recently adopted by IET-CAS [65].

2.6. Other applications of CFBC technology

It should be noticed that in addition to coal-firing, CFBC technology has been vastly applied to burn multi-fuels, including biomass and municipal waste in China.

Biomass is not only considered as an alternative for fossil fuels but also a carbon- neutral fuel. Since biomass usually has a wide range of varying fuel properties, BFB and CFB boilers were often selected for biomass combustion either by directly burning with its original form or by indirectly burning after fuel processing [66–68]. Because of the low heating value and low energy density, the collection, transport, and storage of biomass are costly. Thus, in many cases, it was suggested that biomass could be converted into pellets in fuel processing [68].

Due to the high alkali metal content and low ash-melting temperature, in a CFB boiler, biomass was often co-fired with coals. Applications showed no major modification except the feeding system was needed when biomass thermal input was less 20% [68–70]. However,

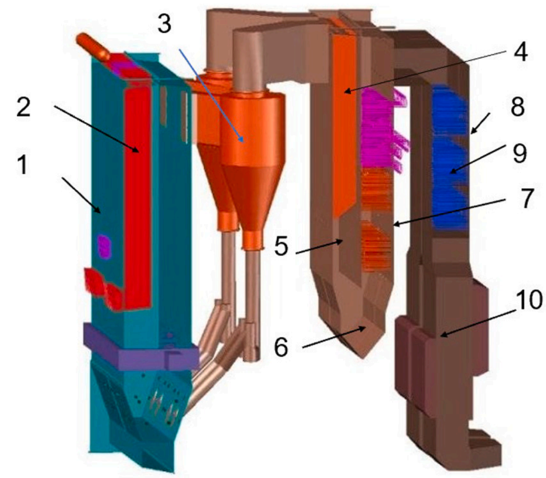

Fig. 11. The structure of a 130 t/h biomass direct combustion CFB boiler [72]. 1-Furnace; 2-High temperature superheater; 3- Cyclone; 4- Low temperature superheater; 5-First downward convection path; 6-U-turn section; 7-Upward convection path; 8-Second downward convection path; 9-Economizer; 10-Air preheater.

experimental results in a full-scale CFB boiler indicated that biomass co-firing was not necessarily enough to reduce NOx emission. To reduce NOx emission, low primary air ratio and locating the feedstock ports of biomass below the secondary air should be considered [68].

With the increasing demand of CO_2 reduction, Chinese researchers developed a series of direct biomass combustion CFB boilers, the largest with steam output of 220 t/h [71,72]. Fig. 11 shows an example of a 130 t/h biomass combustion CFB designed by HBC and Tsinghua University.

In the direct biomass-fired CFB boiler, stainless steel with high resistant to corrosion and coating of anti- corrosion material were applied to the heating surfaces arranged in the furnace, including the superheaters and reheaters hanging in the top furnace. Moreover, an extra U-turn flue gas path was deliberately added and some heating surfaces were arranged there [71,72], different from the structure of a coal-fired boiler. The main purpose of the structure design was to reduce the ash deposition on the heating surfaces and keep the heating surfaces out of the fouling temperature range.

In the furnace, due to massive solid particles, slagging on the water membranes was minimized. In the first downward convection path, low-temperature superheaters were arranged vertically with large pitch. The tube temperature and the vertical downward motion over the tubes were helpful to prevent ash fouling and deposition. The U-turn caused many ash particles to fall to the ash hopper in the bottom of the path. In the upward path, heating surfaces could be horizontally arranged as the temperature of flue gas was out of the fouling range. In the second downward convection path, economizers and air preheaters were installed. The ash temperature was much lower than its melting point, keeping the ash deposition away from the metal surface. Coatings or ceramic coverings were recommended for the air preheaters to avoid low-temperature corrosion [72].

Municipal waste combustion shows another advantage of CFB boilers. Due to the large thermal inertia of the bed material, CFB can reach stable combustion for municipal waste even at high water content and low heating values. Chinese researchers developed several CFB technologies with unique features for municipal waste combustion. Among them, horizontal circulating fluidized bed (HCFB) [73,74] and variant cross-section turbulent circulating fluidized bed (VC-TCFB) [75] are typical examples.

Shown in Fig. 12, an HCFB boiler is featured with triple combustion chambers and dual circulating loops [74]. The primary chamber is a riser as that in a vertical CFB, and the secondary and burnout chambers behave as a horizontal extension. The structure reduces the overall

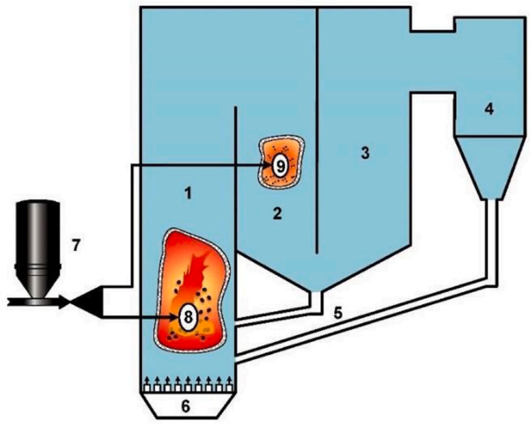

Fig. 12. The schematic configuration of a HCFB boiler [73].
1-primary chamber; 2-secondary chamber; 3-burnout chamber; 4-cyclone; 5-recycling loop; 6-air distributor; 7-coal feeder; 8-1st fuel feeding; 9-2nd fuel feeding.

height of the furnace, making CFBC technology suitable for small industrial boilers. For example, the height of the furnace of a HCFB boiler with steam output capacity of 35 t/h is ~8 m, which is ~60% of that of a regular CFB in the same capacity [74]. Experiments and application confirmed that HCFB boilers have excellent fuel flexibility and high thermal efficiency. They can burn low-rank coals, biomass, or industrial solid waste alone, and the blends of these fuels as well [74].

VC-TCFB boiler was designed to burn wastes. Shown in Fig. 13, it has a drum- shaped dense zone [75]. The cross-section of the furnace first diverges, then converges. Because the shoulders can block the bed materials from moving upwards, the internal circulation is stronger than in a conventional CFB boiler. The drum-shaped dense zone prolongs the residence time of coarse particles. This technology was patented by Tsinghua University and applied to a CFB boiler operating at a paper mill in Vietnam. The fuels burnt includes paper reject, dry sludge, and biogas. When the wastes were not enough, coal was co-fired as a balance fuel. By adjusting the primary/secondary air ratio and amount of coal feedstock, the temperature along the furnace first increased from 700 to 1050 °C, maintained 1050 °C for >2 s, and then decreased. That temperature field is in favor for the pollutant reduction.

3. Fundamental studies and achievements on CFBC technology in China

3.1. Material balance – the key to apply fluidization theory to a CFB boiler

Because CFBC technology originates from chemical engineering, in the early years, the hydrodynamics in a CFB boiler were often described by adopting the concepts and models developed for a conventional CFB reactor. In fact, a CFB boiler is a one-inlet and two-outlet system with bed material of a wide range size distribution, while a CFB reactor is often a one-inlet and one-outlet system with bed material in a narrow range size distribution [24]. Shown in Fig. 14, the one inlet of a CFB boiler refers to the solids input of combustible matter like carbon, ashes formed from fuel, limestone, and, sometimes, inert sand for bed makeup. The two outlets are the exit of the cyclones from which some small particles escape as fly ash, and the drainage ports in the bottom of the combustor to discharge large particles as bottom ash.

For a coal-fired CFB boiler, the bed material balance and size distribution are determined by the characteristics of ash formation, bed material attrition and the overall separation efficiency η_m. Shown in Fig. 15, the bell-shaped η_m profile for particles with a given size distribution is co-determined by the cyclone efficiency and ash drain efficiency. For particles smaller than the peak value, η_m is dominated by the cyclone efficiency and for particles larger than the peak value, η_m is dominated by the ash drain efficiency. The particle-size distribution of the bed inventory is determined by η_m and has a similar curve with the peak value appearing at the same particle size [24].

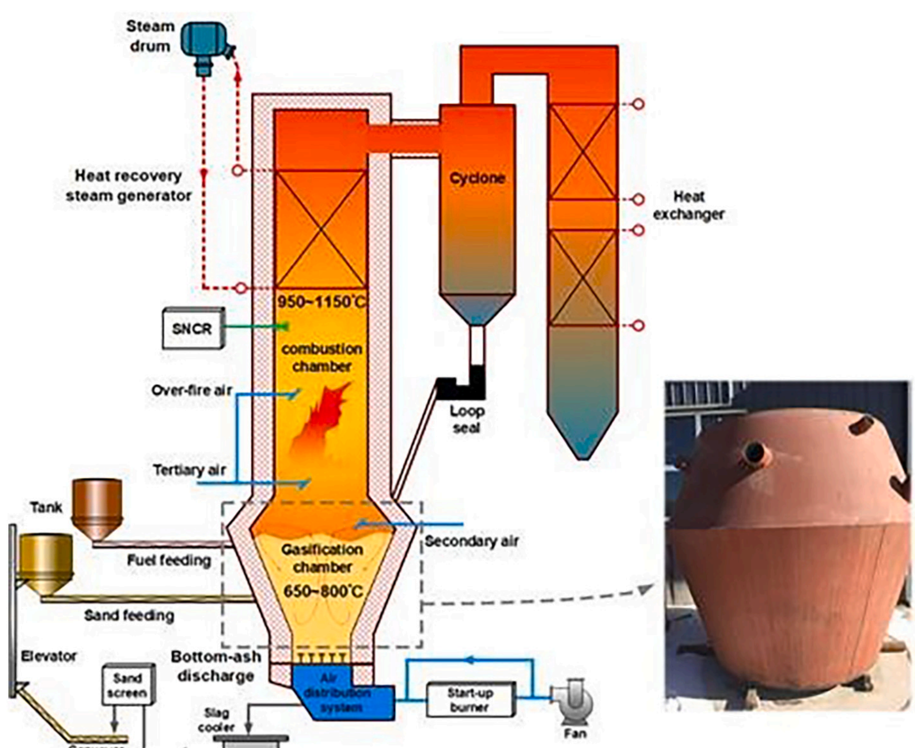

Fig. 13. The schematic configuration of a VC-TCFB boiler [75].

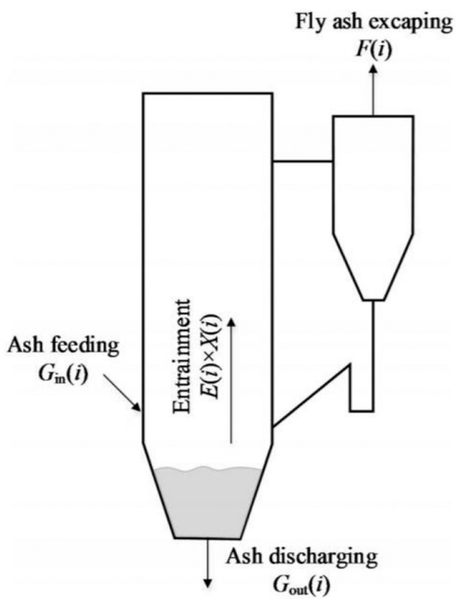

Fig. 14. The bed material balance in a CFB combustor [24,76].

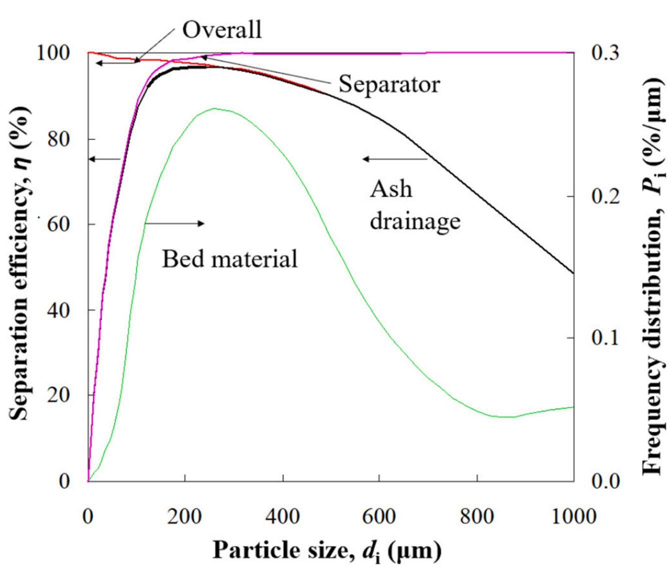

Fig. 15. The efficiencies of different particles in a CFB boiler [24].

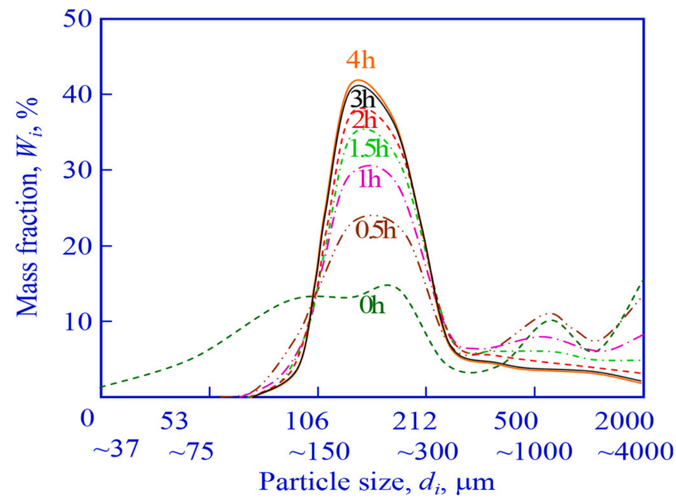

Fig. 16. The simulated temporal variation of size distribution of circulating solid particles in a CFB combustor [77].

Studies found that the CFB combustor has a so-called "size selection" function, making the bed material in the upper combustor narrowly distributed after a certain period of operation even though the solid feedstock is widely distributed, as shown in Fig. 16 [77]. This function, indeed to a great extent, makes the knowledge obtained from a conventional CFB reactor with a narrowly distributed feedstock applicable to describe the fluidization in the upper furnace of a CFB combustor [24,57]. Thus, in general, at a given fluidizing air velocity, the flow pattern in a CFB combustor can be regarded as a superposition of a bubbling bed formed by coarse particles in the bottom and a fast fluidization bed [24,57] or an entrained bed [78,79] formed by fine particles in the upper dilute zone.

It is worth pointing out that although both the conventional CFB reactor and the CFB combustor have dilute zones with narrowly distributed particles, their hydrodynamics are indeed very different. Firstly, in a CFB combustor, the mean size of the circulating ash is largely system determined, namely the average size of the bed inventory (sometimes called bed quality) and the solids circulating rate G_s depends on the performance of the separator and bottom ash drainage, besides the superficial velocity and ash formation characteristics of coal, limestone, and inert material makeup. Secondly, the value of G_s in a CFB combustor is rather small, usually <10 kg/m^{2}s [24]. At such a low G_s, choking does not necessarily occur. Thus, the dense bed in a CFB combustor is caused by the large particles of the feedstock, while the one in a conventional CFB reactor is caused by choking with a large G_s [57]. In the upper furnace, if enough fine particles accumulate, the fluidization state is in the fast and choking is possible there [24], while for a small G_s, the fluidization state behaves as an entrained bed. In the fast bed status, vertical mixing, which is the major cause for a rather uniform temperature distribution in the CFB combustor is intensive.

Therefore, the fluidization state in a CFB combustor is reasonably assumed to be a superposition of an upper fast bed or entrained bed over a lower bubbling bed. If choking takes place, the vertical distribution of the density of the fine particles will have an S-shape. In the lower position of the combustor, the vertical back-mixing, mainly driven by clusters of fine particles, is stronger.

Previous studies also found that the mass transfer between the gas phase (bubble or flow stream) and solid phases (emulsion or cluster) in the combustor is the main control mechanism for fuel combustion and NO_x/SO_2 formation [24,57]. Moreover, different from a BFB combustor, the dense bed and the central zone of the upper dilute section is in a reducing atmosphere [57].

The recognition of differences between a CFB combustor and a conventional CFB reactor, as well as a BFB combustor, motivated Chinese researchers to develop new principles to guide CFB combustor design.

3.2. The fluidization state specification(FSS)design principle

As introduced in the previous sections, the bed inventory in a CFB combustor possesses the feature of a wide range size distribution. According to the theory [80], the fluidization state can be determined by two parameters, i.e., fluidizing velocity *uf*, bed inventory *Iv*, or circulating solid flux G_s. To a one-inlet-two-outlet system, the bed inventory, as well as its size distribution can be adjusted by the bed material discharge. Thus, in the upper furnace of a CFB combustor, where heat transfer and combustion mainly occur, the two-phase flow can be in multiple fluidization states. Obviously, only if the fluidization state in the upper furnace is properly selected, other parameters, e.g., the heat transfer coefficient and the primary/secondary air flow ratio can be consequently determined. This is the core concept of the FSS design principle [57].

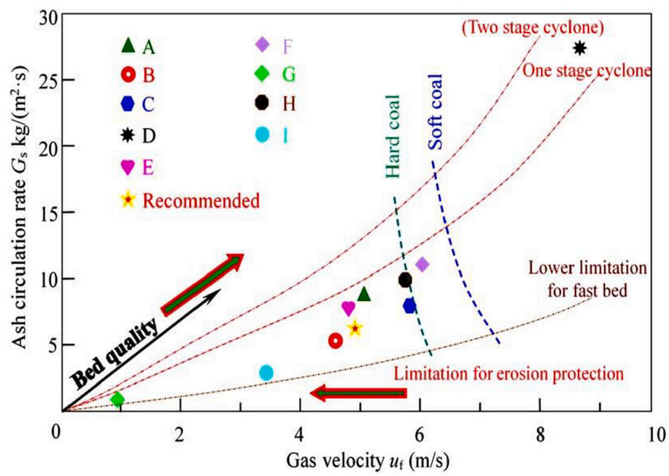

Fig. 17. A diagram of fluidization state specification (FSS) of CFB boilers [24].

By summarizing the fluidization states of tens of CFB boilers, including imported ones, and domestically made ones with foreign technology licenses, Tsinghua University proposed a diagram to guide the proper selection of the fluidization state in the early 2000s, as shown in Fig. 17.

According to the FSS design principle, the selection of the fluidization state in the dilute upper furnace, defined by u_f and G_s should be the first step in CFB boiler design. After such a state is specified, the other boiler parameters, e.g., heat transfer coefficient and the primary/secondary air flow ratio can be determined. Then, based on the material balance calculation, the requirements of cyclone efficiency and the rate and distribution of bed material drainage can be decided.

When the FSS design principle was proposed, it was used to improve boiler reliability. That was, the fluidization state in a CFB boiler, described by u_f and G_s should be limited to a narrow area, bounded by the cyclone efficiencies, the coal properties, and requirements of erosion prevention. Later, the FSS principle was used to select a fluidization state to develop the energy saving CFB boilers. More recently, it was further applied to develop the ultra-low emission CFB boilers [57].

3.3. Fundamental studies on SC and USC CFB boiler

Compared with pulverized coal-fired (PC) technology, CFBC technology is more feasible for supercritical boiler development, as the heat flux distribution on the water wall along the furnace height is much more uniform and the average value is remarkably lower, as shown in Fig. 18 [81,82].

In a SC pulverized-coal-fired (SC-PC) boiler, spiral water tubes with high mass flow rates are usually used to keep uniform heating to avoid heat transfer deterioration. However, such kinds of arrangement are certainly invalid for a CFB boiler as gas-solid flow motion over the tubes will induce severe erosion. Thus, in a CFB boiler, only vertical water tubes can be used, and the mass flux of working medium is much smaller than that in a SC-PC boiler. As a result, the hydrodynamic experiences obtained from SC-PC boilers cannot be directly applied to SC-CFB boilers. Given combustion and emission control knowledge could be largely inherited from those obtained in the subcritical CFB boilers, the studies on hydrodynamic safety of a water wall became the first priority for SC-CFB and USC-CFB boiler development.

The hydrodynamic safety of the water tube depends on the hydrodynamic and heat transfer characteristics in the furnace. However, the furnace of a SC- CFB boiler is tall and large and the hydrodynamics and heat transfer characteristics in such a furnace were still greatly of concern since no associated data were published when Chinese engineers started the SC-CFB boiler design. Consequently, CFB cold test rigs of 240 mm in I.D. and 38 m and 54 m in height, respectively, were set up to investigate the bulk density distribution along the furnace height [83]. The experimental results show that in the bottom dense bed and transition zone the voidage ε_b dramatically decreases as the bed inventory I_v increases, while in the top zone ε_b becomes nearly constant when I_v is greater than a certain value. When the bed height is 38 m, the transient occurs when $I_v = 40$ kg (Fig. 19a), and when the bed height is 54 m, the transient is observed when $I_v = 50$ kg (Fig. 19b). Correspondingly, Gs increases nearly linearly with I_v below the transient value, and then reaches a constant called saturated solid mass flux G_s*. Under the experimental conditions, G_s* = 9–10 kg/m^{2}s [83]. The results indicated that a modest I_v increment could result in a high enough G_s to meet the requirements of heat transfer in furnace and the circulation loop.

Heat transfer in a CFB furnace is a combination of gas-particle convection and radiation between the bed and surrounding heating surfaces [3,15,24]. A semi- empirical correlation of the local heat transfer coefficient (HTC) and local solid-suspension density is often proposed [18,84–88]. Combining measurements on large size CFB boiler and literature data, a correlation to predict the dependence of HTC on the solid density with a temperature correction was proposed as shown in Fig. 20 [52]. Coupling the local HTC model with the suspension density model, the heat flux distribution along the water walls could be well

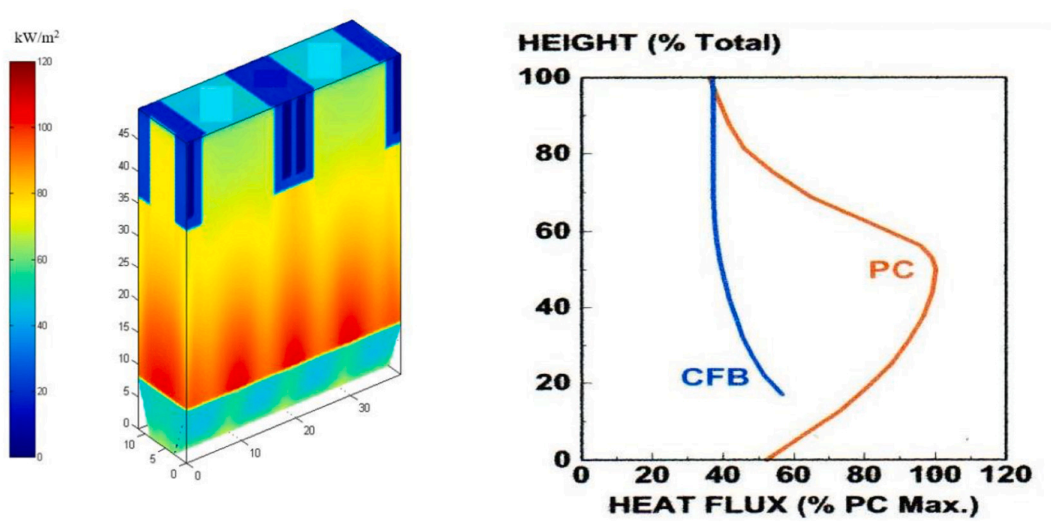

Fig. 18. A The heat flux distribution in a CFB furnace [81,82].

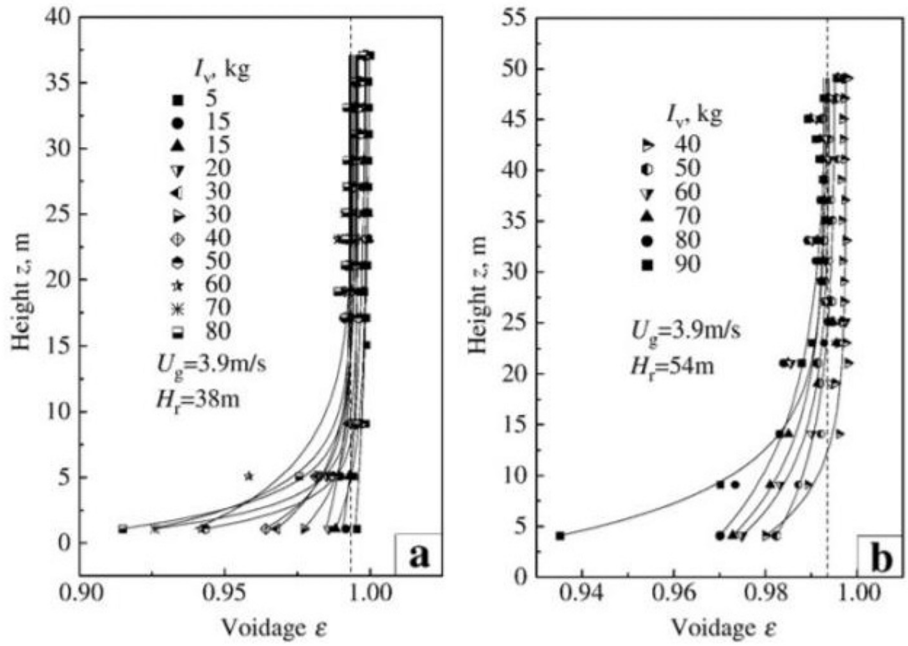

Fig. 19. Variations of axial voidage profile with solid inventory in two risers with heights of 54 m and 38 m [83].

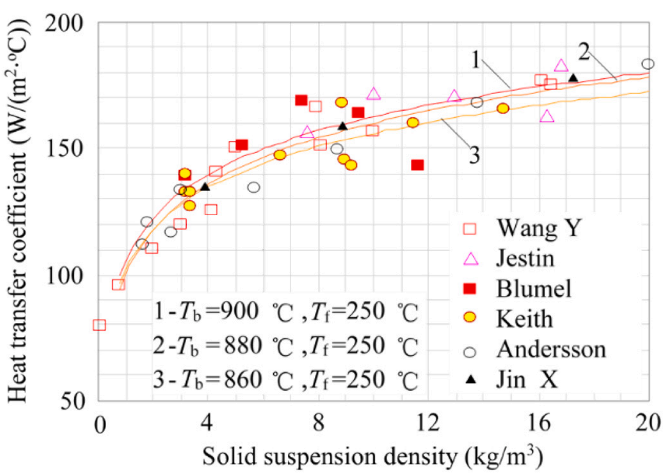

Fig. 20. Variation of heat-transfer coefficients with suspension particle density and temperature [52].

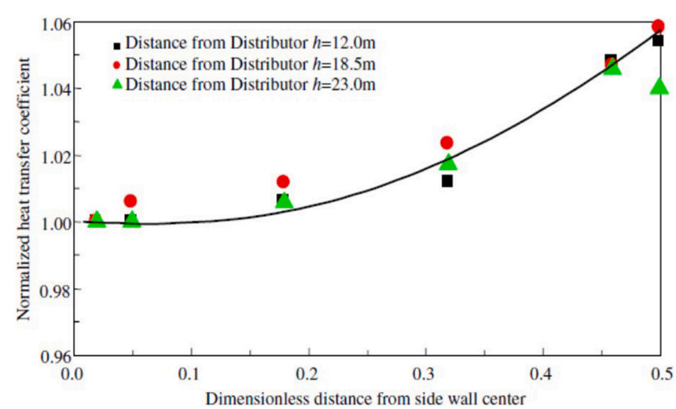

Fig. 21. Normalized heat transfer coefficient distributions along the horizontal direction in the furnace of 300 MWCFB boiler burning lignite coal [42].

predicted [87], thereby the hydrodynamic safety in the water wall could be evaluated [85,86].

For a CFB boiler with a large cross-section area, it is irrational to regard the horizontal distributions of temperature and heat flux as uniform. In a subcritical boiler, the uneven heat flux distribution in the furnace can be automatically compensated by the natural circulation of the working medium in the tubes of the water wall. Namely, the higher the heat flux, the larger the pressure drop and thereby the higher flow rate in the tubes. As a result, the hydrodynamic in the tube is safe no matter if heat flux distribution is uniform. However, such a compensation no longer exists for a supercritical boiler, which uses once-through circulation rather than natural circulation of the working medium in the tubes. To prevent tube damage by thermal stress, the temperature difference between tubes in the water wall should be limited. Therefore, the horizontal distribution of the HTC in a large CFB boiler were measured and used for new SC- CFB boiler design.

Fig. 21 shows the measured horizontal HTC distributions in a 300 MWe CFB boiler [42,44]. The HTC, and thereby the heat flux is high in the furnace corners, but the maximum deviation is about 5% only. Consequently, the hydrodynamics of the working medium in the tubes surrounding the furnace would be safe even with a conventional design [51,53].

The large SC-CFB boiler uses multiple cyclones, thereby multiple circulating loops. For examples, a 300 MW CFB boiler has three or four cyclones and a 600 MW one has four or six cyclones. The imbalanced gas-solid flow among the cyclones could be a threat to the safe operation, causing flow-rate oscillation [88]. Thus, the loop seal should be designed with special care to keep G_s deviation among loops within an allowance [89,90].

The twin-bed or pant-leg structure is often used in the furnace design of a SC-CFB boiler to enhance the gas-solid mixing for efficient combustion [37]. However, the bed inventory imbalance between two beds could cause overturn, which is an issue for safety operation [40]. Based on modeling and experimental results, the reasons for bed inventory overturn were discovered and a method to control such an overturn was suggested [91]. In addition, several measures were taken to enhance fluidization uniformity in the bed cross-section area to alleviate the bed surface fluctuation [56].

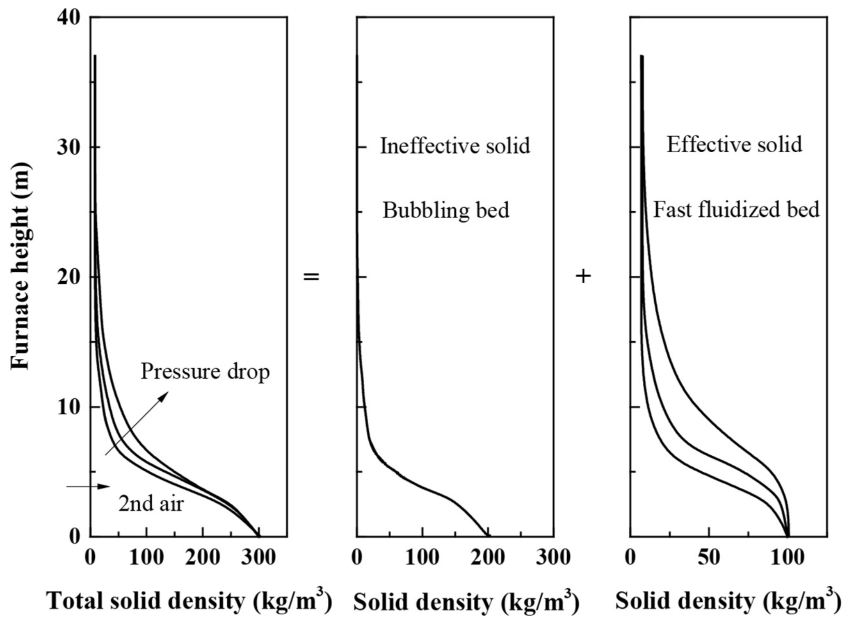

Fig. 22. The schematic of the axial bulk-suspension-density distribution of the coarse and fine particles in a CFB boiler [98].

Based on above studies and the other studies on heating surface structures [92], thermodynamic analysis [93], thermal-hydraulic calculation [94,95], the low mass-flux once-through vertical water wall of the furnace was developed. And the world's largest 600 MW supercritical CFB boiler was successfully demonstrated [96]. In a few years, >80 SC-CFB units, two in 600 MW capacity and the rest in 350 MW capacity have been installed [16]. More fundamental studies were undertaken after the demonstration [97].

3.4. The theory for reconstruction of the fluidization state for energy-saving

CFB boilers used to have a large bed inventory to keep a high reaction efficiency, stability and uniform fluidization. However, such a manner of operation will induce high auxiliary power consumption and possible severe erosion on the heating surface. Therefore, a compromise should be taken to reasonably reduce the bed inventory of the CFB combustor.

Guided by the FSS design principle [24,57], the two-phase flow in a CFB combustor is the superposition of a bubbling bed formed by coarse particles in the bottom and a fast fluidization bed formed by fine particles in the upper dilute zone. Thus, the bed material can be divided into two categories: coarse particles to provide sufficient residence time in the dense bed for the coarse fuel particles to burn out, and fine particles that are necessary to form a fast bed [18,24] or an entrained bed [78,79] in the upper combustor to sustain sufficient heat exchange between the two-phase flow and heating surfaces, as well as enough residence time in the freeboard for the fine fuel particles to burn out and for the limestone particles to capture SO_2 [57]. The fine particles are also called effective particles [98]. Shown in Fig. 22, the overall axial bulk suspension-density distribution of the bed material is a summation of that of the coarse and fine particles in a CFB boiler.

In order to increase the fine particle inventory, two measures were taken. One was decreasing the fraction of coarse particles in the feeding coal, and the other one was improving the performance of the circulating loop including cyclone separation, ash removal and loop seal [57,62,63]. After the fluidization state reconstruction, as shown in Fig. 23, the fraction of fine particles in the bed inventory increased while the total amount of bed inventory decreased. In practice, a novel energy-saving CFBC technology was developed [16,58–64]. As shown in Fig. 9 in the previous section, this energy-saving technology greatly reduced the auxiliary power consumption of a CFB boiler to a level even lower than that of a pulverized boiler with the same capacity. At the same time, it increased the boiler reliability because of less erosion [16,60–64].

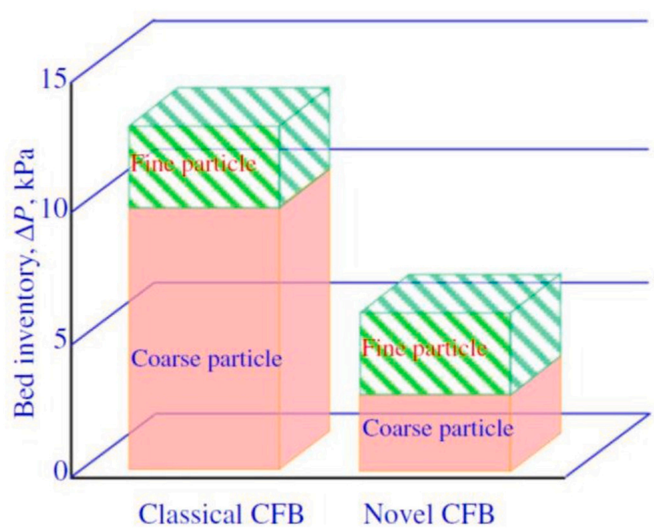

Fig. 23. Comparison of the bed inventory amount and fine particle fraction between the classical and novel energy-saving CFB boilers [60].

3.5. The theory for cost-effective ultra-low emission control of a CFB boiler

As introduced above, the latest ultra-low emission requirement brought a great challenge to traditional CFBC technologies. To avoid the usage of FGD and SCR, Chinese researchers attempted to explore the feasibility to further reduce the NOx and SO_2 emissions from the combustor. According to the FSS design principle, the fluidization state in the combustor is the basis of the reactions including the pollutant formation reaction and the destruction of pollutants in the combustor. From Fig. 17, the fluidization state could also be specified with the change of bed quality, i.e., the average particle size of bed material, even

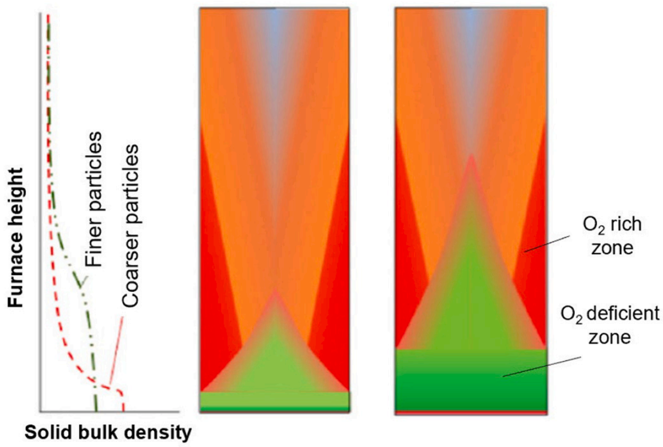

Fig. 24. Expansion of the reducing zone in the dense bed and the core area in the dilute bed with the decrease of the average particle size in a CFB boiler [57].

at a given u_f and G_s [57]. Therefore, theoretical analyses were conducted on the influence of bed quality on the two-phase flow characteristics, and thereby on the pollutant-related chemical reactions in the combustor.

It is well known that a reducing atmosphere is in favor of NOx reduction [99]. Previous studies [13,17,18] found that in a CFB combustor, the dense bed is in an overall reducing atmosphere. Given that average bed material size becomes smaller, at the same u_f of the dense bed, the reducing zone will expand since less air will remain in the emulsion phase [99,100]. Additionally, the fine particles weaken the gas-phase transport, intensifying the reducing atmosphere in the dense bed [100]. On the other hand, in the upper dilute zone, fine particles have a higher tendency to form clusters due to stronger inter-particle forces [101,102], and thereby intensify the local reducing atmosphere to restrain NOx formation [103–105]. That is, reducing the average bed material size benefits the reduction of the NOx emission. Fig. 24 schematically shows the changes of bulk density and areas of reducing atmosphere in a CFB combustor by reducing the bed material size.

In a CFB combustor, limestone is usually used to absorb SO_2 in the flue gas. It seems that large limestone could increase the calcium utilization as the residence time increases. However, it was found the pores on the sorbent are easily blocked by the desulfurization product $CaSO_4$, which is of a large molar volume [4–8,106]. In fact, reducing the size of limestone feedstock enhances SO_2 absorption in the combustor in a few ways. 1) Reducing limestone particle size promotes the calcination reaction and increases the porosity of CaO sorbent [107]. 2) Fine particles have a large specific reaction area for the gas-solid reaction. 3) Reducing limestone particle size will alleviate the pore-blocking effect. 4) Fine sorbent particles have a high tendency to stay in the upper furnace, an oxidizing zone. In the oxidizing atmosphere, the sulfation reaction captures SO_2 and produces $CaSO_4$ [108], while in the reducing atmosphere, CaSO4 dissociates [109,110], releasing SO_2. Thus, the balance between sulfur retention which needs an oxidizing atmosphere and NOx reduction which needs a reducing atmosphere should be carefully considered.

Though fine limestone particles could have the above advantages in SO_2 capture, they could have too short a residence time. Thus, the optimum size is a balance between the desulfurization reaction rate and the residence time, and the recommended sorbent size was found to be around 200 μm in the previous study [111]. This size is not small enough, limiting the in-furnace desulfurization efficiency or the calcium utilization [24]. Obviously, the optimal sorbent size depends on the collection efficiency of the cyclones. If the collection efficiency is improved, the average size of circulating particles will be reduced while keeping the desired residence time.

The above analyses confirmed that FSS re-specification with respect to bed quality could be a cost-effective way to realize ultra-low NOx and SO_2 emission for a CFB boiler. To verify the feasibility of such a concept, a demonstration project was conducted on an existing boiler with capacity of 260 t/h in 2015 [57,62]. To reduce the average bed-material size, some retrofits were done on the improvement of separators and ash coolers, the position of discharging ports and the size reduction of solid feedstocks. With an improved cyclone and loop seal-system, the average size of fly ash was decreased from 20 μm to 11 μm. That of circulating ash decreased from 200 μm to 110 μm. Measurements showed that at the exit of the cyclone, the lowest NOx emission was 20 mg/Nm^3 (@O2 4.2%), and the lowest SO_2 emission 25 mg/Nm^3 (Ca/S ≈ 1.5). The sulfur removal efficiency was over 99% when the ultra-fine limestone with a cut size d_{50} of 10 μm was used [57].

4. The prospects of CFB combustion technology for carbon neutralization

Nowadays, carbon neutralization in energy conversion is a global concern. Although CFBC technology has been mainly applied to coal combustion for decades, it has a great potential for carbon neutralization.

Firstly, CFBC technology is a great measure in energy saving. It could be more widely used in supercritical power generation and CHP (combined heat and power) production for high energy-conversion efficiency [112,113]. Higher efficiency means less CO_2 emissions. When more and more renewable energies are connected to the power grid, to meet the requirement of flexibility, more supercritical units with small capacities rather than 600 MW or above are needed. Nowadays, 350 MWe SC-CFB technology is mature. The development of SC-CFB boilers in smaller capacities is expected to be smooth. In addition, CFBC technology has great advantages in CHP production since CHP units often need to adjust their load and fuel input [114].

Secondly, CFBC technology is very convenient in multi-fuel, low carbon, and non- carbon burning due to its excellent fuel flexibility. As introduced in the previous section, instead of coal-firing, CFB boilers are feasible to solely burn biomass or co-fire coal with biomass, which is regarded as a carbon neutral fuel [115,116]. In this way, some coal could be substituted. In the future, this kind of practice will be more popular to various sizes of CFB boilers. Besides the biomass, CFBC technology could be more popularly applied to burn or treat municipal waste and landfill waste. Non-carbon low-calorific fuels, such as ammonia or some other hydrogen carriers could also be burnt using a CFB combustor.

Thirdly, CFB technology could be coupled with renewable energy systems by taking great advantage of its load flexibility [117]. CFB boilers can adjust the load easily to allow more renewable energy sources, such as wind and solar power, to be connected into the power grid. Due to the thermal inertia of the large amount of bed material, CFB boilers could be operated at a very low load. However, the response time during the load change could be longer than that of a PC boiler. More studies should be conducted on the optimization of CFB operation with the connection of multiple energy sources, as well as the necessary energy storage devices.

Fourthly, CFBC technology is the key component in chemical looping combustion (CLC), a novel combustion technology for CO_2 capture. The CLC system is normally composed of two interconnected fluidized-bed reactors, an air and a fuel reactor [118]. As shown in Fig. 25, oxygen carriers in the form of metal oxide particles transfer oxygen between the two reactors. Instead of directly reacting with the fuel in the air reactor, the air reacts with metal materials sent from the fuel reactor. In the fuel reactor, fuel reacts with metal oxides, releasing reaction products. The exit gas-stream from the fuel reactor contains CO_2 and H_2O, and almost pure CO_2 is obtained when H_2O is condensed. Thus, CLC could avoid large costs and energy penalties of air separation to produce oxygen for CO_2 capture [119].

CLC was originally proposed for gaseous fuel combustion, but now it

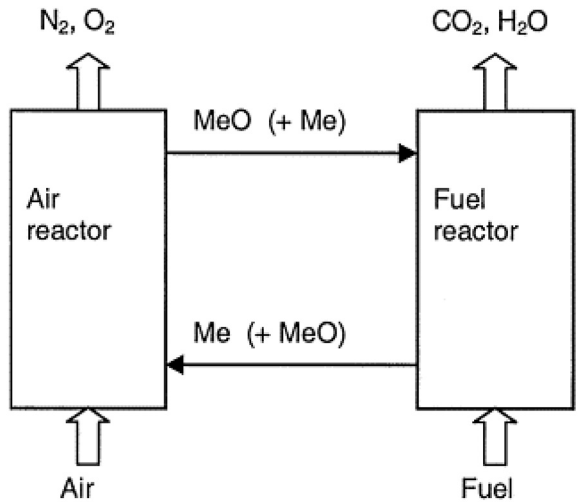

Fig. 25. Schematic of chemical-looping combustion. MeO/Me denote recirculated oxygen carrier solid material [118].

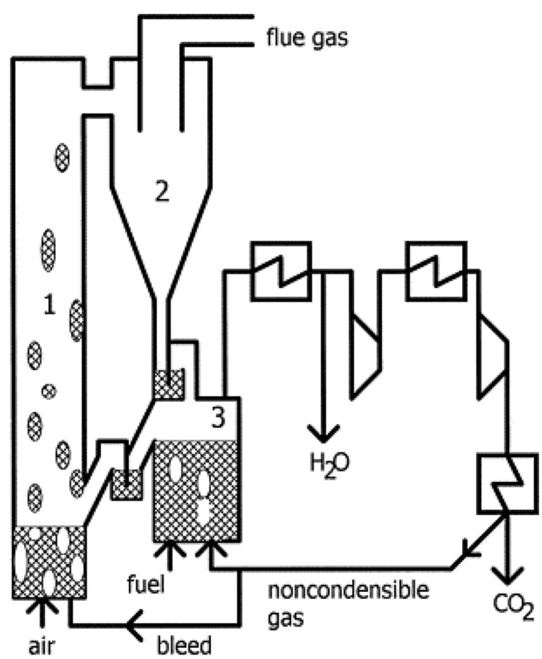

Fig. 26. Layout of CLC process, with two interconnected fluidized beds showing also drying and compression of CO_2 for deposition [118].

has been extended to use solid fuels including coal and biomass [118–120]. In a CLC system, CFBs are usually employed, but combinations of CFB-BFB can also be used. Fig. 26 shows a typical layout for a CFB-BFB. Obviously, CLC combustion is highly similar to CFB combustion [119,120]. CLC is actively studied around the world, in involving >11,000 h of operation with fuel in >49 pilot plants [121]. However, CLC technology is still under development, and the largest demonstration device is limited to 3 MW in thermal input [122]. There are still many studies including the oxygen carrier material and manufacturing, the reactor and system design, and scaling-up needed to be conducted.

5. Concluding remarks

CFBC is a popular clean coal technology, adopted by >3, 500 boilers in China. The development of this technology experienced five stages, including a learning stage, an improvement stage, a scale-up stage, a maturing stage, and an ultra-low emission and ultra-supercritical stage. After a great effort, nowadays, China can design, manufacture, and operate the world's most advanced CFB boilers. Moreover, Chinese researchers proposed their own design principle, which has been used to guide the design of the world's largest supercritical 600 MW CFB boiler, the novel energy saving CFB boilers, and the cost-effective ultra-low emission CFB boilers. CFBC technology, which was originally developed to burn high-carbon containing fossil fuels, will continue to play a positive and important role for carbon neutralization.

Declaration of Competing Interest

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Data availability

Data will be made available on request.

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