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REVIEW ARTICLE

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Development of a supercritical and an ultra-supercritical circulating fluidized bed boiler

Abstract The supercritical circulating fluidized bed (CFB) boiler, which combines the advantages of CFB combustion with low cost emission control and supercritical steam cycle with high efficiency of coal energy, is believed to be the future of CFB combustion technology. It is also of greatest importance for low rank coal utilization in China. Different from the supercritical pulverized coal boiler that has been developed more than 50 years, the supercritical CFB boiler is still a new one which requires further investigation. Without any precedentor engineering reference, Chinese researchers have conducted fundamental research, development, design of the supercritical CFB boilers independently. The design theory and key technology for supercritical CFB boiler were proposed. Key components and novel structures were invented. The first 600 MWe supercritical CFB boiler and its auxiliaries were successfully developed and demonstrated in Baima Power Plant, Shenhua Group as well as the simulator, control technology, installation technology, commissioning technology, system integration and operation technology. Compared with the 460 MWe supercritical CFB in Poland, developed in the same period and the only other supercritical one of commercial running in the word beside Baima, the 600 MWe one in Baima has a better performance. Besides, supercritical CFB boilers of 350 MWe have been developed and widely commercialized in China. In this paper, the updated progress of 660 MWe ultra-supercritical CFB boilers under development is introduced.

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1 Introduction

As coal dominates in energy resources in China, and coal washing and processing is believed to be an important measure to the clean utilization of coal, much low calorific value fuel are by-produced in the process. In addition, there are also certain percentages of low caloric value fuel produced in coal mining. Therefore, the utilization of such huge low caloric value fuel in scale and a clean manner becomes one of the most important issues. In the aspect of using low caloric value fuel, the circulating fluidized bed (CFB) combustion technology has unique advantages including its strong fuel flexibility, pollution control with low cost, and becomes the most commercialized clean coal combustion technology [1]. Therefore, the CFB boiler has been widely used in China with more than 4000 units and a total capacity of more than 100000 MW.

The experience obtained from thermal power generation proves that increasing fresh steam pressure and temperature could improve energy efficiency. Thus it is logical to develop a supercritical CFB boiler [2]. Supported by the National High Technology Research and Development Program (“863”Program, in brief), the researchers began this investigation in 2002. Different from the supercritical pulverized coal boiler, which has a long history of 50 years and several hundred of sets, there is no practical experience for the development of a supercritical CFB boiler in the world [3], except 4 conference papers as reference. This means that the supercritical CFB boiler has to be developed independently in China. The research has to cover many questions from the engineering [4,5]. However, the supercritical CFB boiler was developed in China in pace with international progress [6].

2 International progress in supercritical CFB boiler

2.1 460 MWe supercritical CFB boiler in Poland

In 1990s, Foster Wheeler (FW), Combustion Engineering (CE) and Alstom Stein began to develop the supercritical CFB boiler. FW won the first supercritical CFB boiler order in the world, the 460 MWe supercritical CFB boiler in Lagisza Power Plant in Poland [7], as shown in Fig. 1. This boiler reached full loading in March, 2009 and was put into commercial operation three months later [8].

Fig. 1 460 MWe supercritical CFB unit in Lagisza Power Plant

In the 460 MWe supercritical CFB boiler in Lagisza Power Plant, the low part water wall of the furnace uses smooth tube, while the upper part uses optimized internal ribbed tube produced by Siemens. Besides, it is of vertical tube structure with lower mass flux because vertical tube is necessary to overcome the potential erosion in a CFB boiler. The lower mass flux leads to a lower pressure drop of water tube to decrease feed water pump head to save electric power consumption. The boiler sectional size is 27.6 m×10.6 m with a height of 48.0 m from the air distributor to furnace roof. There are four compact cyclones cooled by steam on each side of the furnace, below each of which there is a loop seal combined heat exchanger (INTREX). Four INTREXs are for the final superheater while the other four INTREXs are for the final reheater. The INTREX is enclosed by the membrane wall cooled by water, which is connected with the furnace. The water from the economizer passes through the water wall of the INTREX enclosure to the lower header of the water wall of the furnace, then flows upward in the vertical tube to the upper header of the water wall of the furnace. Before the steam passes through the furnace roof of the super-heater, it flows into the steam-water separator and then passes the low temperature superheater located in the convective pass, the medium temperature superheater located in the upper furnace, the steam cooled compact cyclone, and the final superheater located in the INTREX. The steam temperature is controlled by the water spraying before and after the steam cooled compact cyclone [9].

The design fuel for the supercritical CFB boiler in Lagisza Power Plant is bituminous, also considering mixing of 30% coal slurry or 10% biomass in heat input [8,10]. The operation coal is much closer to the design one, while there is no operation information on using blend fuels.

The operation of the supercritical CFB boiler in Lagisza Power Plant is very stable, smooth, and reliable. The gas temperature and water/steam temperature are basically the same as the design value, while the bed temperature is 40°C higher than the design value. In this boiler, the exhaust gas temperature is very low by using the low heat exchanger to recover the low temperature heat of gas. The boiler heat efficiency is about 93% when the exhaust gas temperature is 88°C. With the mole ratio of calcium and sulfur Ca/S = 2.4, the SO_2 emission is less than 200 mg/m^3, and NO_x emission is less than 200 mg/m^3 with SNCR [9].

2.2 330 MWe supercritical CFB boiler in Russia

Russian Energy Equipment Manufacturing Company constructed a 330 MWe supercritical CFB boiler in Novocherkasskaya [10]. This boiler, put into commercial operation in the end of 2016, was also supplied by FW Company and has a similar structure to that in Lagisza Power Plant. The design fuel in this project is anthracite and bituminous coal mixed 30% coal slurry in heat input in maximum. The operation bed temperature as well as emission are also higher than the design values but within the scope of the contract [11].

2.3 Other supercritical CFB boiler

In addition to FW, Stein and CE also finished the conceptual design of supercritical CFB boiler. However, Stein and CE failed to find the clients [6].

3 Research and development of the supercritical CFB boiler in China

At the same time, a supercritical CFB boiler was also being developed in China. Due to the lack of precedent and reference, nearly all Chinese researchers from different organizations were mobilized to develop the supercritical CFB boiler technology. The key point of a supercritical CFB boiler is the breakthrough from the nature circulation in subcritical water wall to the once-through in super-critical water wall because the hydrodynamic of the two kinds of wall is completely different. The hydrodynamic in a subcritical wall is the natural circulation without external force. It is the density difference between the gas phase and liquid phase that drives the water flow cooling tube. However, the mass flux and heat flux are positively correlated. Therefore, the flux is not the concern. However, the hydrodynamic in supercritical condition is forced flow, and the water flow is forced by the pump to overcome the flow resistance, in which there is no heat adaptability. So the heat flux distribution should be considered because it is of significant importance. Additionally, the vertical tube must be used in the water wall in a CFB boiler to avoid the erosion of gas-solid two-phase flow in the furnace, which leads to the fact that the water mass flux in the water wall of the supercritical CFB boiler is far lower than that of the supercritical pulverized coal boiler. Thus the knowledge and experience obtained from the supercritical pulverized coal boiler are of no significance in developing the supercritical CFB boiler. Moreover, the furnace cross-section, the furnace height, the number of parallel cyclones and loopseal loops of a 600 MWe supercritical CFB boiler exceed the scope of existing investigations and practices.

A series of investigation were conducted one by one. The characteristics of the gas-solid two-phase flow in the ultra-high riser were discovered, the horizontal material concentration distribution and a novel prediction model were suggested [12]. A local heat transfer model was also proposed [13,14], and a reliable heat flux could be predicted by coupling these two models [15,16]. A heat transfer and flow model under low heat flux of supercritical water were established, and the minimum mass flux of water inside the tube in the circulating fluidized bed was 36 $kg/(m^2 \cdot s)$, which broke the traditional range and classical criterion. The mass transfer mechanism of overturn in the pant-leg furnace and the operating condition, and the structure condition within a bed [17,18] as well as the mechanism of dynamic instability and static inhomogeneity of the multi-parallel loop [19,20] were discovered. In addition, the control measures were also raised. Based on these investigations, the working principle of a supercritical CFB boiler and its complete key technology system were established to form the supercritical CFB boiler design theory and overall arrangement technology as well as performance calculation method. A series of key parts were invented, such as once through vertical water wall with low mass flux, discontinuous double-side heating membrane water wall, etc. The hydrodynamic safety was confirmed by model prediction under both of static and dynamic conditions. It was estimated that the predicted maximum steam temperature deviation at the outlet of the water wall should be less than 20°C. However, it was found that maximum steam temperature deviation at the outlet of the water wall was only 17°C in practice, which is far better than that of the supercritical pulverized coal supercritical boiler furnace of 50°C [21,22]. This is a breakthrough in the existing design practice of supercritical water wall. The positive response of the low mass flux in supercritical vertical water wall tube was, for the first time, realized in a real boiler [23] in the world. The longitudinal flow in fluidized bed heat exchanger (EHE) and the corresponding fixed structure of heating surface were invented to solve the vibration wear of immersed tubes. The thermal process was developed to solve the lower steam temperature problem at low boiler load with low combustion temperature. The world's first unit of 600 MWe supercritical CFB boiler was developed with a lot of world initiative [24].

In the demonstration, the control of the 600 MWe supercritical CFB boiler is the heart of the matter. Due to the thermal inertia and combustion delay of CFB, the concept and soft measurement method of burning carbon were proposed, and the precise control and load adjustment of steam temperature were realized. Based on the mechanism model, the 600 MWe supercritical CFB unit simulator was developed to train the operator and to provide guidance for control logic inspection and startup commissioning. The system integration technology and operation technology were established, and the series of excellent auxiliary machines were developed, which formed the technology of auxiliary machine selection and auxiliary machine design and manufacturing. The 600 MWe supercritical CFB boiler installation technology, commissioning technology, and start-up and running technology were also developed with the related installation standard and construction method, and the first 600 MWe supercritical CFB boiler was operated in 2013.

4 Demonstration of the first 600 MWe supercritical CFB boiler

The first 600 MWe supercritical CFB boiler was demonstrated in Baima Power Plant, Shenhua Group. The idea of the project started in 2002 and the project proposal was admitted in 2005. The construction began in 2010, and it started its 168 h operation on April 14, 2013, as shown in Fig. 2.

Fig. 2 600 MWe supercritical CFB boiler in Baima

The design fuel of the 600 MWe supercritical CFB boiler in Baima is lean coal with a low caloric value, an ash content of 43.82%, and a sulfur content of 3.3%. The water wall in the furnace is vertical tube with a low mass flux. The lower part of the furnace is made of smooth tube while the upper part is made of ordinary internal ribbed tube. The furnace section is 28 m in depth and 15 m in width. The height from the air distributor to the roof of the furnace is 55 m. There are twin air distributors with a pant-leg structure, between which there is discontinuous double-side heating membrane water wall. There are three steam cooled round cyclones on each side of the furnace, below each of which there is a loopseal and an EHE. The circulating ash is divided into two flows by the cone valve located in the end of the loopseal, one flow passes though the EHE and the other directly flows back to the furnace. Of the EHEs, four are for the medium temperature superheater while the other two are for the final reheater. The reheat steam temperature is controlled by changing the ash flow rate into the final reheater EHE to change the heat absorbed by immersed tubes. The bed temperature is controlled by changing the ash flow rate into the superheater EHE to change the heat absorbed by immersed tubes. The final superheater is the wing wall located in the upper furnace. The convective pass is a single pass. The low temperature superheater, low temperature reheater, economizer, and air preheater were arranged from top to bottom.

Four years commercial operation confirmed the excellent performance of the 600 MWe supercritical CFB boiler in Baima[1)]. The gas temperature and water/steam temperatures agree well with design values, indicating the research work and design technology are satisfying.

Compared with the 460 MWe supercritical CFB in Lagisza, the 600 MWe supercritical CFB boiler in Baima is more efficient and has less emission. Although the fuel in Baima is inferior, the carbon contents both in the bottom ash and the fly ash are lower. With the same SO_2 emission, the desulfurized limestone equivalent consumption in Baima is only 80% of that in Lagisza, and NO_x is 40% less than that in Lagisza.

Baima Demonstration implements the parameter breakthrough from the subcritical to the supercritical and the capacity leaps from 300 MWe to 600 MWe. It was regarded as a symbol of international CFB technology progress by International Energy Agency, as shown in Fig. 3[2)]. It also indicates that the CFB boiler technology in China has reached the world leading level[1)].

At present, two 660 MWe supercritical CFB boilers and one 600 MWe supercritical CFB boiler are underconstruction.

5 Demonstration of the 350 MWe supercritical CFB boiler

Besides, Dongfeng Boiler Co. Ltd., Harbin Boiler Co. Ltd., and Shanghai Boiler Co. Ltd. are also making attempts to develop supercritical CFB boilers. There is a huge market for the 350 MWe supercritical CFB boiler in China after the successful demonstration of the first 600 MWe supercritical CFB boiler in Baima. These three boiler corporations have developed 350 MWe supercritical CFB boilers respectively with the technology of the 600 MWe supercritical CFB boiler. Therefore, the 350 MWe supercritical CFB boilers of three boiler corporations are very similar with the simplified design of single furnace without EHE. The final superheater and final reheater wing walls are hanged in the front of the upper furnace. Three steam cooled round cyclones are located between the furnace and the convective pass. A loopseal is installed below each

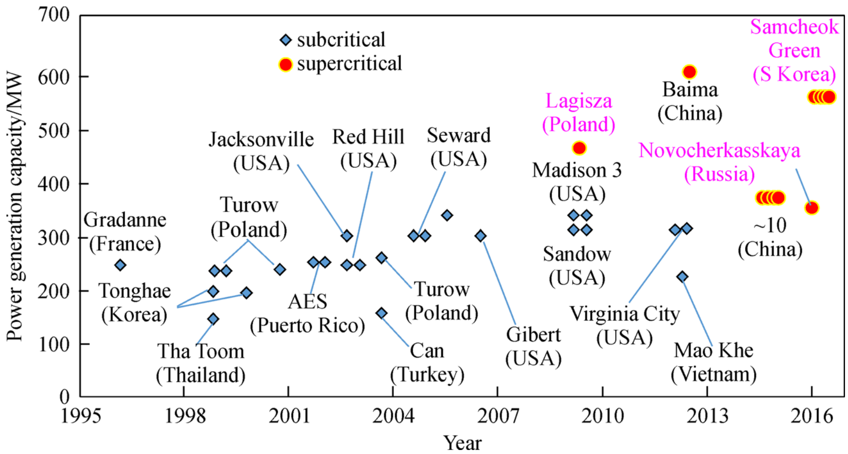

Fig. 3 Symbol during CFB combustion development

1) The world's first 600 MW circulating fluidized bed plant (Baima, China) [EB/OL]
2) Zhu Q. Developments in circulating fluidised bed combustion. copyright © IEA Clean Coal Centr. CCC/219 ISBN 978-92-9029-539-6

cyclone. The convective pass is divided into parallel passes upon the economizer, the front pass being for the reheater, and the rear pass for the superheater. The air preheater is installed under the economizer. The main differences between the three designs are the water mass flux in the water wall and the double-side heating membrane wall process that connects with the water wall in parallel or in series. Because the 350 MWe supercritical CFB boiler uses the structure validated in the 600 NW supercritical CFB boiler in Baima, the development of the 350 MWe supercritical CFB boiler is very smooth. The first 350 MWe supercritical CFB boiler was put into commercial operation on September 18, 2015 in Guojin, Shanxi as shown in Fig. 4.

Fig. 4 350 MWe supercritical CFB boiler in Guojin

Since then, a series of 350 MWe supercritical CFB boilers have been put into operation in Shenhua Hequ (Fig. 5), Huadian Shouzhou Company and Gemeng Hepo Company in Shanxi Province, and Huamei Power Company in Xuzhou, Jiangsu Province, respectively.

So far, the total capacity of the in-service supercritical CFB boiler is 4100 MWe. Additionally, about 80 sets of 350 MWe supercritical CFB boilers are under construction, including 3 sets exported overseas.

Fig. 5 350 MWe supercritical CFB boiler in Hequ

6 Development of the ultra-supercritical CFB boiler

As the fresh steam parameter increases, the thermal efficiency of a thermal power plant increases, too, which leads to the ultra-supercritical CFB boiler [25]. In 2011, FW Company won the order of 4 units of 550 MWe ultra-supercritical CFB boiler with a fresh steam temperature of 603°C and a reheat steam temperature of 603°C in Smacheok Green Power Company in South Korea. The design fuel in this project is sub-bituminous considering mixing wood Pellet. The steam from the two boilers is combined into one steam turbine with a capacity of 1100 MWe [26]. The fresh steam pressure is lower, which is 25.7 MPa. This boiler is similar to that in Lagisza Power Plant but the size is enlarged. Unexpectedly, the advantage of CFB combustion in pollutant emission of desulphurization by limestone injection into the furnace and low NO_x combustion as well as SNCR have been abandoned, while flue gas desulphurization for SO_2 control and selective catalytic reduction (SCR) for NO_x control have been adopted [27].

The successful experiences of the 600 MWe supercritical CFB boiler in Baima Power Plant and batch of 350 MWe supercritical CFB boiler [3] provide technical references for the 660 MWe ultra-supercritical CFB boiler [28]. The National Key R&D Program of China started to financially support the project named “development of ultra-supercritical CFB boiler technology and its demonstration” in 2016. Compared with the 600 MWe supercritical CFB boiler in Baima, the fresh steam pressure increases to 29.4 MPa at a fresh steam temperature of 605°C and a reheat steam temperature of 623°C in the 660 MWe ultra-supercritical CFB boiler. The emission of the 660 MWe ultra-supercritical CFB boiler must match ultra-low emission requirement in which NO_x is less than 50 mg/m^3, SO_2 less than 35 mg/m^3, and dust in gas less than 10 mg/m^3. The emission of SO_2 in this boiler will be controlled mainly by the limestone injection into the furnace and NO_x will be controlled by low NO_x combustion plus SNCR. This demonstration will be built by the end of 2020.

7 Conclusions

Without any precedent and reference, the supercritical CFB boiler was developed in China. A series of investigations were conducted systematically to solve the great theoretical and engineering challenges posed by the breakthrough from subcritical natural circulation of 300 MWe to supercritical once-through of 600 MWe. The complete set of supercritical CFB boiler design theory and calculation model were independently established.

Besides, the key technological system of supercritical CFB boiler was innovated. The first 600 MWe supercritical CFB boiler was demonstrated with safe operation technology. The performance of this boiler exceeds the other supercritical CFB boilers, which is regarded as a symbol of international CFB technology progress by the International Energy Agency. Currently, the 660 MWe ultra-supercritical CFB boiler is under development and its demonstration will be put into operation by the end of 2020.

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References

1. Le Guevel T, Thomas P. Fuel flexibility and petroleum coke combustion at Provence 250 MW CFB. In: Proceedings of the 17th International Conference on FBC. ASME, 2003: 643–649
2. Yu L, Lu J F, Wang Z W, Yue G X. The future investigation of circulating fluidized bed combustion technology. Journal of Engineering for Thermal Energy and Power, 2004, 19(4): 336–341 (in Chinese)
3. Yue G X, Lu J F, Xu P, Hu X K, Ling W, Chen Y, Li J F. The up-to-date development and future of circulating fluidized bed combustion technology. Electric Power, 2016, 49(1): 1–13
4. Lu J F, Yu L, Zhang Y J, Yue G X, Li Z Y, Wu Y X A. 600 MWe supercritical pressure circulating fluidized bed boiler with domestic technology. Power Engineering, 2007, 27(4): 497–501
5. Lu J F, Yu L, Yue G X, Yang H R, Zhang J S, Zhang M, Yang Z M. Heat flux distribution in circulating fluidized bed boiler water wall. Power Engineering, 2007, 27(3): 336–340
6. Yang H R, Lu J F, Zhang H, Yue G X, Xing X, Zhang S Y, Yang H. Update progress of supercritical circulating fluidized bed boiler. Boiler Technology, 2005, 36(50): 1–6
7. Ilkka V, Rafa L P. 460 MWe supercritical CFB boiler design for Lagisza power plant. Power Gen Europe, Barcelona, 2004
8. Hotta A. Features and operational performance of Lagisza 460 MWe CFB boiler. In: Proceedings of the 20th International Conference on FBC. Xi'an, China, 2009
9. Goidich S J, Hyppanen T, Kauppinen K. CFB boiler design and operation using the INTREXTM heat exchanger. In: Proceedings of the 6th International Conference on CFB, Würzburg, Germany, 1999
10. Jäntti T, Lampenium H, Ruuskanen M, Parkkonen R. Supercritical OTU CFB projects–Lagisza 460 MWe and Novercherkasskays 330 MWe. Russia Power, Moscow, 2011
11. Giglio R, Wehrenberg J. Fuel flexible power generation technology advantages of CFB technology for utility power generation. Power Gen International, Orlando, 2010.
12. Hu N, Zhang H, Yang H, Yang S, Yue G, Lu J, Liu Q. Effects of riser height and total solids inventory on the gas–solids in an ultra-tall CFB riser. Powder Technology, 2009, 196(1): 8–13
13. Wang Y, Lu J, Yang H, Zhao X, Yue G. Measurement of heat transfer in a 465t/h circulating fluidized bed boiler. In: Proceedings of the 18th International Conference on FBC. ASME, 2005: 327–335
14. Zhang R Q, Yang H R, Zhang H, Liu Q, Lu J F, Wu Y X. Research on heat transfer inside the furnace of large scale CFB boilers. In: Proceedings of the 10th International Conference of CFB, Sunriver, USA, 2011: 66–74
15. Zhang P, Lu J F, Yang H R, Zhang J S, Zhang H, Yue G X. Heat transfer coefficient distribution in the furnace of a 300 MWe CFB boiler. In: Proceedings of the 20th International Conference on FBC. Berlin: Springer, 2009: 167–171
16. Zhang R Q, Yang H R, Hu N, Lu J F, Wu Y X. Experimental investigation and model validation of the heat flux profile in a 300 MW CFB boiler. Powder Technology, 2013, 246: 31–40
17. Li J J, Wang W, Yang H R, Lu J F, Yue G X. Bed inventory overturn in a circulating fluid bed riser with pant-leg structure. Energy & Fuels, 2009, 23(5): 2565–2569
18. Mo X, Cai R, Huang X, Zhang M, Yang H. The effects of wall friction and solid acceleration on the mal-distribution of gas–solid flow in double identical parallel cyclones. Powder Technology, 2015, 286(5): 471–477
19. Yue G X, Yang H R, Nie L, Zhang H. Hydrodynamics of 300 MW and 600 MW circulating fluidized bed boilers with asymmetric cyclone layout. In: Proceedings of the 9th International Conference on CFB. Hamburg, 2008: 153–158
20. Yang S, Yang H, Liu Q, Zhang H, Wu Y X, Yue G X, Wang Y Z. Research on flow non-uniformity in main circulation loop of a CFB boiler with multiple cyclones. In: Proceedings of the 20th International Conference on FBC, Xi'an, 2009: 341–344
21. Wu Y, Lu J, Zhang J. Heat flux and hydrodynamics of the membrane wall of supercritical pressure circulating fluidized bed boiler. In: Proceedings of the 5th International Symposium on Multiphase Flow, Heat Mass Transfer and Energy Conversion, Xi'an, 2005
22. Li Y, Li W K, Wu Y X, Yang H R, Nie L, Huo S S. Hydrodynamics of the water wall in a 600 MW supercritical circulating fluidized bed boiler with water cooled panels within the furnace. Proceedings of the CSEE, 2008, 28(29): 1–5
23. Yue G X, Ling W, Lu J F. Development and demonstration of the 600 MW supercritical CFB boiler in Baima power plant. In: Proceedings of the 22nd FBC, Turku, Finland, 2015: 126–134
24. Li Y, Nie L, Hu X K, Yue G X, Li W K. Structure and performance of a 600 MWe supercritical CFB boiler with water cooled panels. In: Proceedings of the 20th International Conference on FBC. Berlin: Springer, 2009: 132–136
25. Jäntti T, Räsänen K. Circulating fluidized bed technology towards 800 MWe scale — Lagisza 460 MWe supercritical CFB operation experience. Power Gen Europe, Milan, 2011
26. Jäntti T, Nuortimo K, Ruuskanen M, Kalenius J. Samcheok green power 4 × 550 MWe supercritical circulating fluidized bed steam generators in South Korea. Power Gen Europe, Colon, 2012
27. Nuortimo K. State of the art CFB technology for flexible large scale utility power production. Power Gen Russia, Moscow, 2015
28. Lu J F, Zhang M, Yang H, Liu Q, Liu Z, Zhao Y. Conceptual design of a simplified 660 MW ultra-supercritical circulating fluidized bed boiler. Proceedings of the CSEE, 2014, 34(5): 741–747