Study on the actual operation characteristics of fluidized bed heat exchanger in a supercritical CFB boiler

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Abstract. On the basis of measurements on the fluidized bed heat exchanger (FBHE) in a 600MW supercritical CFB boiler fueled by lean coal under different boiler load, the actual operation characteristics of the FBHEs, such as post-combustion characteristics and heat absorption shares in the FBHE were obtained in this paper, as well as ash flow rate through the FBHE. The measured and calculated results indicate that the post-combustion phenomenon exists in the FBHEs of the boiler fueled by lean coal. As steam parameter raises from subcritical to supercritical parameter, heat absorption share of heating surface in the FBHEs are quite different from each other regardless of boiler load. Moreover, as the boiler load decreases, ash flow rate through FBHE arranging reheater is almost the same, while ash flow rate through FBHE arranging superheater changes significantly. These results can provide referential materials for the optimized design and operation of the FBHE in large-scale CFB boilers.

1. Introduction
Circulating fluidized bed (CFB) boilers are usually consisted by furnace, cyclone, loop seal and fluidized bed heat exchanger (FBHE). As a key component of the CFB boiler, FBHE is favorable for adjusting furnace temperature and steam temperature [1]. To an extent, heat absorption share and post-combustion phenomenon in the FBHE represents the regulation ability of furnace temperature, which are important issues in the design of supercritical CFB boiler at this stage and ultra-supercritical in the future [2-3].

Research works on characteristics of the FBHEs were mainly conducted on laboratory-scale test rigs [4-9]. However, because of limit of experiment condition, the practical value of the experimental data was rather limited. Lu, J.Y. et al. measured gas concentration at outlet of the FBHE in a 300MW CFB boiler burning lean coal, and post-combustion characteristics of the external circulation loop were studied [10]. Zhang, M. et al. measured heat absorption share of the heating surfaces in FBHEs of a 300MW CFB boilers fueled by lignite, and operation characteristics of the FBHE was analyzed [11]. Song G. L. et al. and Wang H. et al. measured outer wall temperature of the heating surface pipes to investigate the heat transfer uniformity for FBHEs in a 300MW CFB boiler, respectively [12-13]. Sun X. B. et al. and Cai R. X. et al. measured outer wall temperature of the heating surface tube panels, and the wall temperature distribution characteristics of the FBHEs in a 600MW CFB boiler were obtained, respectively [14-15]. In fact, due to the change of coal quality, the operation characteristics of the FBHEs of large-scale CFB boiler were quite different. When the boiler burned lean coal, there
is a certain combustion phenomenon in the FBHEs. In addition, since the field test is very difficult, the research data about actual operation characteristics of the FBHEs considering the combustion characteristics were rare in the public published literatures. Consequently, studies on operation characteristics of the FBHE in a 600MW supercritical CFB boiler fueled by lean coal were carried out in the present work. In this study, operation parameters, such as steam gauge pressure, steam temperature and flow rate of heating surfaces in the FBHEs, flue gas and ash temperatures at the inlet and outlet of each chamber in the FBHE were measured. After analyzing the operation parameters of FBHE, some suggestions are given in an attempt to provide reference for the optimized design and operation of FBHE in large-scale CFB boilers.

2. Experiment

2.1. Experimental objects
It involved a 600MW supercritical CFB boiler, shown in Figure 1(a). Six FBHEs were placed on the two sides of the boilers’ furnace symmetrically, which arranged in the front wall, the middle wall and the back wall of the furnace, respectively. Every FBHE was divided into two chambers along ash flow direction, one was in the absence of heating surfaces, not covered in Figure 1(b), the other was arranging high temperature reheater (HTR) in front FBHE of the boiler, superheater II (ITS-II) in middle FBHE of the boiler, and superheater I (ITS-I) in rear FBHE of the boiler, respectively.

![Figure 1. Schematic diagram of the boiler and FBHE.](image)

2.2. Experiment methodology
A measuring point was installed specifically in the ceiling at the exit of each FBHE for gas sampling. A custom-made probe was used to take gas samples from the FBHE [10]. A MGA5 infrared gas analyzer (O₂ precision accuracy of ±0.2%, CO precision accuracy of ±5% measured value) was employed to monitor the online gas concentrations. To prevent condensation inside the probe, the gas temperature was kept at 120°C by an electrical heating system.

Other ash-side and steam-side operation parameters, such as ash temperatures at the inlet and out of the FBHE, steam gauge pressure, steam temperature and flow rate of heating surfaces, volumetric flow rate and the fluidizing air temperature of each chamber in the FBHE, were all obtained from the Distributed Control System (DCS) database.

Heat absorptions of the heating surfaces were products of the corresponding steam mass flow rates and enthalpy increments from inlet to outlet. Heat released by residual char combustion in each FBHE, directly according to combustion reaction equation of carbon in every FBHE, then ash flow rate through every FBHE soon obtained according to mass and heat balances in the chamber [16].
2.3. Test process
The tests were conducted under 60% and 99% boiler load. Proximate and ultimate analyses for the feeding coal were shown in Table 1.

| Table 1. Coal characteristics of the boilera. |
|---------------------------------------------|
| Proximate analysis                                      | Ultimate analysis                                      |
| \( M_{ad} \) | 0.88 | \( C_{ar} \) | 41.10 |
| \( A_{ar} \) | 44.71 | \( H_{ar} \) | 1.87 |
| \( V_{daf} \) | 20.08 | \( N_{ar} \) | 0.48 |
| \( Q_{ar,\text{net}} \) | 15.61 | \( S_{tar} \) | 3.22 |

\( a \) Notes: weight unit wt. %; \( Q_{ar,\text{net}} \) unit MJ/kg.

3. Results and discussion
3.1. Field measurements
The steam-side and ash-side thermal parameters of the FBHEs at different boiler loads are given in Tables 2-4.

| Table 2. Steam-side thermal parameters of the FBHE of the boiler at 60%BMCR. |
|-------------------------------------|-------------------------------------|
| Item                                | Unit                  | HTR     | ITS-II   | ITS-I     |
| steam flow rate                     | t\( \cdot \)h\(^{-1} \) | 456.06  | 455.57   | 494.25    | 505.40    | 484.68    | 491.63    |
| inlet steam pressure                | MPa                   | 2.48    | 2.47     | 17.20     | 17.21     | 17.33     | 17.35     |
| inlet steam temperature             | °C                    | 458.66  | 457.57   | 481.67    | 469.63    | 448.89    | 445.26    |
| outlet steam pressure               | MPa                   | 2.40    | 2.38     | 17.09     | 17.11     | 17.20     | 17.21     |
| outlet steam temperature            | °C                    | 569.95  | 570.40   | 513.96    | 509.95    | 492.62    | 484.39    |

| Table 3. Steam-side thermal parameters of the FBHE of the boiler at 99%BMCR. |
|-------------------------------------|-------------------------------------|
| Item                                | Unit                  | HTR     | ITS-II   | ITS-I     |
| steam flow rate                     | t\( \cdot \)h\(^{-1} \) | 759.85  | 758.84   | 861.34    | 870.40    | 837.33    | 835.46    |
| inlet steam pressure                | MPa                   | 4.05    | 4.04     | 25.05     | 25.09     | 25.30     | 25.34     |
| inlet steam temperature             | °C                    | 473.16  | 474.88   | 479.05    | 475.86    | 453.49    | 456.11    |
| outlet steam pressure               | MPa                   | 3.92    | 3.91     | 24.86     | 24.89     | 25.05     | 25.09     |
| outlet steam temperature            | °C                    | 566.87  | 566.87   | 516.03    | 519.82    | 490.26    | 491.98    |

| Table 4. Ash-side thermal parameters of the FBHE of the boiler at 99%BMCR. |
|-------------------------------------|-------------------------------------|
| Item                                | Unit                  | 60%BMCR | 99%BMCR |
| fluidized air temperature           | °C                    | Left side | Right side | Left side | Right side |
| HTR inlet air flow rate             | Nm\(^{-3}\)\( \cdot \)h\(^{-1} \) | 13502.52  | 16958.80  | 13064.61  | 19377.05  |
| HTR inlet ash temperature           | °C                    | 787.23   | 821.89   | 880.08    | 911.67    |
| HTR outlet ash temperature          | °C                    | 638.20   | 671.38   | 671.79    | 694.98    |
| ITS-II inlet air flow rate          | Nm\(^{-3}\)\( \cdot \)h\(^{-1} \) | 10675.98  | 11004.52  | 10821.49  | 10942.76  |
| ITS-II inlet ash temperature        | °C                    | 787.23   | 823.81   | 880.88    | 872.96    |
| ITS-II outlet ash temperature       | °C                    | 585.64   | 604.35   | 662.12    | 673.79    |
| ITS-I inlet air flow rate           | Nm\(^{-3}\)\( \cdot \)h\(^{-1} \) | 10572.77  | 10545.06  | 10436.31  | 10622.88  |
| ITS-I inlet ash temperature         | °C                    | 824.01   | 788.90   | 870.11    | 871.32    |
| ITS-I outlet ash temperature        | °C                    | 584.02   | 552.78   | 642.72    | 593.73    |
Figures 2 and 3 give gas concentrations at the outlet of the three different FBHEs at 60% and 99% BMCR. It can be seen that O₂ concentrations at the outlet of the boilers’ FBHEs are all lower than that at the inlet, while the CO concentrations are high; indicating there is combustion occurring in the FBHEs of the two boilers and the combustion is not complete.

These Figures also show there are differences of combustion characteristic among different FBHEs, regardless of boiler load. For example, actual operation parameters obtained from the DCS database show the openings of the incoming ash flow control valves of the FBHEs at 99% BMCR are 28% (front FBHE), 25% (middle FBHE) and 21% (rear FBHE), respectively. Meanwhile, the inlet air flow rates of the three FBHEs are nearly the equivalent, so it is easy to understand that there are gas concentration differences at the outlet of the three FBHEs. Actual operation parameters also show that the inlet ash temperature of three FBHEs are all about 880 °C, but the outlet ash temperatures are 695 °C (front wall side), 674 °C (middle) and 594 °C (rear wall side), which indicated there is a great difference of the inside ash temperature distribution between the FBHEs. It may be another reason for gas concentration differences at the FBHEs outlet.

3.2. Heat absorption shares of heating surface in the FBHE at different boiler load

Heat absorption shares of reheater and superheater in the FBHE at different load are shown in Figures 4 and 5. It is seen that there exists a remarkable difference in the heat absorption shares of reheater and superheater in different FBHEs. Heat absorption shares of reheater and superheater in the FBHE are 7.61% and 8.40% at 60% boiler load, while they are 6.73% and 11.35% at 99% boiler load, indicating that when steam parameter from subcritical to supercritical parameter, heat absorption shares of the FBHE would be quite different from each other.
Figure 4. Heat absorption shares at 60%BMCR.

Figure 5. Heat absorption shares at 99%BMCR.

3.3. Ash flow rate through the FBHE at different load

Figure 6 gives ash flow rate through the arranging reheater and superheater FBHEs at different load.

It is shown that with the boiler load decreasing total ash flow rate through the FBHEs decreases. Moreover, to adjust the furnace temperature, ash flow rate through the arranging superheater FBHE changed obviously, while ash flow rate through the arranging reheater FBHE a little raised. It is mainly influenced by the heat transfer characteristics inside the FBHE. The heat transfer characteristics inside the FBHE are affected by ash flow rate through the FBHE and solid temperature at the entrance of the FBHE. In the tests, inlet solid temperatures at the front wall FBHE obtained from the DCS database were 880 °C (left side) and 912 °C (right side) at 99% boiler load, while they were 787 °C (left side) and 850 °C (right side) at 60% boiler load. To ensure outlet steam temperature of reheater and keep sufficient heat absorption, more hot particles are needed to pass through the FBHE to improve the ash-side heat-transfer intensity. Additionally, DCS database also showed that the openings of the incoming ash flow control valves of the front wall side FBHEs were 35% (left side) and 28% (right side) at 99% boiler load, but they were 42% (left side) and 34% (right side) at 60% boiler load. To a certain extent, it indicates that the ash flow rate through the arranging reheater FBHE indeed doesn’t decrease as the boiler load decreases.

4. Conclusions

Actual operation characteristics of the FBHEs in a supercritical CFB boiler were studied in this paper. The main findings of this paper include:
Measured results indicate O₂ concentrations at the outlet of the FBHEs in the boiler fueled by lean coal are about 15% at different boiler load, which shows that there exists post-combustion phenomenon in the FBHEs. In addition, there are also differences on combustion characteristic among different FBHEs, regardless of boiler load. With steam parameter raises from subcritical to supercritical steam parameter, heat absorption shares of heating surface in the FBHEs would be quite different significantly. Heat absorption shares of reheater and superheater in the FBHEs are 7.61% and 8.40% at 60% boiler load, while they are 6.73% and 11.35% at 99% boiler load. As the boiler load decreases, ash flow rate through front FBHE adjusting reheater steam temperature changes from 370.17kg/s to 394.54kg/s, while ash flow rate through middle and rear FBHEs adjusting furnace temperature changes from 600kg/s to 316.95kg/s.

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References
[1] Yue G X, Lv J F, Xu P 2016 The up-to-date development and future of circulating fluidized bed combustion technology Electric Power 49 1
[2] Jiang M H, Xiao P Large capacity circulating fluidized bed boiler technology China Electric Power Press 2009
[3] Hu C H, Lu X F 2012 Equipment and operation of 600MW supercritical circulating fluidized bed boiler China Electric Power Press 2012
[4] Yue G X, Lv J F, Zhang H 2005 Design theory of circulating fluidized bed boilers 18th International Conference on Fluidized Bed Combustion 2005
[5] Cheng L M, Xu L J, Xia Y F 2015 Key issues and solutions in development of the 600 MW CFB boiler Proceedings of the CSEE 35 21
[6] Lee J M, Park K, Kim D W 2015 Operation experience and comparison in large CFB boilers Proceedings of the 22nd International Conference on Fluidized Bed Combustion 2015
[7] Sun X B 2014 Plan design and research of 700°C ultra-supercritical circulating fluidized bed boiler Proceedings of the CSEE 34 23
[8] Rodriguez O M H, Pecora A A B, Bizzo W A 2002 Heat recovery from hot solid particles in a shallow fluidized bed Applied Thermal Engineering 22 2
[9] Ji X Y, Lu X F, Xue X L 2012 Development on a small scale industrial CFB boiler with an evaporating loop seal Applied Thermal Engineering 36
[10] Lu J Y, Lu X F, He H H Combustion characteristics of the external circulation loop on Baima’s 300 MWe circulating fluidized bed boiler Energy Fuels 25 8
[11] Zhang M, Wu H B, Lv Q G Heat transfer characteristics of fluidized bed heat exchanger in a 300MW CFB boiler Powder Technology 222
[12] Song G L, Lv Q G, Xiao F 2018 Experimental research of heat transfer uniformity for fluidized bed heat exchangers in a 300 MW CFB boiler Applied Thermal Engineering 130
[13] Wang H, Lu X F, Zhang W Q 2015 Study on heat transfer characteristics of the high temperature reheater tube panel in a 300 MW CFB boiler with fluidized bed heat exchanger Applied Thermal Engineering 81
[14] Sun X B, Hu C H, Li X H 2014 Tube wall temperature characteristic of external heat exchanger in 600 MW supercritical CFB boiler Power Constr. 35
[15] Cai R X, Zhang M, Mo X 2018 Operation characteristics of external heat exchangers in the 600 MW supercritical CFB boiler Fuel Processing Technology 172
[16] Huang Y S, Zhang L J, Wang H 2019 Operation characteristics of fluidized heat exchanger of a 300 MW circulating fluidized bed boiler Thermal Power Generation 49 8