THE HYDRODYNAMIC CHARACTERISTICS OF EMBATTLEMENT SHAPED WATER WALL OF A 350 MW SUPERCRITICAL CIRCULATING FLUIDIZED BED BOILER

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Abstract – Thanks to the economic value and environmental value for low calorific value solid fuel, circulating fluidized bed (CFB) boiler had a good development. Now, development of CFB boiler is towards supercritical and large-size, which may influence hydrodynamic safety. So, it is vitally important to calculate the hydrodynamic characteristics to insure the operation safety. This paper took the embattlement shaped water wall of a 350 MW supercritical CFB boiler as object, made some simplification and divided it into calculation circuits and pressure nodes. According to the conservation of mass, momentum and energy, a closed system of equations which describes the flowing system was gotten. The system of nonlinear equations was solved by using a modified Powell hybrid algorithm and a finite-difference approximation to the Jacobian. With this model, the hydrodynamics characteristics at the load of boiler maximum continuous rating (BMCR), 75% turbine heat-rate acceptance (THA), 50% THA and 30% BMCR were studied. The reasons of mass flux distribution were analyzed. The vertical and horizontal temperature distribution was also calculated and analyzed. It is found that the horizontal temperature deviations of working fluid at the same height in the neighbor circuits are lower than those of outer wall and inner wall. This is often neglected in previous research. According to the calculation, the metal temperature and temperature deviation of water wall are all in the safety limitations, so the water wall can work well and safely.

INTRODUCTION

Thanks to the advantages of low-cost emissions control, great flexibility for types of coal and low calorific value solid fuel, high combustion efficiency and proved original ultra-low emission, the circulating fluidized bed (CFB) boiler is widely applied to the thermal power generation. By combining with the supercritical boiler technique and increasing capacity, the efficiency of supercritical CFB is improved. So, the supercritical CFB boiler is greatly adapted to coal-based energy structure, especially for China. The number of boilers which are being built and operated in China is more than 70.

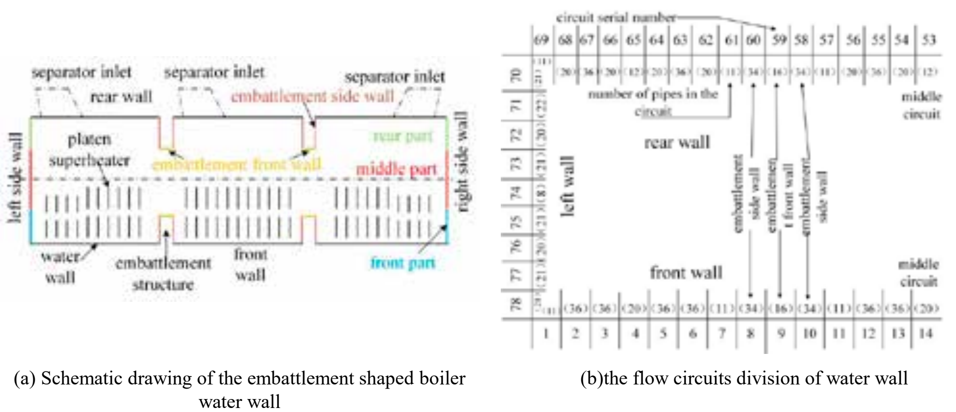
However, with the improvement of the capacity and main steam parameters, the granules fluid in boiler will be more complex and the diameter of water wall pipes will be smaller, and the hydrodynamic characteristics of a supercritical CFB boiler will be influenced. Heat transfer deterioration may occur and do harm to the safety of water wall. Thus, it is necessary to calculate the hydrodynamic characteristics, including the distributions of mass flux, pressure drops and the temperature distribution of the water wall metal to insure the safety of water wall during the design stage. As a significant step of boiler design, the hydrodynamic calculation is aimed at getting the water wall flow resistance and temperature distribution of water wall.

The hydrodynamic research originated from the 1950s. It was revitalized from the 2000s thanks to the widespread of supercritical technology. The research can be divided into two parts. One is the experiment and simulation whose target is to figuring out the mechanism, the other is the calculation research which serves for the engineering application. Some commercial corporations such as Siemens have developed some calculation methods for hydrodynamics, but these methods and data were not published. In order to break the commercial monopoly, Chinese scholars worked a lot and developed kinds of published and mature methods for hydrodynamics, eventually. By using these methods, the hydrodynamics characteristics of many kinds of boilers were calculated. Zhao et al. (2004) represented a universal calculation model which is suitable for subcritical boilers by regarding all equipment of boiler such as circulating pumps and pipes as the abstract pipes. Yang et al. (2008), Zhang et al. (2009), Zhou et al. (2013), Wu et al. (2013), Zhu et al. (2015) and Bi et al. (2015) developed a new method. They divided water wall into flow circuits and pressure nodes. Then, a system of equations was built. After solving the system of equations, the mass flux distribution was figured out. Besides, the temperature distribution of water wall metal was also gotten. This method suits supercritical direct current boilers. It can provide reasonable result for different kinds of direct current boiler. Zhang et al. (2014) calculated the hydrodynamics for a symmetric 600MW supercritical braize boiler. Zhang didn't make division for water wall, but calculated the mass flux and temperature of every pipe by regarding the pressure of fluid in mixing header uniform and using iterative algorithm. Up to now, the published papers for low mass flow (~700 kg/(m^2·s) at BMCR) are truly rare. What's more, the horizontal metal temperature deviation which influences the safety at the same height is ignored.

This paper took the water wall of a 350 MW supercritical circulating fluidized bed boiler as object and calculated its hydrodynamics. The structures such as the secondary air inlets, coal feeding inlets, separator inlet, loop seal inlet and so on were regard as the basis of circuits division. A new method of solving system of equations was applied. The rules of mass flux distribution and water wall temperature distribution at the heat flux of high in corner and low in middle for a CFB boiler were analyzed. Besides, the temperature deviation of working fluid at the 62m height, the temperature deviation of water wall metal was also taken into account.

BRIEF INTRODUCTION OF THE BOILER AND CIRCUITS DIVISION

As depicted in Fig.1(a), the embattlement boiler whose size is 32,000×9,700 mm is divided into three units. Embattlement shaped boiler have an advantage of controlling granules balance in each unit, which can be found in (Lyu et al., 2014). The boiler is bilateral symmetry. The separator of middle unit is eccentrically arranged. The platen superheaters are arranged at front wall. The outlet header of front wall and rear wall is the same one, which is over the rear wall. Refractory is applied near platen superheaters installing position, the inlet of separators and the same height in the left wall and right wall. The inlet and outlet headers of embattlement wall are independent. The number of inlet headers of left wall and right wall is three, while the number of their outlet headers is only one. This special arrangement of water wall makes the flow more complex, which needs to be taken into account. The structures such as the secondary air inlets, coal feeding inlets, separator inlet, loop seal inlet and so on are taken as the basis of circuits division. The circuits division for the water wall is depicted in the Fig.1(b). The outside numbers are the serial numbers of circuits, while the inside numbers are the numbers of pipes in the circuits. Because the furnace is bilateral symmetry, Fig.1(b) only shows one part of the circuits division. The No.1-27 circuits are in the front wall, while No.8-10, 18-20 circuits are the embattlement circuits. The No.28-36 circuits are in the right wall. No.70-78 circuits are in the left wall. The No.37-69 circuits are in the rear wall, while No.46-48, 58-60 circuits are the embattlement circuits. The water wall was divided into 78 circuits.



(a) Schematic drawing of the embattlement shaped boiler water wall

(b)the flow circuits division of water wall

Fig. 1. Schematic drawing of the embattlement shaped boiler water wall and its flow circuits division.

The flow path of this boiler is depicted by Fig.2. The working fluid from economizer flows to 2 distributed headers which is located near the rear wall through the centralized downcomers. Next, the working fluid goes through the water wall inlet distributed pipes and flows to the water wall inlet headers. Then, the working fluid absorbs the heat from combustion in the water wall and flows into the collection headers over the rear wall, left wall, right wall and embattlement side walls. Then, the working fluid flows to the mixing header through connecting pipes and finally flows to the steam separator. The number of water wall inlet distributed pipes is 34, which were divided into 18 circuits (No.79-96). The number of water wall outlet pipes is 24, which were divided into 12 circuits. (No.97-108). The number of connecting pipes between mixing header and steam separator is 12, which are divided into 2 circuits (109-110). There are totally 31 headers in the concerned flow system whose serial number are 111-139 (2 distributed headers near the rear wall have no serial number.)

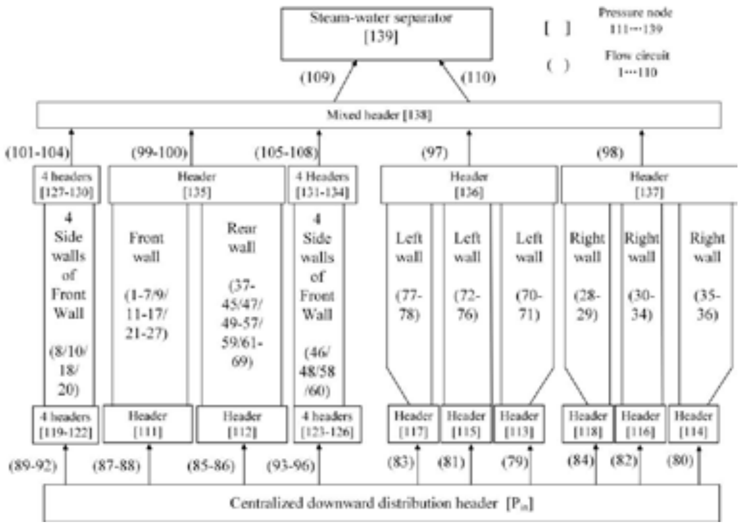


Fig. 2. Schematic diagram of the water wall flow network system

The heat load is the normal CFB boiler heat load, which is high and nearly uniform at low and gradually decreases with height increasing. This conclusion can be found in (Lyu et al, 2007). The heat load deviation coefficients at the same height vary from 0.9 to 1.1, which are high in corner and low in middle in every unit of the boiler.

MATHEMATICAL MODEL

The model of flow distribution calculation was mainly based on that of Wang et al. (2016). When the flow is in steady state, the mass flux of working fluid leaving from header is equal to that of flowing into header, according to the mass conservation. Therefore, the flow equation can be listed on every pressure node. For example, the Eq.1 can be gotten on the No.138 pressure node, mixing header:

$$0=\sum_{i=97}^{108} x(i)n(i)-\sum_{i=109}^{110} x(i)n(i) \tag{1}$$

where, the first term at the right of equation refers to the total mass flux which flows into the mixing header, the second term refers to the total mass flux which flows out of the mixing header. Similarly, the equations on No.111-139 pressure nodes can also be gotten.

According to structure of the boiler, the pressure in headers can be regarded as uniform. On the element which consists of a circuit and two pressure nodes at the end of the circuit, a pressure drop equilibrium equation can be listed according to the momentum balance. The pressure drop mainly contains three parts: friction pressure drop, gravity pressure drop and local resistance loss. There is also acceleration pressure drop in fact. But it’s so small that it could be ignored. In heated circuits, the pipes were divided into 33 short sections and the pressure drop were calculated section by section. In every section, the working fluid absorbs the heat from furnace and its enthalpy value increases where energy conservation can be applied.

For example, on the element which consists of No.116 and No.137 pressure nodes and No.30 circuits, the following equation can be gotten:

$$0=p(116)-p(137)-\left(\Delta p_{\mathrm{f}}+\Delta p_{\mathrm{g}}+\Delta p_{\mathrm{jb}}\right)_{30} \tag{2}$$

where, $p(116)$, $p(137)$ refer to the pressure of No.116 and No.137 pressure nodes, respectively. The subscript 30 refers to the No.30 circuit. Δp_f, Δp_g and Δp_{jb} refer to friction pressure drop, gravity pressure drop and local resistance loss, respectively. Similarly, the equations on No.1-110 circuits can also be gotten.

According to the circuits and the conservation of mass, momentum and energy, a closed system of equations which contains 110 pressure drop equations and 29 mass flow equations was acquired. After solving the system of equations, each mass flux of No.1-110 circuits and every pressure of No.111-139 were figured out. The method taken to solving system of equations was the modified Powell hybrid algorithm and a finite-difference approximation to the Jacobian. This method showed better convergence and faster solving speed when the calculation procedure was being debugged and executed.

The temperature calculation formulas, which combine those in the papers of (Liu, J., 2007) and (Wang et al., 2016), were taken to calculating the inner-wall temperature, middle pipe wall temperature, outer-wall temperature and temperature in the tip of fin. When calculating the water wall metal temperature, the local heat load was improved by 50%. Li et al. (2014) have proved that at a wide heat load, Nussle number correlation can effectively predict temperature. For the heat transfer in supercritical pressure, because CFB boiler's heat load is so low that it's almost beyond the range of application of the correlations which were researched by Pioro et al. (2004). Most of those correlations give too high heat transfer coefficient. They were not applied. Besides, comparing to the research of Mokry et al. (2010), because in most region heat transfer coefficient is so high that it only has a little influence on temperature calculation, the Dittus-Boelter correlation was still applied.

RESULTS AND ANALYSIS

Fig.3 depicts the mass flux distribution of No.1-78 circuits at the load of BMCR, 75%THA, 50%THA and 30%BMCR. From the Fig.3, it is found that the mass flux in rear wall is the highest, that in front wall take the second place, while that in left wall and right wall are the lowest. The decisive reason of this mass flow distribution is that the flow resistances for different circuits at the same mass flux are different. This deviation is mainly caused by the different length of water wall inlet distributed pipes, water wall pipes and the connecting pipe. Because the boiler has a large length width rate, centralized downcomers are located near the rear wall, and the mixing header is right over the boiler, the total length of pipes where working fluid flows through left wall and right wall is the longest, therefore the mass flux in left wall and right wall is the lowest in order to meet the condition that the pressure drop along any circuit form distributed header and mixing header is same.

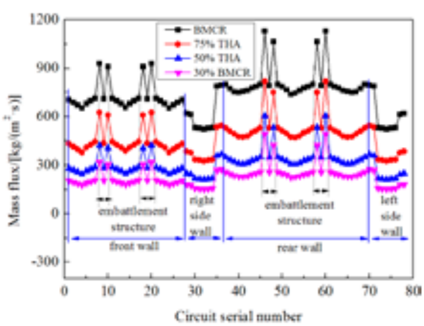


Fig.3 Mass flux distribution of every circuit at different heat loads

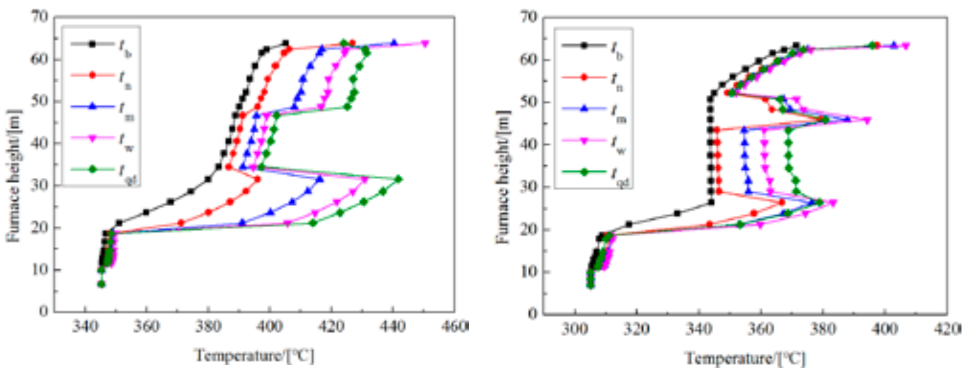
At the four heat load, the embattlement side wall circuits (No.8, 10, 18, 20) have higher mass flux than that in front wall and rear wall. One reason is that these circuits have their own inlet headers and outlet headers. Another important reason is that in these circuits, the number of water wall pipes which a distributed pipe and a connecting pipe need to supply water for is less than those in normal circuits of front wall and rear wall. In order to meet the pressure drop condition, these circuits have higher mass flow. These circuits are located in the corner of every unit of boiler and they have higher heat flux, higher mass flux can make the metal temperature lower.

In left wall and right wall, there are 3 inlet headers and 1 outlet header. The lengths of distributed pipes are also different. The number of water wall pipes which a distributed pipe need to supply water for is also different. These reasons make the mass flux in No.30-34 and No.72-76 circuits is lower than that in No.28-29, No.35-36, No.70-71 and No.77-78 circuits. Because the total length for No.35-36 and. No.70-71 circuits is shorter than that of No.28-29 and No.77-78, No.35-36 and No.70-71 circuits have higher mass flux than No.28-29 and No.77-78 circuits. The mass flux deviation in left wall and right wall will be larger when the average mass flux is larger.

For the No.38-40, No.51-53 and No.66-88 circuits which have longer pipe because of the inlet of separator in rear wall, they have lower mass flux. Besides, the decrement of mass flux will be larger with the mass flux increasing. When the heat load and mass flux is low, the mass flux deviation which is caused by structure is not larger than that caused by heat load deviation. For example, at the load of 30%BMCR, the mass flux shows good symmetry in No.37-45, 49-57, 61-69 circuits and the mass flux deviation is caused by heat load deviation. While, at the load of BMCR, mass flux in these circuits has a bad symmetry because the mass flux caused by longer pipe in No.38-40, No.51-53 and No.66-88 circuits becomes large.

The calculation shows that the boiler has lower mass flux at the four heat loads. In this condition, flow resistance accounts for a small part of total pressure drop. This can help to develop positive flow response. It is to say that at any heat load of this boiler, the circuits which get more heat from furnace will have higher mass flux. So, it is helpful to reduce the metal temperature when pipes get more heat, but it can’t totally offset the effect of heat to temperature increment.

According to the mass flux shown in Fig.3, the No.30-34 circuits in right wall and No.72-76 circuits in left wall have the lowest mass flux. They are potential dangerous circuits. Among them, No.30, 34, 72, 76 circuits have the highest heat load and mass flux, so they will have the highest metal temperature. Besides, the circuits in front wall have the longest heated pipe, those who are located in corner will become potential dangerous circuits, namely No.1, 7, 11, 17, 21, 27 circuits. Among these circuits, No.1, 27 circuits have lower mass flow than No.7, 11, 17, 21 circuits but their heat loads are almost same. This condition leads to that No.1, 27 circuits are dangerous. The following vertical temperature analysis will take these dangerous circuits as objects.



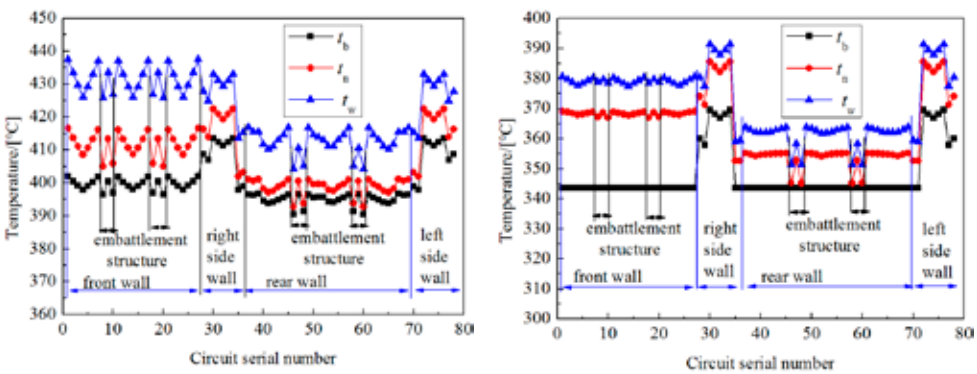
(a)BMCR, No.1 circuit (b)50%THA, No.30 circuit

Fig.4 Temperature distribution of in vertical direction at the heat load of BMCR and 50%THA

At the load of BMCR and 75% THA, No.1, 27 circuits have higher metal temperature than No.20, 34, 72, 76 circuits, according to the result of calculation. The vertical temperature distribution of No.1 circuit at the heat load of BMCR is depicted in Fig.4(a). (According to symmetry, No.27 circuit have the same temperature distribution.) Because the limit of fin temperature calculation method, the fin tip temperature can’t reflect the temperature well in some condition, so the outer-wall temperature was taken to the criterion of temperature safety. Fig.4(a) shows that working fluid in pipes is in single phase and its temperature increases with heat absorbing process. At the bottom refractory area, temperature of working fluid and metal increases a little. When the height is over 20m, the working fluid enter the highest heat flux area, temperature of working fluid and metal increases greatly. At the height from 34m to 46m, because refractory is applied, the heat flux decreases and temperature of working fluid increases slowly, while temperature of metal decreases. When the height is over 46m, the heat flux recovers normal level, temperature of working fluid and metal increases rapidly, again. After working fluid flows through the incline top of furnace, temperature increment is 25.8℃. At the load of BMCR, the maximum temperature of No.1 circuit occurs at the outer-wall, which is 450.4℃. The temperature distribution at the 75%THA is similar to that of BMCR. At the load of 75%THA, the maximum temperature is 445.3℃, which occurs at the outer-wall of top furnace. Maximum temperature increment of top furnace is 37.2℃.

At the load of 50%THA and 30%BMCR, maximum temperature occurs at the No.30, 34, 72, 76 circuits. The vertical temperature distribution of No.30 circuit at the heat load of 50%THA is depicted in Fig.4(b). (According to symmetry, No. 34, 72, 76 circuits have the same temperature distribution.) At inlet of water wall, the working fluid is in liquid state. At the bottom refractory area, temperature change is similar to that of No.1 circuits. When the height is over 20m, the heat flux is the highest and temperature of working fluid and metal increases rapidly. With temperature of working fluid up to saturation temperature, working fluid enters two-phase region and heat transfer is enhanced greatly. At the height near 46m, vapor quality is high enough that the second kind transfer deterioration (dry out) occurs and temperature of metal sharply rises. At the height of 46m to 52m, working fluid enters liquid deficient region, temperature of metal decreases with liquid drops falling back to inner-wall. At the height from 52m to 62m where refractory is applied, because the heat flux decreases and working fluid is totally changed into gas phase, temperature of working fluid increases slowly and metal temperature level falls down to low level but still increases. At the height over 62m, heat flux recover to normal level and metal temperature continues to increase. Maximum metal temperature occurs at the outer-wall and it's 402.8℃. The maximum temperature change caused by refractory is 27.7℃. The temperature distribution at the 30%BMCR is similar to that of 50%THA. At the 30%BMCR, the maximum temperature is 375.0℃, which occurs at the outer-wall of top furnace. The maximum temperature change caused by refractory is 25.7℃.

When the metal temperature deviation is large enough to cause large thermal stress, it may cause the water wall avulsion. This phenomenon may greatly do harm to CFB boilers. In order to avoid this phenomenon, the horizontal temperature difference at any height should be as low as possible. So, it's vital necessary to pay attention to the horizontal temperature distribution. The temperature deviation of two neighbor pipes is related to both heat flux and mass flux. At the bottom of furnace, the amount of absorbed heat is so small that the temperature difference caused by flow deviation is small. But at the top of furnace, the amount of absorbed heat is large enough to enlarge the effect of heat flux deviation and mass flux deviation, so the horizontal temperature deviation will be the largest. The horizontal temperature distribution of 62m was analyzed.



(a)BMCR (b)50%THA

Fig.5 Horizontal temperature distribution at the height of 62m at the load of (a)BMCR and (b)50%THA

Fig.5(a) shows the horizontal temperature distribution of working fluid, inner-wall and outer-wall at the height of 62m at BMCR. It's found that in the circuits whose inlet header and outlet header are same, horizontal temperature distribution is similar to that of the heat flux, they're all low in the middle and high in corner. Besides, what is ignored in the previous research is that the outlet temperature deviation of working fluid may be lower than that of metal. The front wall has the highest temperature level, the middle part of left wall and right wall take the second place. The reason for front wall is that it has the longest heated pipes and heat transfer coefficient becomes small. The reason for middle part of left wall and right wall is mainly that the mass flux is small. These embattlement circuits, No.8, 10, 18, 20, 46, 48, 58, 60, have low temperature because mass flux is high. The embattlement front wall in rear wall, No.47, 59 circuits have lower temperature than those circuits in rear wall because No.47, 59 circuits have shorter heated length and heat flux is lower. No.35, 36 circuits in right wall and No.70, 71 circuits in left wall, which are near to the rear wall, have high mass flux, so the temperature of working fluid and metal is low. No.28, 29 circuits in right wall and No.77, 78 circuits in left wall, which is near to the front wall, have low mass flux, so temperature of working fluid and metal is high. The maximum temperature deviations in neighbor circuits of front wall, right wall, rear wall and left wall are 11.2°C, 19.3°C, 11.6°C, 19.3°C, respectively. The 19.3°C occurs between No.34 and 35 circuits in right wall. By symmetry, it also occurs between No.71 and 72 circuits in left wall. It is mainly caused by great mass flux deviation.

At the load of 75%THA, the horizontal temperature distribution is similar to that of BMCR. The maximum temperature deviations in neighbor circuits of front wall, right wall, rear wall and left wall are 21.7°C, 33.9°C, 7.6°C, 33.9°C, respectively. The 33.9°C occurs at No.34-35 circuits and No.71-72 circuits. It is mainly caused by great mass flux deviation.

Fig.5(b) shows the temperature distribution of working fluid, inner-wall and outer-wall at the height of 62m at 50%THA. It is clear that in most of circuits, working fluid is in two-phase, besides the middle and rear part of left wall and right wall. Although temperature is same for two-phase working fluid, metal temperature varies from circuit to circuit, because their heat flux is different. So, it's not enough to only take outlet working fluid temperature into account, the horizontal metal temperature deviation should be paid more attention. Apart from embattlement circuits, No.46, 48, 58, 60, metal temperature is much higher than working fluid temperature. It means that vapor quality is high and dry out occurs. Working fluid has entered the liquid deficient region. The rear wall embattlement front wall, No.47, 59 have a lower temperature because they have shorter heated lengths and heat flux is lower. No.28-34 circuits in right wall and No.72-78 circuits have low mass flux, so the working fluid is all changed into gas phase. The maximum temperature deviations in neighbor circuits of front wall, right wall, rear wall and left wall are 1.8°C, 32.2°C, 12.4°C, 32.2°C, respectively. The maximum temperature deviation still occurs at No.34-35 circuits and No.71-72 circuits.

At the load of 30%BMCR, the horizontal temperature distribution at the height of 62m is similar to that of 50%THA. The maximum temperature deviations in neighbor circuits of front wall, right wall, rear wall and left wall are 28.0°C, 38.7°C, 1.2°C, 38.7°C, respectively. The maximum temperature deviation still occurs at No.34-35 circuits and No.71-72 circuits.

As discussed above, it is clear that at the height of 62m, the horizontal temperature deviation at the four loads will not be larger than 40°C. The maximum metal temperature will not be larger than 460°C. According to calculation, the boiler can work well and safely for a long time.

CONCLUSION

The water wall system of a 350MW supercritical CFB boiler is regarded as a flowing network. This system is divided into circuits and pressure nodes. The water wall pipes, distributed pipes, connecting pipes and headers are simplified as heated parallel circuits, unheated circuits and pressure nodes. According to conservation of mass, momentum and energy, a closed system of equation which describes the flowing network is gotten. By solving the system of equation with the modified Powell hybrid algorithm and a finite-difference approximation to the Jacobian, mass flow distribution, pressure of headers and flow resistance can be gotten. Further, temperature of heated flowing fluid and water wall metal temperature can be calculated to help to insure whether the boiler can work well and safety at the heat load.

The calculation shows that the mass flux in middle part circuits of left wall and right wall is obviously lower than those in the other circuits. Both structure of water wall and heat load deviation affect mass flux distribution. At the load of BMCR and 75%THA, maximum metal temperature circuits are No.1, 27, which are located at the corner of front wall. At the load of 50%THA and 30%BMCR, maximum metal temperature circuits are No.30, 34, 72, 76, which are located at the edge of middle part of left wall and right wall. At the four loads, maximum metal temperature is lower than 460°C.

With the heat flux of low in middle and high in corner, the horizontal temperature distribution is similar to that of horizontal heat flux deviation for neighbor circuits whose inlet header and outlet header are same. Maximum working fluid temperature deviation is 25.9℃ (75%THA). At the subcritical load of 50%THA and 30%BMCR, although working fluid temperature is same when it is in two-phase, horizontal temperature deviation is large. At the four load, the maximum horizontal temperature deviation all occurs at No.34-35 circuits in right wall and No.71-72 circuits in left wall. The maximum is 38.7℃ at 30%BMCR, while it's also the maximum in all circuits of water wall. According to the hydrodynamics calculation, it can be predicted that the water wall of boiler can work well and safety.

NOTATION

x	mass flux, kg/(m^2·s)
i	serial number of circuits
n	number of pipes in a circuits
p	pressure, Pa
Δp	pressure drop, Pa
Nu	Nusselt number
t_b	bulk fluid temperature, ℃
t_n	tube inner-wall temperature, ℃
t_m	metal temperature in the middle of pipe wall, ℃
t_w	pipe outer-wall temperature, ℃
t_{qd}	metal temperature in the tip of fin, ℃
t_{qg}	metal temperature in the root of fin, ℃

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REFERENCES

Bi, Y., Wang, S., Shen, Y. 2015. Hydrodynamic characteristic calculation for a 600 MW unit once-through tower boiler. Thermal Power Generation 01, 25-29+38.

Li, Z., Wu, Y., Lu, J. 2014. Heat transfer to supercritical water in circular tubes with circumferentially non-uniform heating. Applied Thermal Engineering 70, 190-200.

Liu, J. 2007. Study on temperature calculation of boiler's water wall and tube busting under low-load, Master thesis, Institute of Nuclear Science and Technology, Dalian University of Technology, Dalian.

Lyu, J., Yu, L., Yue, G. 2007. Heat flux distribution along water walls of circulating fluidized boilers. Journal of Power Engineering 03, 336-340.

Lyu, J., Zhang, M., Yang, H. 2014. Conceptual design of a simplified 660 MW ultra-supercritical circulating fluidized bed boiler. Proceedings of the CSEE 05, 741-747.

Mokry, S., Pioro, I., Kirillov, P. 2010. Supercritical-water heat transfer in a vertical bare tube. Nuclear Engineering and Design 240(3), 568-576.

Pioro, I., Khartabill, H., Duffey, R. 2004. Heat transfer to supercritical fluids flowing in channels—— empirical correlations(survey). Nuclear Engineering and Design 230, 69-91.

Wang, L., Yang, D., Shen, Z., Mao, K., Long, J. 2016. Thermal–hydraulic calculation and analysis of a 600 MW supercritical circulating fluidized bed boiler with annular furnace. Applied Thermal Engineering 95: 42-52.

Wu, Y., Yang, D., Chen, G. 2013. Calculation and analysis of hydrodynamics characteristics for first 600-MW supercritical down-fired boiler. Electric Power 02, 24-30.

Yang, D., Yu, H., Hua, H. 2008. Numerical computation on the mass flow rate profile and metal temperature in vertical water wall of an ultra-supercritical boiler. Proceedings of the CSEE 28(17), 32-38.

Zhang, D., Wu, Y., Zhang, Hai. 2014. Hydrodynamic characteristics of vertical tubes with low mass flux in supercritical pulverized coal boiler. Proceedings of the CSEE 32, 5693-5700.

Zhang, W., Yang, D., Huang, Y. 2009. Calculation on flow rate distribution and wall temperature of water wall with spiral tube coils of supercritical once-through boilers. Journal of Power Engineering 29(4), 342-347.

Zhao, Z. 2004. Universal model for hydrodynamic calculation. North China Electric Power 34(12): 1-4.

Zhou, Y., Yang, N. 2013. Flow distribution characteristics of water wall in a 600MW unit boiler in thermal state. Thermal Power Generation 12, 34-39.

Zhu, X., Wang, W., Xu, W. 2015. A study of the hydrodynamic characteristics of a vertical water wall in a 2953t/h ultra-supercritical pressure boiler. International Journal of Heat and Mass Transfer 86, 404-414.