Journal of Zhejiang University SCIENCE A
ISSN 1673-565X (Print); ISSN 1862-1775 (Online)
www.zju.edu.cn/jzus; www.springerlink.com
E-mail: jzus@zju.edu.cn

Experimental and thermal stress investigation on side wall deformation at the pendent convective pass in a utility boiler*

Li-ping PANG†, Bao-min SUN, Tong LIU
(*MOE, Key Laboratory of Condition Monitoring and Control for Power Plant Equipment, North China Electric Power University, Beijng 102206, China*)
†E-mail: liping_pang@163.com

Received Nov. 3, 2008; Revision accepted June 13, 2009; Crosschecked Sept. 9, 2009

Abstract: An experimental investigation is performed on side wall deformation at the pendant convective pass (PCP) in a 300 MW and a 600 MW utility boiler. The temperature distributions are measured on the side wall areas of the water-cooled wall, the PCP and the horizontal convective pass (HCP) in the two utility boilers. These experiments show that there are great temperature differences in the side wall areas during the startup process in both utility boilers. These temperature differences can reach 80~150 °C with the side wall temperature in the PCP area higher than those in the water-cooled wall and the HCP. The highest temperature in the PCP is close to the flue gas side temperature at the same position in the horizontal flue gas pass. Thermal stress analyses are conducted in the side wall areas in the water-cooled wall, the PCP and the HCP with the software ANSYS. The results show that, at great temperature differences, the PCP side wall undergoes negative thermal stresses that exceed the yield strength causing deformation in the PCP side wall.

Key words: Utility boiler, Horizontal flue gas side wall in pendant convective pass (PCP), Deformation, Temperature measurement, Thermal stress analysis
doi:10.1631/jzus.A0820763 **Document code:** A **CLC number:** TK223.2

INTRODUCTION

In a series of 200, 300 and 600 MW drum utility boilers with subcritical parameters and natural circulation manufactured by a certain boiler company, deformation in the side wall at the pendant convective pass (PCP) generally occurs. The deformation is the greatest in the 200 MW utility boiler, with a maximum vertical deformation length of 15~20 cm. The deformation in the 300 MW utility boiler is 10~15 cm, and the deformation in the 600 MW utility boiler is even smaller. Because of the overall similarity of their superheating steam systems, these three kinds of utility boilers also have similar wall superheating steam systems. Fig.1 shows the overall schematics of the boiler construction with all components related to the deformation. Area 1 belongs to one part of the water-cooled walls; area 2 is the side wall of the PCP, which is one part of the wall superheater; area 3 is the side wall of the horizontal convective pass (HCP) and also one part of the wall superheater. Deformation area appears in area 4, located in the middle of area 2.

A flow chart of the wall superheater is shown in Fig.2. Figs.1 and 2 show a typical arrangement of a wall superheating system in 200, 300 and 600 MW utility boilers. Boiling water in the water-cooled wall passes through area 1 in Fig.1, at which point the wall temperature is close to saturated water temperature. Saturated steam coming from the steam drum passes through the PCP area. Under normal operating conditions, the wall temperature should be close to the temperature of saturated steam. Superheated steam passes through the HCP area coming from the wall superheating steam system. The wall temperature in

* Project supported by Program for Changjiang Scholars and Innovative Research Team in University (No. PCSIRT0720), and the Overseas Returnee Scholar Foundation of North China Electric Power University, China

area 3 should be close to the steam temperature at the HCP wall superheater. Therefore, the temperature differences in these three areas should be distributed as follows: The wall temperature at the side wall of the PCP should be greater than that at the water-cooled wall, and the wall temperature at the HCP should be greater than that at the side wall of the PCP under normal operating loads. The three areas, the water-cooled wall and the side walls of the PCP and HCP, are welded together in all experimental utility boilers and can be regarded as rigidly connected. Generally, the differences in wall temperatures in these three areas are small under normal operating conditions. If the wall temperature differences are greater than the normal, however, deformation in the PCP side wall may appear.

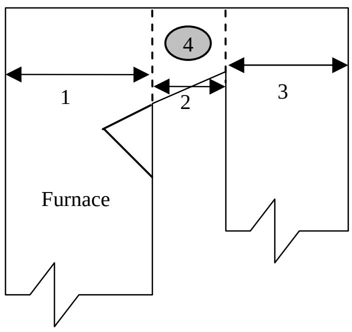

Fig.1 Overall schematics of utility boiler construction
1: water-cooled wall area; 2: pendent convective pass; 3: horizontal convective pass; 4: deformation area

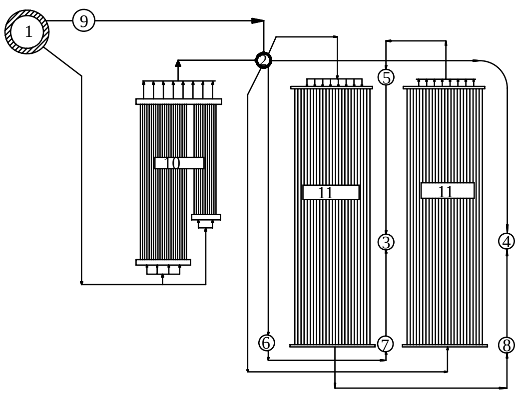

Fig. 2 Flow chart of wall superheater
1: steam drum; 2: convective pass front wall upper header; 3: rear inlet header of primary superheater; 4: front inlet header of primary superheater; 5: baffle wall upper header; 6: convective pass front wall lower header; 7: baffle wall lower header; 8: convective pass rear wall lower header; 9: roof inlet header; 10: side wall of PCP; 11: side wall of HCP

Few papers have reported on deformation at the PCP in this kind of utility boilers. Li *et al.*(1998) discussed the deformation and leakage in the side wall of the PCP in a 300 MW utility boiler, and found that the deformation was caused mainly by the manufacture and construction of the metal material used in the PCP area. Because of sympathetic vibrations between the flue gas and the wall superheater, leakage happened frequently in the side wall of a 300 MW utility boiler (Shi and Zhang, 2000). They offered individual reasons why the deformation happened at the PCP side wall, but did not clarify why the phenomenon occurs in a series of utility boilers. Sun *et al.*(2007) also gave theoretical calculations on the flow distribution in the wall superheater according to Bao and Lu (1988) and Huang (1982). The results show that the steam in wall superheater is well distributed as designed. They also visited some power plants and held discussions with the operating and maintenance engineers. In general, deformation may stem from several factors: manufacture, material selection, material strength, the construction and operating factors. Operating factors include the effects of startup, load following and the shut-down process on area 4 of the side wall. According to our inquiries of operating engineers from different experimental power plants, the drainage valve is shut down strictly when an appropriate operating parameter is reached, as required in the operating manual.

After the initial investigation, the focuses moved to temperature differences at the side wall during the startup and rise-up process. An experimental investigation was done to find out why deformation happens at the PCP side wall. A temperature measuring system was arranged to record the temperature distribution at the side wall during the startup. Main steam temperature and pressure are taken simultaneously from the Data Acquisition System (DAS) to analyze the processes occurring at the PCP side wall. Throughout the experiments, the temperature distributions at the side wall can be obtained during the startup process. Finally, a theoretical analysis using the ANSYS 6.0 software is performed to calculate the thermal stress distributions at the side wall.

EXPERMENTAL

To measure the temperature changes in the finned tube during the startup and rise-up process, the temperature measuring system is located at the side wall in the water-cooled walls, the PCP and the HCP. In consideration of the deformation shape and area, the temperature measurement probes were distributed in and adjacent to the area of deformation. The measuring probes are arranged at the side wall in the flue gas side, the finned tube and the fin outside convective pass. The arrangement is described below:

1. Every measuring probe is located around severe deformation areas; Twenty-two temperature probes are arranged on the upper and lower portions of every two finned tubes outside the side wall of the PCP. This measuring arrangement provides coverage of the area that has been known to deform in this kind of utility boilers. The distance between the upper and lower probes is 1100 mm.

2. There are two temperature measurement probes located in the fin between two finned tubes.

3. There are two temperature measurement probes located at the finned tubes on the flue gas side to make sure that the flue gas temperature changes during startup in PCP. For the safety and reliability of the probes, they are installed at the end of the PCP.

4. There are eight temperature probes located in the water-cooled wall at the same height as the probes at the PCP. Two temperature probes are located at the side wall in the HCP. The probe distribution is given in Fig.3.

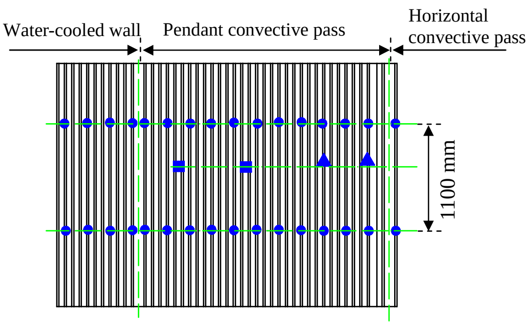

Fig.3 Temperature probe location in the water-cooled wall, the PCP and the HCP

All temperature probes are arranged from left to right at upper position from No. 1 to No. 16 and lower position from No. 17 to No. 32. The temperature probes in the flue gas side are denoted as inner 1 and inner 2 (Fig.3). Temperature probes in the fin between two finned tubes are denoted as outer 1 and outer 2. Ni-Cr K-type thermocouples are used as the temperature probes in this experiment. The probes are welded to the outside surface of the side wall tubes and the fin as shown in Fig.3. This scheme is used to ensure the reliability and accuracy of the temperature measurements.

The experiment covers the whole process from cold startup to full loading of the 300 MW utility boiler and the startup of 600 MW utility boiler. Temperature changes are recorded at the side walls of the water-cooled wall, the PCP and the HCP. In this study, all temperatures measured at the side wall are referred to as the wall temperature, while wall temperature difference refers to the temperature differences between area 2 and area 1 and between area 3 and area 2 in Fig.1.

The wall temperature measurements during startup are shown in Figs.4 and 5. The experiments reveal changes in the wall temperature from the beginning to higher operating loads in the 300 MW and 600 MW utility boilers. At the beginning, the differences in the side wall are almost zero. After the drainage valve is shut down, differences in the wall temperature appear and increase as the main steam pressure and temperature increase. The temperature differences change substantially from startup to lower loads at the side wall in the PCP. The temperature difference in these three areas can reach 80~150 °C. The temperature differences pass several stages. At the beginning, the operating parameters are lower and the main steam pressure is below 1.0 MPa. Differences in the wall temperature are not present in the PCP area. As the pressure increases, temperature differences at the side wall in the PCP begin to appear. When the pressure reaches a range from 5.0 to 8.3 MPa, a higher temperature difference is maintained. The maximum difference is 150 °C and the average temperature difference is 100 °C. The wall temperature differences disappear as the main steam pressure and flow rate rise. Both the 300 MW and 600 MW utility boilers undergo similar trends in the side wall temperature difference, as shown in Figs.4 and 5.

The maximum wall temperature in the PCP reaches 400~450 °C, the same as the main steam temperature in Fig.4. The wall temperatures on the

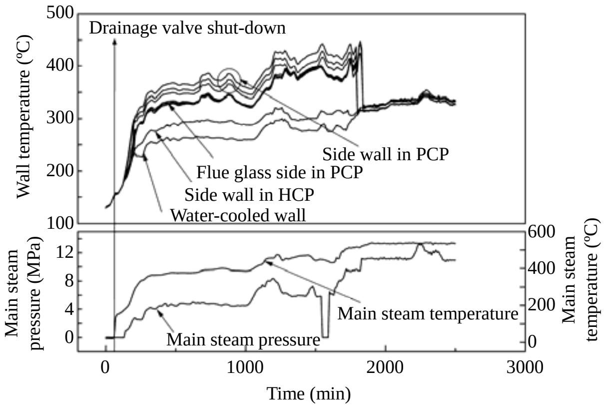

Fig.4 Side wall temperature at the water-cooled wall, the PCP and the HCP in the 300 MW utility boiler

Note: according to operating record, drainage valve is shut down after drum pressure from DAS is more than 0.3 MPa

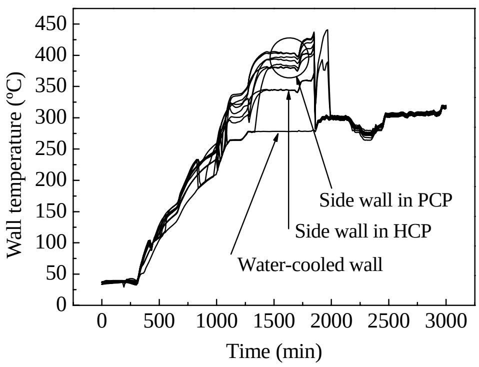

Fig.5 Side wall temperature at the water-cooled wall, the PCP and the HCP in the 600 MW utility boiler

flue gas side are shown by the outer temperature probes Nos. 13, 15, 29 and 31, as shown in Fig.4 (the temperature probe number is given in Fig.3). The experimental results show that the heating surface in the PCP has either no steam or enough steam to flow through. For lack of DAS data in 600 MW utility boiler, only the outer side wall temperature distribution is given in Fig.5. The water-cooled wall and the HCP have water and superheated steam to cool down. Therefore, distinct temperature differences are clearly observed at the side wall in the water-cooled wall, the PCP and the HCP from Figs.4 and 5.

Although the PCP side wall area should expand significantly because of the higher temperatures, the rigid connection among the PCP, the water-cooled wall and the HCP areas makes the PCP area suffer negative stress. Thermal stress appears in the PCP areas. A thermal stress analysis is done to investigate the thermal stress in the PCP area during high temperature differences.

THERMAL STRESS ANALYSIS

Experimental results show that thermal stress can be generated from the temperature differences at the side wall in the PCP. The wall temperatures measured in the experiment are input as the initial conditions for thermal stress analysis. Using the initial temperature distribution as a boundary condition, the thermal stress distribution is calculated with ANSYS software (ANSYS Inc., 2000a; 2000b). The analysis tool, the software ANSYS 6.0, is a popular finite element analysis tool for structure, fluid flow, electric field, and acoustic field. Liu *et al.*(2004) and Ray *et al.*(2003) discussed and demonstrated thermal stress calculations for utility boiler tubes using ANSYS.

In this stress calculation, the three side wall areas are divided into the water-cooled wall, the PCP and the HCP. One of the measuring wall temperature distributions at the side wall from Fig.4 is given in Fig.6 when time is 1110 min. To simplify the thermal stress calculation, every area is processed as a constant temperature distribution because of the rigid connections among the water-cooled wall, the side walls in the PCP and the HCP. Thus, the temperature distribution is set at 275 °C in the water-cooled wall area, 350 °C at the PCP and 300 °C at the HCP in this thermal stress calculation (Fig.6). The initial calculating mechanical parameters for the calculation are given in Table 1.

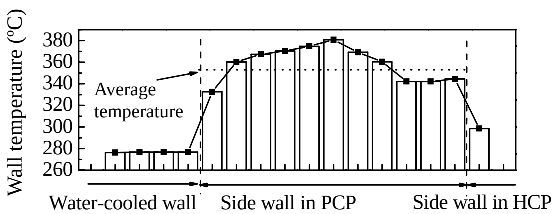

Fig.6 Calculated temperature distribution at the side wall

The material model for stress calculations, derived from the system’s material properties, is shown in Fig.7. The static structure analysis focuses on the thermal stress from the great temperature differences

Table 1 Mechanical parameters of side wall material

Parameter	Value
Specific capacity (kJ/(kg·K))	0.536
Conduct coefficient (W/(m·K))	42.3
Elastic module (MPa)	1.61×10^{11}
Density (kg/m^3)	7820
Yield strength (MPa)	325
Tensile strength (MPa)	510
Linear expansion coefficient (°C^{-1})	13.83×10^{-6}
Shearing module (MPa)	2×10^4

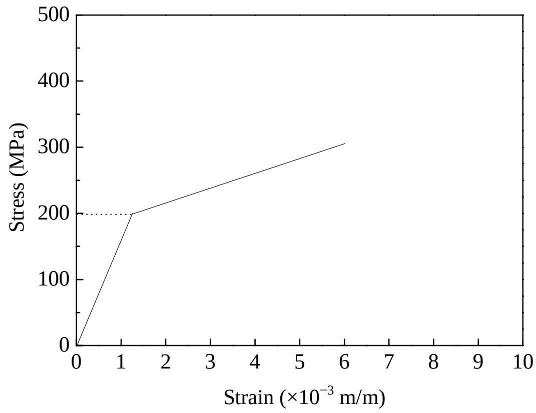

Fig.7 The material model for stress calculations

among the water-cooled wall and the side walls in the PCP and the HCP. The movement, stress and the distribution of those can be achieved through the thermal stress calculation (Pan, 2004; Xu, 2005). The boundary condition restrictions are shown in Fig.8, and the cell style is PLANE42. The boundary condition of the L_{15} and L_{16} connection positions is regarded as rigid, with no freedom to move. Deformation, movement and distortion in other boundary conditions in the PCP area are allowed.

The thermal stress calculation is based on the assumption that there is no residue stress in the PCP area, and that after deformation in the PCP area, the stress will be redistributed. The geometrical dimensions of the side wall areas are given according to the 300 MW utility boiler in this experiment. The calculated results are shown in Figs.9~11. The thermal stress and deformation distributions in different directions are also listed.

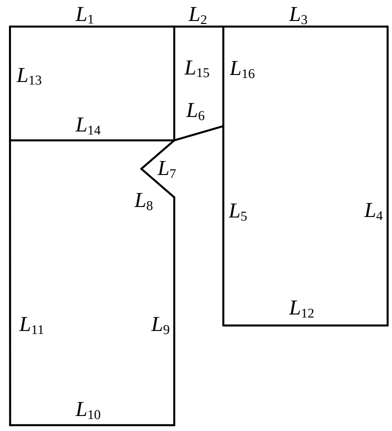

Fig.8 The boundary condition restrictions in the stress calculations

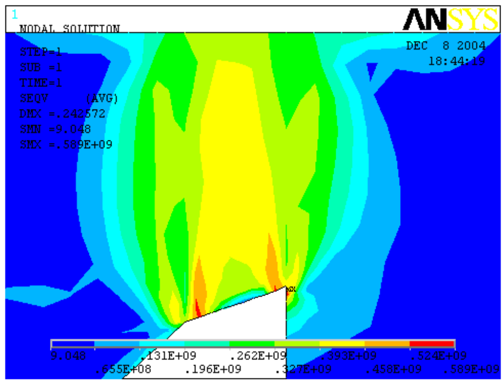

Fig.9 von Mises thermal stress distribution when the side wall temperature remains at 275 °C, 350 °C and 300 °C

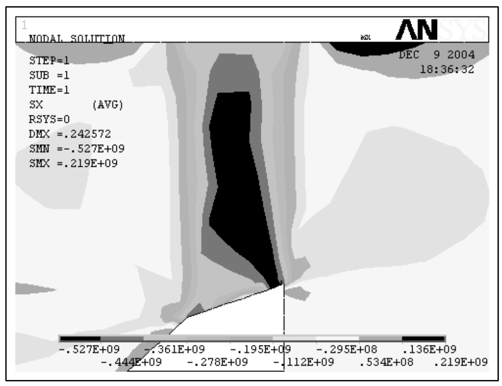

Fig.10 Thermal stress distribution in the *x* direction when the side wall temperature remains at 275 °C, 350 °C and 300 °C

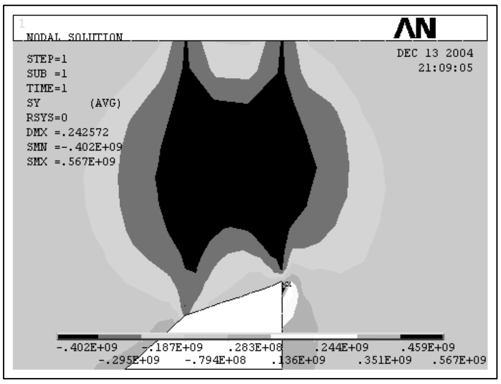

Fig.11 Thermal stress distribution in the *y* direction when the side wall temperature remains at 275 °C, 350 °C and 300 °C

From Fig.9, the side wall in the PCP area experiences a higher thermal stress when the temperature differences remains at 75 °C between area 1 and area 2 and at 50 °C between area 2 and area 3. Fig.9 gives the von Mises average thermal stress. The thermal stress is greater than the yield strength of the PCP material, leading to deformation. There is a great negative thermal stress on the roof and the side wall of the PCP in the *x* direction (Fig.10).

In Fig.11, there is a negative thermal stress of more than 400 MPa at the side wall of the PCP in the *y* direction (vertical direction). This stress value is greater than the yield strength of 320 MPa for the PCP material. From the upper thermal stress distribution, a permanent deformation forms in area 4, as shown in Fig.1.

CONCLUSION

Deformation on the side wall of the PCP is a comprehensive problem. Although related to thermal stress, it is also concerned with heat transfer, fluid dynamics and elastic and plastic mechanics. Addressing this issue requires a general solution.

There are great temperature differences in the side wall areas during the startup and rise-up process. The temperature differences are in the range of 80~150 °C, which exceeds the temperature distribution at these three areas under normal operating loads. The wall temperature on the side wall of the PCP is the same as the temperature on the flue gas side. Among the water-cooled wall, the PCP side wall and the HCP side wall, the PCP side wall has the greatest wall temperature. There is either no steam or enough steam to cool down the PCP side wall. Because of the rigid connections among these components, the side wall of the PCP can not expand freely, creating negative thermal stress in these areas. According to thermal stress distributions on the side wall of the PCP calculated with the ANSYS 6.0 software, the thermal stress is greater than the yield strength in the PCP material, causing permanent deformation appears on the PCP side wall.

References

ANSYS Inc., 2000a. Advanced Analysis Techniques Guide. Canonsburg, PA, p.158-230.

ANSYS Inc., 2000b. Structural Analysis Guide. Canonsburg, PA, p.245-278.

Bao, Y., Lu, H., 1988. Hydraulics and Inside Equipment in Utility Boiler. Harbin Industry University Publishing House, Harbin, p.127-145 (in Chinese).

Huang, C., 1982. Hydraulics and Inside Equipment in Utility Boiler. Harbin Industry University Publishing House, Harbin, p.145-160 (in Chinese).

Li, G., Li, J., Pang, J., 1998. Analysis on leakage of wall superheater of Unit 1 at Dalate power plant. *Inner Mongolia Electric Power*, **10**(1):57-60 (in Chinese).

Liu, T., Xu, G., Pang, L., Liang, Z., 2004. Creep analysis and lifetime calculation on pressured parts in utility boiler. *Power Engineering*, **24**(5):631-635 (in Chinese).

Pan, Z., 2004. Finite Element Analysis and Application. Tsinghua University Publishing House, Beijing, p.205-234 (in Chinese).

Ray, A.K., Sahay, S.K., Goswami, B., 2003. Assessment of service exposure boiler tubes. *Engineering Failure Analysis*, **10**(6):645-654. [doi:10.1016/S1350-6307(03)00063-3]

Shi, D., Zhang, J., 2000. Analysis on frequent leakage of front side wall superheater of Unit 1 at Huaneng Yueyang power plant. *Hunan Electric Power*, **20**(5):46-47 (in Chinese).

Sun, B.M., Pang, L.P., Liu, T., 2007. Theoretical and Experimental Study on Side Wall Flow Distribution at Pendant Convective Pass (PCP) in RBC Utility Boilers. Technical Report, CE2006-04, North China Electric Power University, China (in Chinese).

Xu, Z., 2005. Elastic Mechanics. Higher Education Publishing House, Beijing, p.112-127 (in Chinese).