

Sensitivity analysis of several operational parameters on gas temperature deviation in a tangential firing boiler

Cong Yu^{1,*}, Haiquan Yu², Wenpeng Hu³, and Hanlin Wu¹

¹Jiangnan University, School of Intelligent Manufacturing, 430056 Wuhan, P.R. China

²Southeast University, School of Energy and Environment, 210096 Nanjing, P.R. China

³Wuhan Hengxintai Oil Production Equipment Manufacturing Co., Ltd., 430299 Wuhan, P.R. China

Abstract. In this work, an integrated numerical model combining combustion and fluid heating was established for a 660 MW coal-fired boiler. To validate the accuracy of the developed model, related experiment was also conducted, and shows that the relative errors (REs) of several predicted parameters on both flue-gas side and water-steam side of the boiler are less than 7 %, which meets the requirement of analysis. The results indicate that the effect of SOFA tilt angle on gas temperature deviation (GTD) is greatest, and that of SOFA's proportion follows; while GTD presents a smallest sensitivity to the concentration of O₂. This is because O₂ concentration mainly affects the average value of the gas temperature, but barely changes its distribution. By contrast, altering SOFA's tilt angle and its proportion directly varies the shape, location, and area of the high-temperature and low-temperature regions at the entrance profile of the horizontal crossover pass, so these two factors play a more important role in the variation of GTD.

1 Introduction

During the past decades, to improve the thermal efficiency of the coal-fired power plants, utility boilers have been developed towards a larger capacity and a higher steam parameters. In this context, the fluid inside the tubes can be heated to a supercritical or even ultra-supercritical pressure, and the steam temperature of some boilers can reach as high as 700 °C [1]. However, once overheating failure occurs among these tubes, not only would it waste the fuel and energy, but also the leaked steam with high momentum and temperature could impact the adjacent tubes, causing a secondary damage. Therefore, it is necessary to guarantee the security of the steam tube system during the process of the electricity generation.

Among all heat exchangers, final superheaters and reheaters receive the greatest attention, because their tube walls attain the highest temperatures in the boiler [2]. It has been suggested that the tube overheating problem of these high-temperature heating surfaces results from an unexpected gas temperature deviation (GTD) in the horizontal crossover pass of the boiler [3-4]. In recent years, several researchers [5-8] have paid attention to revealing the causes and characteristics of this deviation. Liu [5] found that the residual swirl at the furnace exit plays an important part in generating GTD. By retrofitting the boiler's structure, Tan et al [6] optimized the in-furnace flow field and successfully alleviated such a temperature deviation. In addition, the effects of several boiler's settings such as the opposing

tangential angle of the air jets [7] and the vertical burner tilt angle [8] on GTD have also been studied. However, few studies have conducted a sensitivity analysis to compare the degrees and mechanisms that these factors act on GTD.

In this work, a simulation which combines coal combustion and fluid heating was carried out for a 660 MW tangential firing boiler, and related experiment were performed for the model validation. Based on the model, the effects of O₂ concentration, separated over-fire air (SOFA) tilt angle, and SOFA's proportion on GTD were further discussed.

2 In situ measurements

2.1. Boiler description

As shown in Fig. 1, the boiler considered in the present work is a 660 MW supercritical pulverized coal-fired boiler, which has a furnace equipped with a tangentially fired system. A set of low-NO_x concentric firing burners were installed in the furnace, composed of six groups of primary air nozzles, six groups of secondary air nozzles, two groups of CCOFA nozzles and five groups of SOFA nozzles.

2.2. Operational condition and measurements

To validate the numerical model of the boiler, an experiment at the full load condition was conducted, and

* Corresponding author: congy@seu.edu.cn

several key parameters were measured, including the concentrations of O₂ and CO after the economizer, the gas temperature at the exit of the final reheater (RH), and the pressure, temperature and mass flow rate at the inlet and outlet of four high-temperature heat exchangers, namely the division superheater (SH), the platen SH, the final RH, and the final SH.

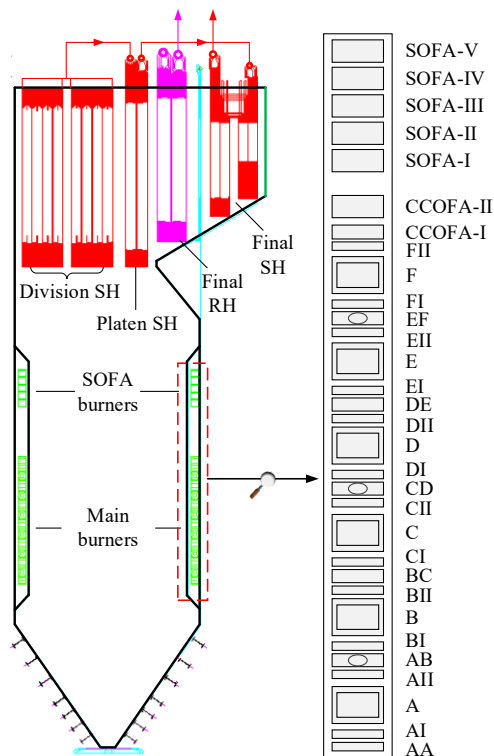


Fig. 1. Schematics of the furnace and burners.

Table 1 provides the coal properties during the experiment. Apart from that, the value of pulverized-coal finenesses R90 and R200 were also measured as 33.6% and 3.3%, respectively. Thus, the distribution of the coal particles can be estimated, which follows the Rosin-Rammler ruler with a mean diameter of 61 μm and a spread parameter of 1.15.

Table 1. Coal properties during the experiment.

Proximate Analysis (ar ¹ , wt. %)				Q _{net, ar} (MJ/kg)
Moisture	Volatile	Ash	Fixed carbon	
7.48	24.34	23.73	44.45	22.447
Ultimate Analysis (ar ¹ , wt. %)				
C	H	O	N	S
56.4	3.18	8.01	0.64	0.55

¹ As received basis

The experiment was carried out at the full load of 660 MW. In this case, the total mass flow rate of the pulverized coal was 282 t/h, which was equally distributed to the mills A to F. The air had a total mass flow rate of 2360 t/h, of which 27.4% was the primary air with a temperature of 351 K and 72.6 % was the secondary air with a temperature of 581 K. Five layers of SOFA took up 26 % of the total air and had a same vertical tilt angle of -12°. For the water-steam cycle, the

mass flow rates of the SH and the RH were 1955 t/h and 1632 t/h, respectively. At the inlet of the water wall heaters, the division SH, and the final RH, the temperature and pressure of the fluid were separately 596 K/26.9 MPa, 687 K/25.9 MPa, and 733 K/4.4 MPa.

3 Numerical modelling

3.1. Mathematical models

The mathematical models are presented in **Table 2**. These models were applied to describe the complex physical and chemical processes within the furnace, and considered the conjugate heat transfer in the tubes of the water wall heaters, the division SH, the platen SH, the final RH, and the final SH. In the present work, the models related to coal combustion was solved using Fluent 14.5, while the thermal hydraulic model inside the tubes was numerical simulated via MATLAB coding. More detailed descriptions of these models, the modelling parameters in them, and the coupled methods have been provided in our previous work [4].

Table 2. Mathematical models.

Physical and chemical processes	Models used in this work
Turbulent flow	Realizable k-ε model
Coal particle transport	Discrete phase model (DPM)
Coal devolatilization	Two competing rate model
Gaseous combustion	Mixture fraction/PDF model
Char oxidation	Kinetics/diffusion limit rate model
Radiation	P-1 model
Fluid heating	Thermal hydraulic model

3.2. Modelling cases and boundary conditions

In this study, 8 cases were modelled. Case 1 was conducted for validation and had the same operational conditions with that of the experiment, in which the O₂ molar fraction, the SOFA tilt angle, and the proportion of SOFA were 2.9%, -12°, and 26%, respectively. To further investigate the effects of these three parameters, Case 2 to Case 8 were designed. Case 2, Case 3, and Case 4 set the SOFA tilt angle to +30°, 0°, and +20°, respectively, and remain the other boiler settings identical to those in Case 1. In addition, on the basis of Case 4, Case 5 and Case 6 set the concentration of O₂ to 2 % and 3.5 %, respectively; while Case 7 and Case 9 change the proportion of SOFA to 15 % and 35 %, respectively.

4 Results and discussion

4.1. Validation

Table 3 shows some key operational parameters on both flue-gas side and water-steam side of the boiler. It can be seen that the predicted data from the CFD modelling and

the experimental results are close. The relative errors (REs) of all the parameters are less than 7 %, which means the accuracy of the developed model is acceptable and this model can be used for the following analyses.

Table 3. Results from CFD modelling and experiment.

Parameters	CFD	test
Gas temperature/ K	962	1027
O ₂ molar fraction/ %	2.92	2.89
CO molar fraction/ ppm	575	593
Heat absorption of division SH/ MW	140.3	146.1
Heat absorption of platen SH/ MW	105.6	109.7
Heat absorption of Final RH/ MW	109.5	107.3
Heat absorption of Final SH/ MW	109.3	113.4

4.2. Causes of gas temperature deviation

As shown in the Fig. 2, the pulverized coal and air were injected into the furnace, combusting and forming a counter-clockwise fire ball, which results in a residual swirling flow at the furnace exit. Thus, on the Cross-section P1, the velocity on the left side is higher than that on the right side. This further affects the distribution of gas temperature. A higher local velocity means the hot flue gas releases less heat in this place, namely at the left part of the upper furnace, the division SH and platen SH absorb less heat. Therefore, on the P1 plane, the gas temperature on the left side is also higher than that on

the right side, generating a GTD at the entrance of the horizontal crossover pass.

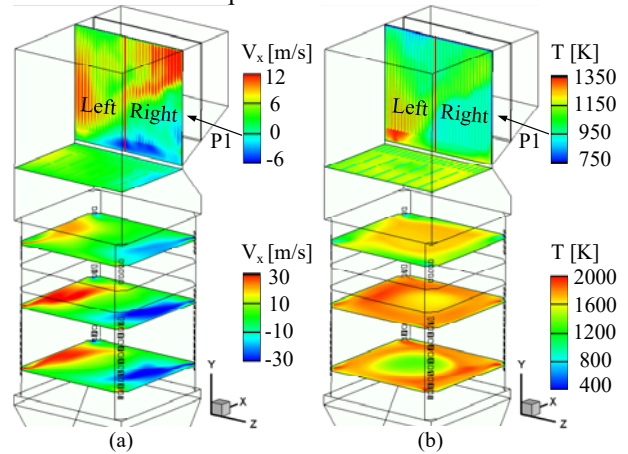


Fig. 2. Distributions of gas velocity and temperature on different planes from Case 1.

4.3. Effects of O₂ and SOFA on gas temperature deviation

Fig. 3 shows the gas temperature distributions on plane 1, which is the entrance profile of the final RH and SH. To perform a further quantitative analysis of GTD on this plane, Eq. 1 was defined as following:

$$T_{dev} = T_{ave,left} - T_{ave,right} \tag{1}$$

where $T_{ave,left}$ and $T_{ave,right}$ are the gas average temperature in the left and right parts on the P1 plane, respectively.

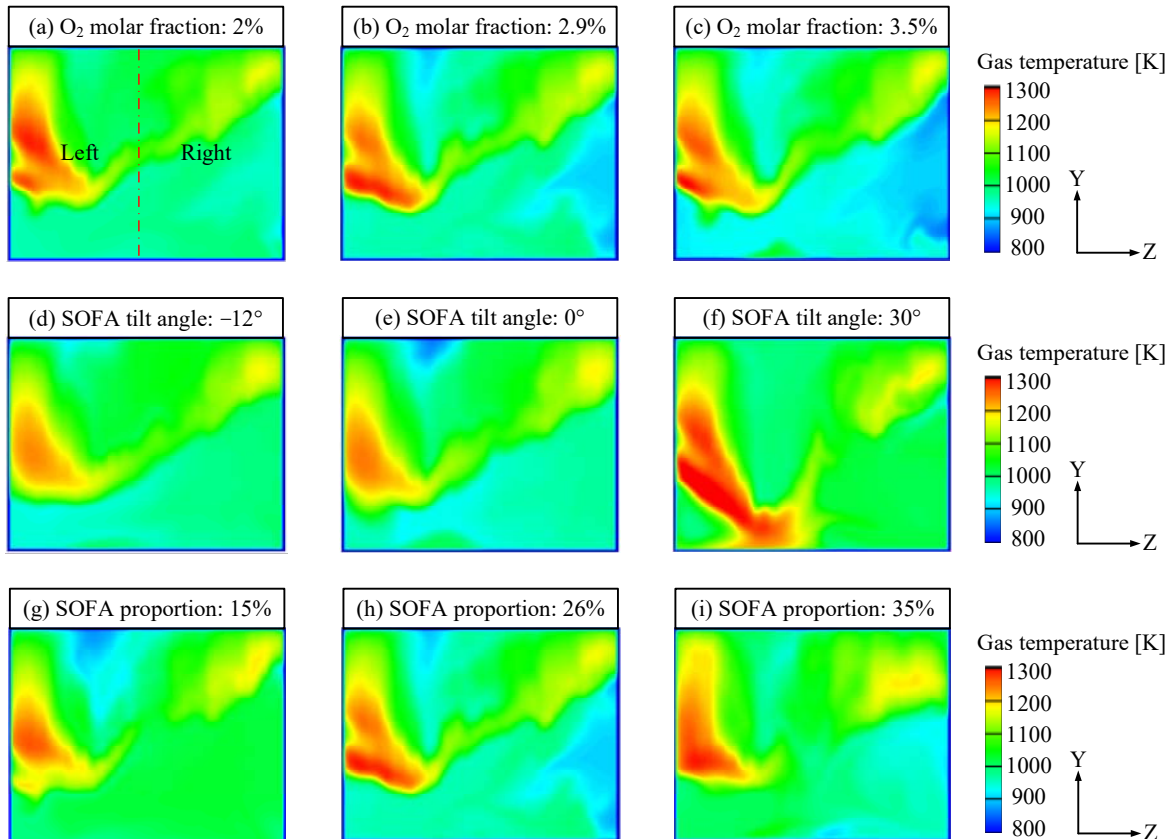


Fig. 3. Gas temperature distributions on plane 1 at different operational conditions.

As shown in Fig. 4, when the concentration of O_2 , the SOFA tilt angle, and the proportion of SOFA increase within their regular operational intervals, the maximal differences of T_{dev} are separately 14 K, 29 K, and 53 K, which indicates that the proportion of SOFA has the greatest influence on GTD, and the effect of SOFA tilt angle follows; while this temperature deviation presents a smallest sensitivity to the O_2 concentration.

It is found from Fig. 3(a) to Fig. 3(c) that, as the boiler operated at different O_2 contents, the temperature distributions on the P1 plane are quite similar, which means that the shape, location, and area of the high-temperature and low-temperature regions show few differences. When adjusting the O_2 concentration from 2 % to 3 % and 3.5 %, the gas average temperature on the left side of P1 separately dropped from 1059 K to 1043 K and 1038 K, and that on the right side separately declined from 1017 K to 1000 K and 981 K. This unbalanced decreases in gas temperature of the two parts cause the variations of GTD. By contrast, as shown from Fig. 3(d) to Fig. 3(i), altering SOFA, namely its tilt angle and proportion, directly changes the distribution of the gas temperature on the P1 plane. This is because, by determining the ratio of the air in the main stream to the air with an opposing tangential angle, SOFA settings can induce a different distribution of momentum within the furnace, so have a greater effect on GTD.

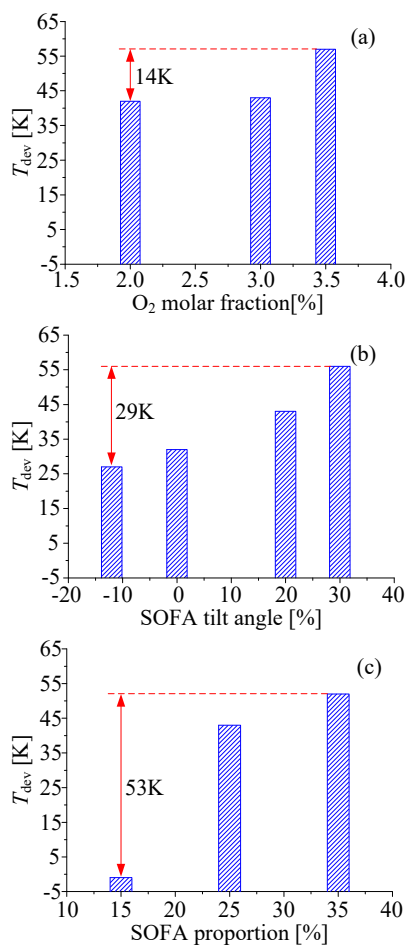


Fig. 4. Gas temperature deviations on plane 1 at different operational conditions.

5 Conclusion

In this work, an integrated numerical model was established for a 660 MW tangential firing boiler, and related experiment was also conducted for the model validation. Based on this model, the effects of the O_2 concentration, the SOFA tilt angle, and the proportion of SOFA on GTD were compared. The main conclusions can be drawn as follows:

- (1) The effects of SOFA's tilt angle on GTD is the greatest, and that of its proportion follows; while GTD presents a smallest sensitivity to the O_2 concentration.
- (2) The way that O_2 concentration affects GTD is by producing an unbalanced temperature variations on both sides of the P1 plane, but rarely changing the distribution of temperature.
- (3) Altering SOFA's tilt angle or its proportion directly change the shape, location, and area of the high-temperature and low-temperature regions on the P1 plane, so these two factors show a greater effect on the variations of GTD.
- (4) SOFA is an important factor both in changing the value of GTD and reducing NO_x emission, so it needs to take a comprehensive account for this when doing combustion optimization.

References

1. C. Schuhbauer, M. Angerer, H. Spliethoff, F. Kluger, H. Tschaffon. *Fuel* **122**, 149-163 (2014).
2. V. Maakala, M. Jarvinen, V. Vuorinen. *Energy* **160**, 361-377 (2018).
3. G.W. Tang, B. Wu, K. Johnson, A. Kirk, D. Fu, C.Q. Zhou. *Appl. Therm. Eng.* **102**, 261-271 (2016).
4. C. Yu, W. Xiong, H. Ma, J.X. Zhou, F.Q. Si, X.M. Jiang, X.W. Fang. *Appl. Therm. Eng.* **154**, 87-101 (2019).
5. Y.C. Liu, W.D. Fan, M.Z. Wu. *Appl. Therm. Eng.* **110**, 553-563 (2017).
6. P. Tan, Q.Y. Fang, S.N. Zhao, C.G. Yin, C. Zhang, H.B. Zhao. *Appl. Therm. Eng.* **139**, 135-143 (2018).
7. Y.G. Zhou, M.C. Zhang, T.M. Xu, S.E. Hui. *Energy Fuels* **23**, 5375-5382 (2009).
8. P. Tan, D.F. Tian, Q.Y. Fang, L. Ma, C. Zhang, G. Chen, L.J. Zhong, H.G. Zhang. *Fuel* **196**, 314-324 (2017).