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CFD analysis of temperature imbalance in superheater/reheater region of tangentially coal-fired boiler

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Abstract. This paper presents a CFD analysis of the flow, velocity and temperature distribution in a 700 MW tangentially coal-fired boiler operating in Malaysia. The main objective of the analysis is to gain insights on the occurrences in the boiler so as to understand the inherent steam temperature imbalance problem. The results show that the root cause of the problem comes from the residual swirl in the horizontal pass. The deflection of the residual swirl due to the sudden reduction and expansion of the flow cross-sectional area causes velocity deviation between the left and right side of the boiler. This consequently results in flue gas temperature imbalance which has often caused tube leaks in the superheater/reheater region. Therefore, eliminating the residual swirl or restraining it from being diverted might help to alleviate the problem.

1. Introduction

Despite the current demand for cleaner and environment-friendly energy, fossil fuel remains to be the major source of energy in the world. The U.S. Energy Information Administration (EIA) reported that in 2012, coal continues to be the most widely used source for electricity generation, covering 40% of the world's total electricity generation [1]. This proves the relevance of coal as the main source for electricity generation thus studies are continuously being carried out to find methods to overcome its downsides, especially the environmental-related ones. For example, techniques such as over fire air (OFA), low NO_x burner and flue gas recirculation are designed to abate the NO_x emission problem.

For most coal-fired power plants, tangential firing boiler is used, thanks to its advantages of providing complete combustion and uniform heat distribution. However, there is an inherent problem associated with the tangential firing boiler which is steam temperature imbalance in the superheater/reheater region. Excessively higher steam temperature on one side of the boiler frequently causes superheater or reheater tube leaks which interrupt the boiler operation, affecting plant's reliability.

There have been a number of studies on the temperature imbalance problem, most of which are with the aid of Computational Fluid Dynamics (CFD) technique [2-4]. When modelling the boiler, some literatures include the platen superheater/reheater in the upper part of the boiler. These platen superheaters/reheaters are most commonly modelled as porous media to account for the effect of the plates on the flow and pressure drop [5-7]. There are also researchers who modelled the plates as solid domain [8, 9] and some even model their boilers without the plates [10]. In Malaysia particularly, to the authors' knowledge, there has been no published CFD study on this problem that includes the platen superheaters/reheaters in the boiler model. All the available literatures model 'empty' boiler and disregard the presence of platen superheater/reheater. Each of these available methods of modelling



the boiler has its advantages and drawbacks, and the relevancy and validity of its application depend primarily on the objective of the study.

The objective of this study is to analyze the flow, velocity and temperature distribution in one of the coal-fired power plant boilers in Malaysia, in order to understand the temperature imbalance occurrence better. The platen superheaters/reheaters are modelled and treated as porous media. With the knowledge and findings gained from this study, feasible mitigation scheme could be figured out to alleviate or eliminate the temperature imbalance occurrence.

2. Boiler modelling

2.1. Geometry

The boiler studied is of tangential firing type and has generating capacity of 700 MW. The cross section of the furnace has 18.4 width \times 19.5 depth dimension, and is 72.58 high. It comprises several sections namely hopper, windbox, furnace, nose, horizontal pass and rear pass, as depicted in Figure 1. In the horizontal pass, there are 2 groups of 6 plates low temperature superheater (LTS), 2 groups of 22 plates high temperature superheater (HTS), and a group of 46 plates high temperature reheater (HTR). In the windbox section, there are 7 elevations of pulverized coal (PC) burners, 13 elevations of secondary air (SA) nozzles, and 4 elevations of fuel oil (FO) burners. At normal operating condition, only 6 PC burners and 12 SA nozzles are operated while the remaining are set on standby. For the purpose of analysis, 7 horizontal planes are created, of which 3 are in the furnace section (F1, F2, F3), 1 at the furnace exit (FE), and 3 in the horizontal pass (HP1, HP2, HP3), while 2 vertical planes are created upstream the second group of HTS (X1) and just before the HTR (X2), respectively. These planes are illustrated in Figure 2.

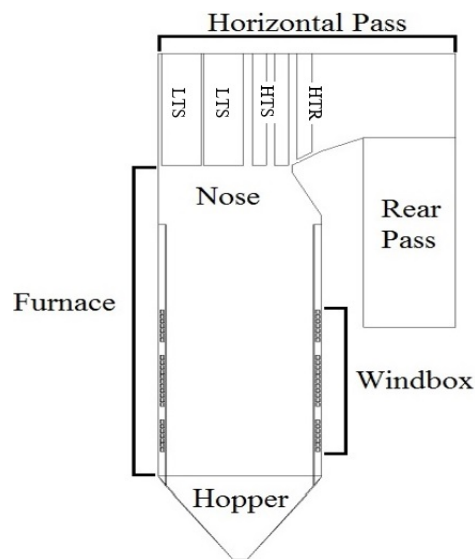


Figure 1. Sections in the boiler.

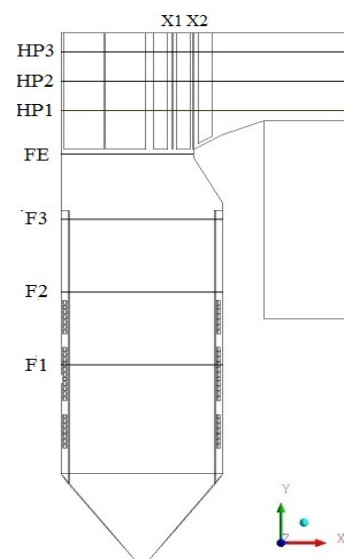


Figure 2. Locations in the boiler used for analysis.

2.2. Mesh

The mesh employed for this study consists primarily of hexahedral meshes, except for the nose and hopper sections which consist of tetrahedral meshes. This is shown in Figure 3. To reduce the effect of pseudo-diffusion, the mesh of the horizontal cross section in the furnace is made to follow the dominant swirling direction of the flow in the furnace, as displayed in Figure 4. The overall quality of the mesh is deemed very good, based on the values of equiangle skewness and orthogonal quality. The average and maximum values of equiangle skewness are 0.08 and 0.82, respectively, while the average and minimum values of orthogonal quality 0.965 and 0.265, respectively. Mesh independence test is performed for three simulations which respective total number of mesh are 1500620, 1923879, and

2100856. Due to complexity of the geometry, the mesh in the furnace section only is refined. Figure 5 shows the plots of temperature along the boiler height for the three simulations. Based on the plots, the solution can be considered mesh-independent and the mesh with 1500620 cells is employed for further analysis to save computational time.

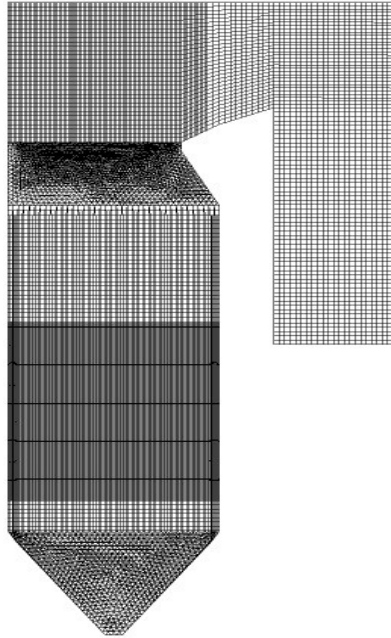


Figure 3. Mesh of the whole domain.

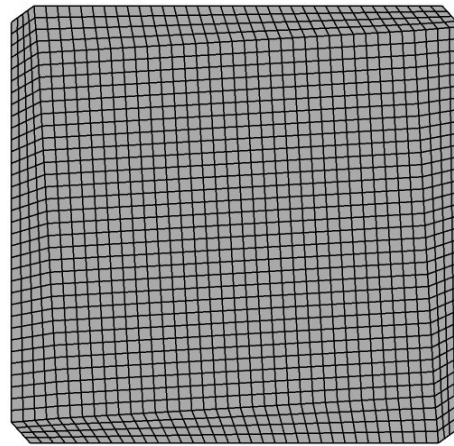


Figure 4. Mesh of horizontal cross section in the furnace.

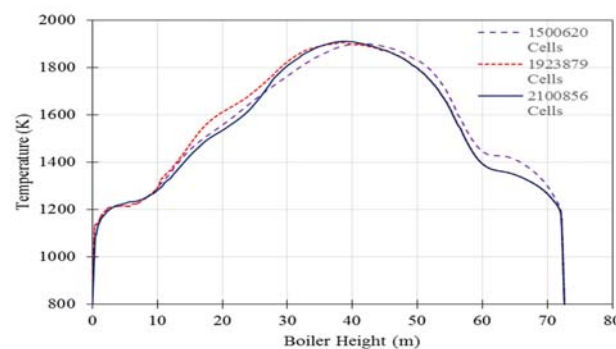


Figure 5. Result of mesh independence test.

2.3. Boundary conditions

The LTS, HTS and HTR in the horizontal pass are treated as porous media to consider the effect of the plates or tube bundles on the flow and pressure drop. The porosity of the plates is set to 0.2 which is determined based on the ratio of total area of gaps in a plate to the total area of the plate. The inertial resistance in x- and y-direction is set to 0.35 while in the z-direction is set to 50 to consider anisotropic influence of the plates on the flow. These values are assumed as in [11] due to the absence of experimental or on-site data. The LTS, HTS and HTR are also treated as heat sinks, to include heat transfer from the flue gas to the plates. Heat transfer to the water walls is considered by fixing its temperature at 800 K.

Adaro sub-bituminous coal is used for the study. The proximate and ultimate analysis of the coal are given in Table 1. The high heating value (HHV) for the coal is 20.64 MJ/kg. Coal and air are injected into the furnace from the corners, forming anti-clockwise swirling flow at the center. The

firing angles are illustrated in Figure 6. The mass flow rate and temperature of PA, SA, and PC at the inlets are summarized in Table 2. Excess air of 20% is supplied into the furnace, which corresponds to air-fuel ratio (AFR) of 11.28.

Table 1. Proximate and ultimate analysis of Adaro coal.

Proximate Analysis (% as-received)	
Volatile Matters	35.6
Fixed Carbon	33.8
Moisture	27.8
Ash	2.8
Ultimate Analysis (%)	
Carbon	73.7
Hydrogen	5.17
Oxygen	20.09
Nitrogen	0.89
Sulphur	0.15

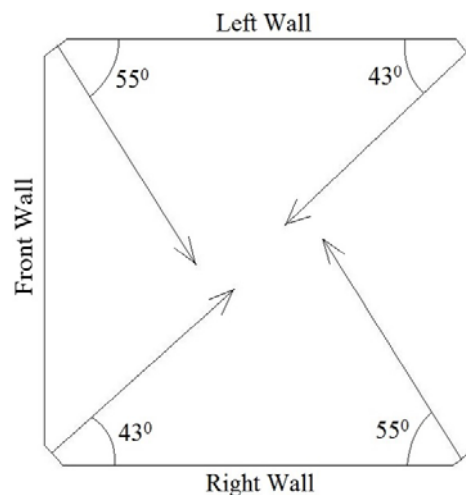


Figure 6. Firing angles of coal and air.

Table 2. Mass flow rates and temperatures of PA, SA and PC at the inlets.

	Primary air (PA)	Secondary air (SA)	Pulverized coal (PC)
Mass flow rate at one inlet (kg/s)	14.143	13.152	3.585
Total mass flow rate (kg/s)	339.432	631.296	86.04
Temperature (K)	630	623	350

2.4. CFD model

The numerical simulations for this study are carried out using CFD commercial code – FLUENT. Turbulence is modelled using realizable k -epsilon model as it has been proven to provide the best performance of all the k -epsilon models [12]. Turbulent intensity, I of 10% [13] and hydraulic diameter of 0.54 are set at the inlets. Radiation is the most dominant mode of heat transfer in a flow involving combustion. P1 gray radiation model is used to model radiation heat transfer as it is relatively simpler than other radiation models and works reasonably well when the optical thickness is large. The emissivity of the walls is set to 0.7 while weighted-sum-of-gray-gases model (WSGGM) is used to calculate the emissivity of the flue gas.

Coal combustion generally involves three sub-processes which are devolatilization, volatiles combustion and char combustion. Devolatilization starts when the coal temperature reaches

vaporization temperature, which is set to 350 K in this case. During this process, mineral matters or volatiles are released from the coal particles. The rate at which this process occurs is determined by two-competing-rates model [14], which suggests that two kinetic rates control the devolatilization process over two different temperature ranges. The combustion of the volatile matters is modelled using non-premixed combustion model, under the assumption of chemical equilibrium. Two-mixture-fraction approach is employed, in which the thermochemical state of the fluid is related to two conserved scalar mixture fractions. Instantaneous species mass fractions, density and temperature of the fluid are derived from the calculated mixture fractions. Turbulence-chemistry interaction is modelled using beta probability density function (PDF). Kinetics/diffusion limited model is used to model char combustion. In this model, the diffusion rate coefficient and kinetic rate are weighted to obtain a char combustion rate.

The pulverized coal particles trajectories are tracked using Lagrangian approach. The Rosin-Rammler diameter distribution method is used for the coal particles size distribution. The minimum, maximum and mean diameters of coal particles in each stream are 1.7×10^{-5} m, 12.7×10^{-5} m, and 5.5×10^{-5} m, respectively. There are 10 different diameters in each stream with spread diameter of 1.3. Turbulence effect on the particles trajectories is considered using stochastic tracking technique (random walk model) with 10 number of tries.

3. Results and discussion

3.1. Model validation

The solution is validated based on the flue gas temperature at the furnace exit (FE) and the general trend of this parameter along the furnace height. The general design value for flue gas temperature at furnace exit is approximately 1600 K [11], while the predicted value is 1621 K. Therefore the solution can be deemed acceptable with only about 1% error.

3.2. Flow and velocity distribution

As coal and air are injected into the furnace, intense swirling flow in anti-clockwise direction is observed in the windbox. Figure 7 shows the velocity profiles on several representative elevations (F1, F2, F3 and FE).

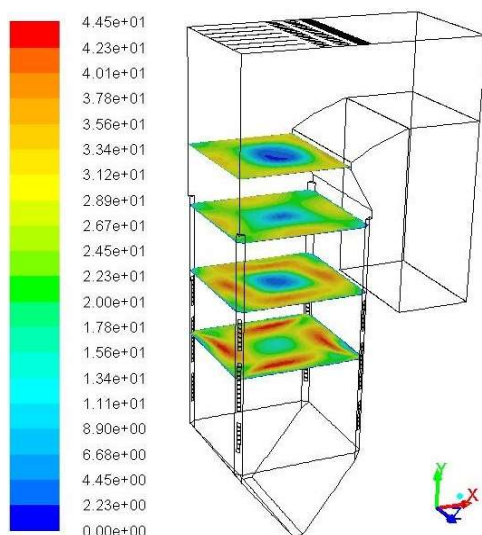


Figure 7. Velocity contours on several elevations (F1, F2, F3 and FE).

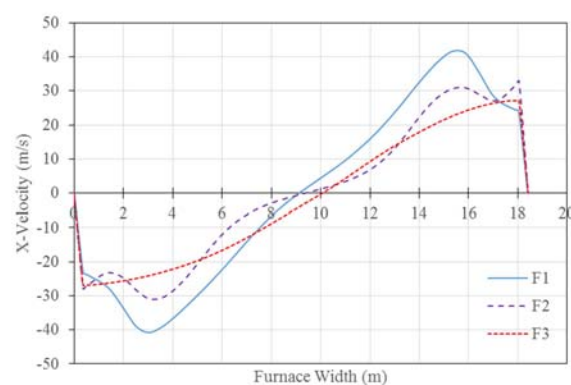


Figure 8. X-velocity distribution along furnace width.

The swirl shape can be seen at all elevations, preserved even until the furnace exit (FE). This is well known as residual swirl which is believed in some previous studies to be the cause of temperature imbalance problem. It can also be noticed that the magnitude of velocity decreases as the flue gas flows upwards due to energy loss from heat transfer to the walls. As the elevation increases, higher velocity spots are found to be closer to the walls. This suggests that as the height increases, the swirl becomes weaker but its diameter is enlarged. The x-velocity distribution along the furnace width on F1, F2 and F3 is plotted as in Figure 8. From the graph, it is evident that the x-velocity decreases and higher x-velocity is observed nearer to the walls as the height increases. In the furnace, the swirl remains uninterrupted at the center along the height. As it passes through FE, the swirl seems to be a little shifted towards the rear wall due to the significant reduction of cross-sectional area.

Figure 9 (a) and 9 (b) display the velocity vectors near the right wall and left wall, respectively. On the right side, the flue gas flows towards the rear wall and enters the horizontal pass directly from the lower part. On the left side, the flue gas initially flows towards the front wall and later reverses into the horizontal pass from the upper part. Such flow patterns result from the anti-clockwise swirling flow in the furnace. From the observation of the streamline in the horizontal pass, it is found that after passing the furnace exit (FE), the swirl is shifted towards the left wall as it flows upwards, which may be due to the abrupt expansion of the cross section. A large portion of high-speed flue gas flowing on the left side in the furnace turns to flow through the middle plates, leaving slow-moving flue gas flowing near the left wall. As the flue gas flows into the rear pass after passing through the middle plates, it curves back towards the left wall, forming a small swirl. This can be observed clearly from the velocity vectors on planes HP1, HP2 and HP3 in Figure 10 (a) – 10 (c).

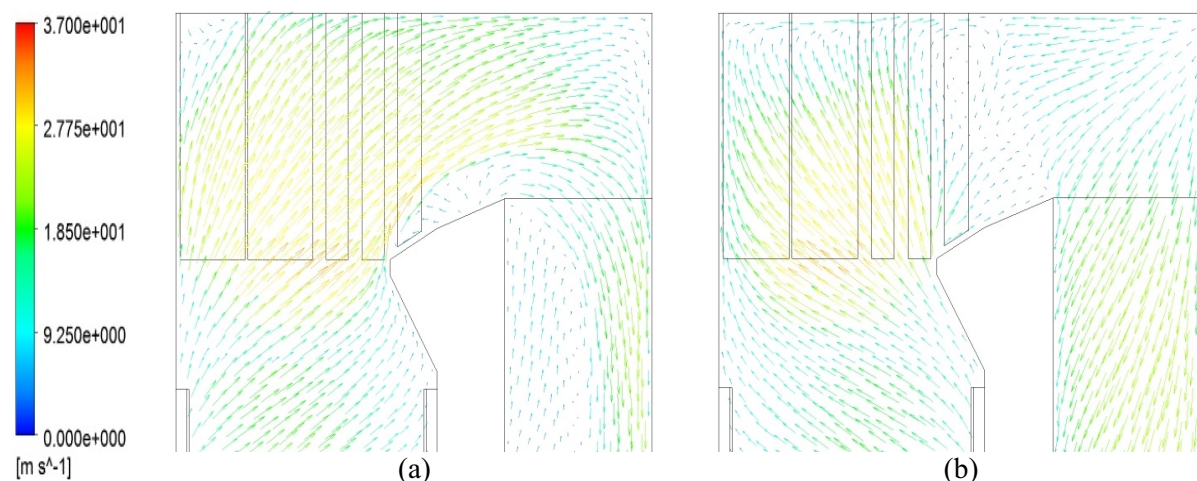


Figure 9. Velocity vectors on plane (a) near right wall and (b) near left wall.

In these figures, the swirl is seen to bias towards the left wall as the height increases and subsides as it reaches HP3. This explains the trend of velocity plot along the furnace width in Figure 10 (d) and 10 (e) which show the velocity on the left side declines as the elevation increases. The velocity in the middle is higher in the upper part (HP2 and HP3) compared to the lower part (HP1). This justifies the earlier observation that a larger portion of flue gas flowing near the left side in the furnace curves inwards and enters the horizontal pass through the upper part of the middle plates. Before the second group of HTS (plane X1), the velocity deviation between the right and left sides exists but is not really serious. However, before flowing through the HTR (plane X2), velocity deviation is very large between the right and left sides. Looking at the velocity vectors in Figure 10 (a) – 10 (c), the swirl shifts towards the left and rear wall and happens to settle and subside at the left side of HTR. Based on all these findings, it can be inferred that the residual swirl in the horizontal pass causes flow imbalance thus is the key factor of the velocity deviation in this region.

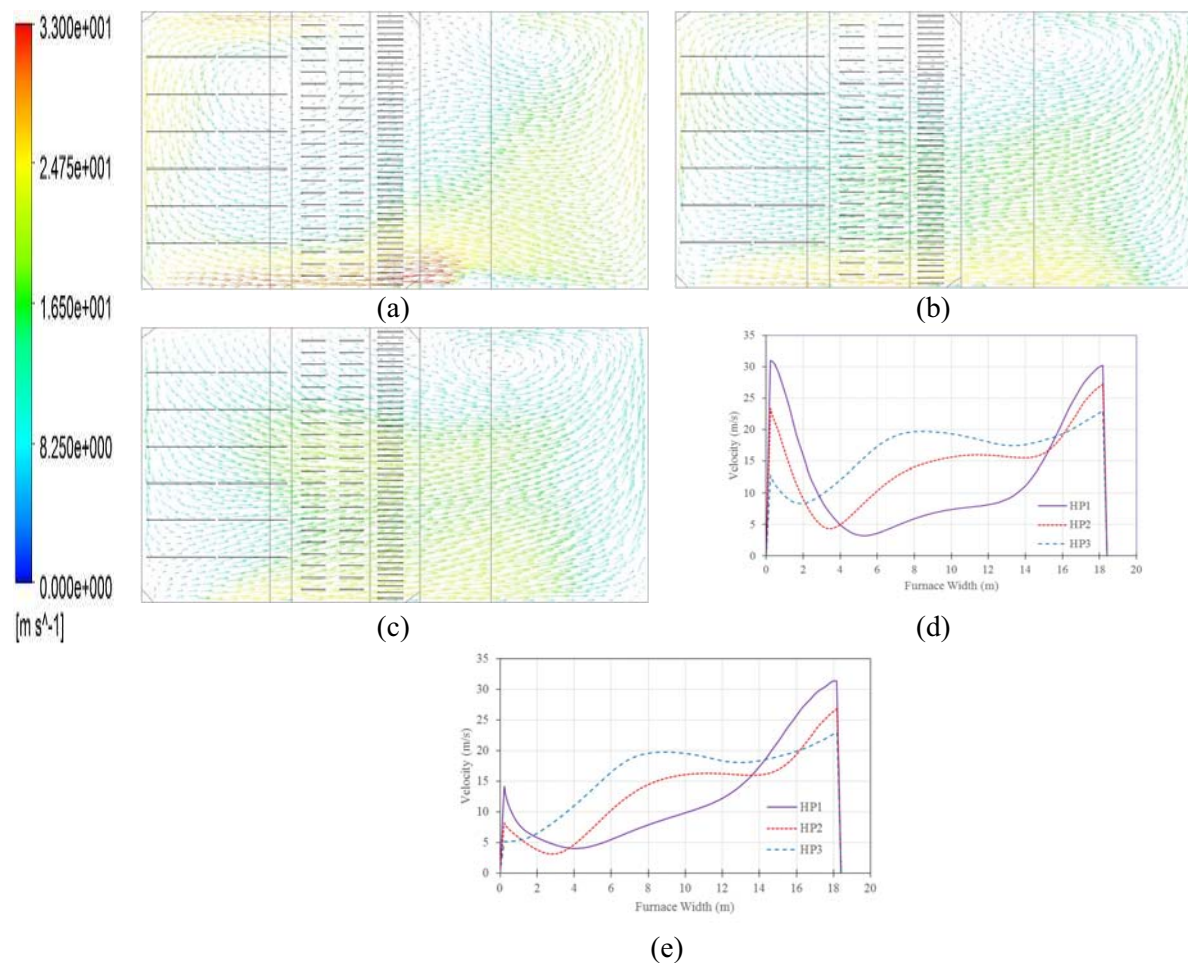


Figure 10. Velocity vectors on (a) HP1 (b) HP2 (c) HP3 and plot of velocity along furnace width on plane (d) X1 and (e) X2.

3.3. Temperature distribution

The trend of temperature along the furnace height can be referred from Figure 5. Basically, the temperature starts to increase rapidly in the windbox section where the combustion starts. After the windbox, the temperature begins to drop as heat energy is being transferred to the water walls and the platen heat exchangers. As the objective of this study is on the temperature imbalance problem occurring in the horizontal pass, the analysis and discussion of temperature distribution will focus only on the horizontal pass section.

Figure 11 shows the temperature contour on HP1, HP2, and HP3. Generally, the temperature is seen higher on the right side, except at the LTS area which is relatively balanced between the right and left sides. Low temperature spot can be obviously noticed at the location of the residual swirl. This evidently implies that the residual swirl is the main factor responsible for the temperature imbalance occurrence. The left side of the HTR is the most affected by the low temperature spot compared to other platen heat exchangers. To have a clearer view, temperature contours on plane X1 and X2 are observed, as depicted in Figure 12 (a) and 12 (c). Figure 12 (b) and 12 (d) are their corresponding temperature plots along the boiler width. On both planes, temperature imbalance is evident between the right and left sides. On plane X1, the deviation is less severe (between 200-300 K) compared to that on plane X2 which ranges between 400-550 K. Notably higher temperature is observed at the lower right part of plane X2. The temperature deviation on plane X1 is about the same irrespective of the elevation while on plane X2 larger temperature deviation occurs at the middle elevation (HP2).

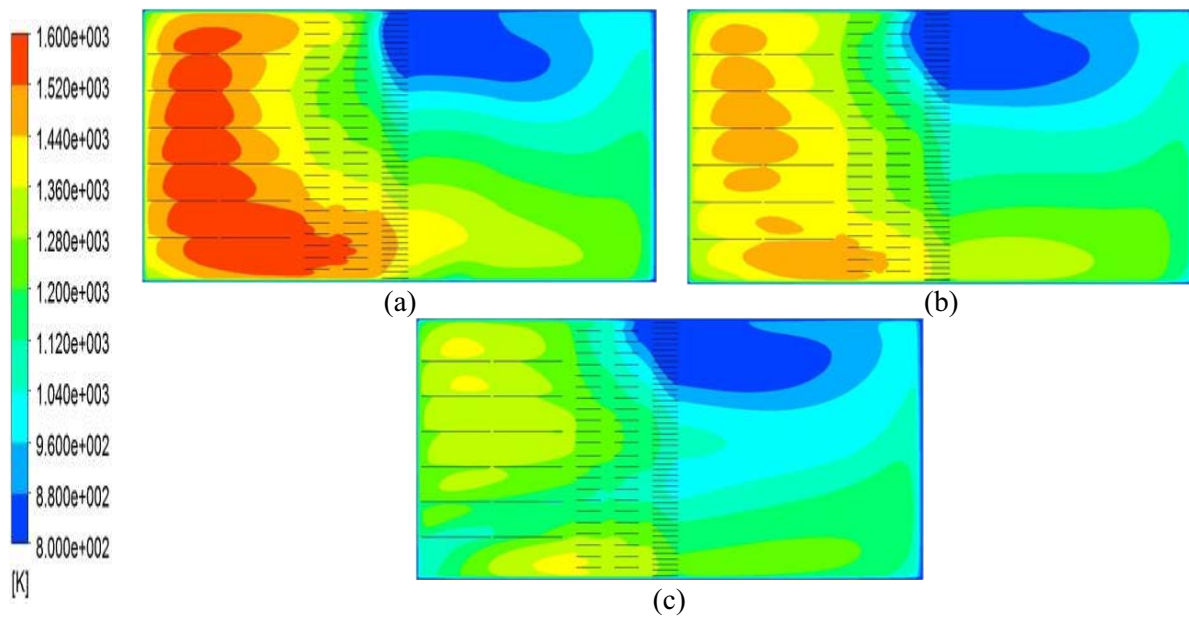


Figure 11. Temperature contour on plane (a) HP1 (b) HP2 (c) HP3.

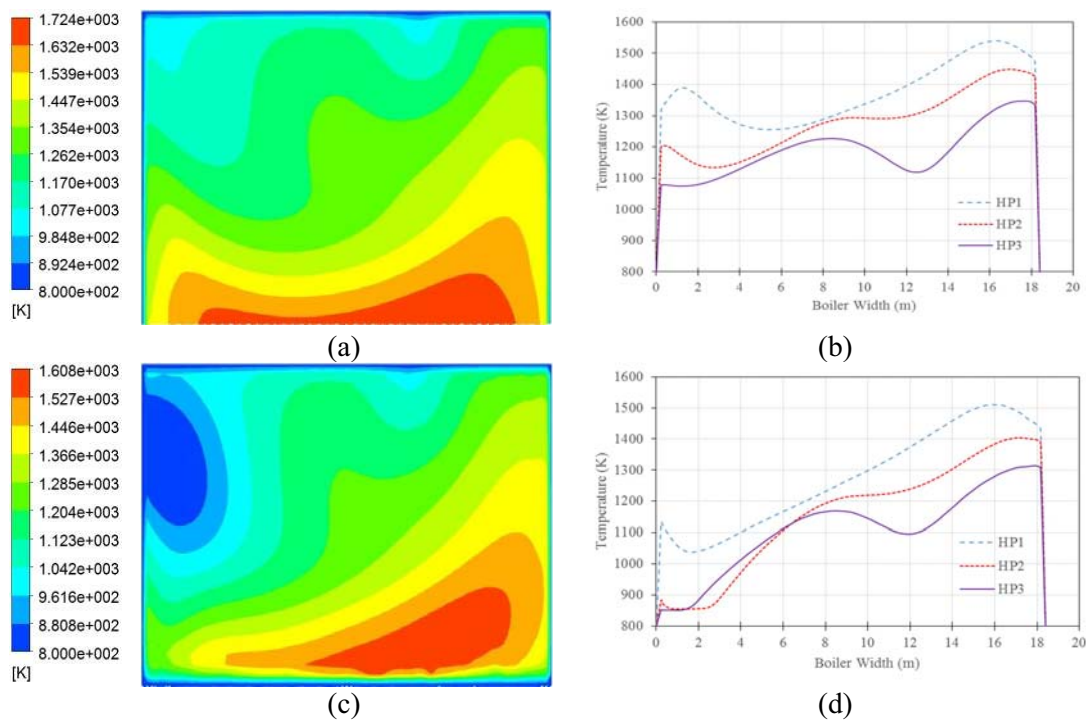


Figure 12. Temperature contour and the corresponding temperature plot on plane X1 (a and b) and X2 (c and d).

Based on these observations, several relations can be made between the velocity and temperature distributions in the horizontal pass. When the velocity of flue gas as it flows through the plates is low, its temperature becomes low, and vice versa. At the location of the residual swirl where the velocity is low, the flue gas temperature is hence low. This residual swirl which happens to concentrate on the left side causes the flue gas temperature on the left side to be low. On the right side, the velocity of flue gas is high thus its temperature is high. The more the velocity deviation, the larger the temperature imbalance between the right and left sides. This is because when the flue gas flows through the plates with low velocity, its residence time increases allowing more heat to be transferred

to the plates which consequently lowering its temperature. High velocity flue gas flowing on the right side has shorter residence time hence less heat is transferred to the plates resulting in only small drop of its temperature.

4. Conclusions

The flow, velocity and temperature distribution in the 700 MW coal-fired tangential firing boiler has been studied using CFD numerical simulation. The model has been well validated and proven to be mesh-independent. Several conclusions that can be made from the study include:

- a) The swirl formed in the furnace remains uninterrupted at the center until the furnace exit where it is shifted towards the rear wall due to the significant reduction of cross-sectional area. After the furnace exit, it is further shifted towards the left wall due to sudden increase of cross-sectional area and eventually subsides. A new swirl is formed in the rear pass after the flue gas flows pass the HTR.
- b) The shift of the residual swirl to the left side causes the flue gas from the left side to curve inwards and flows through the middle plates from the upper part.
- c) The residual swirl is the factor that causes low-velocity flue gas on the left side. This causes velocity deviation between the right and left sides.
- d) Temperature imbalance is the consequence of velocity deviation due to the difference of flue gas residence time between the plates and amount of heat transferred to the platen heat exchangers.
- e) Since the root cause of the temperature imbalance is the residual swirl, the solution would be to eliminate the residual swirl in the horizontal pass region or to prevent it from shifting and remain at the center of the furnace cross section.

Acknowledgement

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