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CFD Analysis on the Effects of Different Coal on Combustion Characteristics in Coal-fired Boiler

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ABSTRACT

Coal quality is essential for the optimum functioning of coal-fired power plants. One of the issues associated with coal quality deterioration is poor combustion behaviour which could result in ash deposition and environmental issues. This paper presents a CFD investigation of flow and combustion process in a full-scale furnace. Three different sub-bituminous coals with different properties were tested namely Coal A, B and C. The aim is to predict the combustion performance of these coals by observing its flow, temperature and species concentration inside the furnace. The exact boiler furnace geometry obtained from boiler operator was translated into CFD model with very little modification made for optimizing mesh. Grid dependency test carried out prior to the work shows the current mesh scheme is sufficient to accurately resolve the flow field. The results of the study show that combustion temperature for Coal B is the highest at approximately 1400°C. Coal C is predicted to give the highest velocity peak at certain regions of the furnace and interestingly enough, the same coal shows the shortest flame length and thus requiring additional flow to achieve the same penetration compared to other coals. Tracing of oxygen concentration inside the furnace show minimum oxygen left in the rear pass given by Coal A, indicating optimum combustion.

1. Introduction

Malaysia has been following fuel mix policy in which the country cannot become overdependent on any single fuel source. At the moment, coal dominates the fuel mix due to its abundance in resource and its obtainability at relatively lower cost compared to other hydrocarbon fuels, despite its contribution to greenhouse gas emissions [1, 2]. Even though renewable energy is expected to play bigger role in fuel mix beyond 2050, it is foreseen that Malaysia will still be relying on coal for power generation [3].

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Coal-fired power plants in Malaysia have been receiving coals, namely bituminous and sub-bituminous with wide quality variations. Even though the coals fall within the acceptable specification and range, they tend to give significant issues to boiler, such as ash deposition and reduced boiler efficiency [4]. Thus, the combustion of non-preferred coal needs to be efficient to ensure its consumption is at the optimum level to reduce the operational risks.

Research on the combustion performance of bituminous coal have been widely performed decades ago either by using computer simulation or by experimental works [5-9]. This can be attributed to the high utilization of such type of coal at that instant. As a result, most of the equations derived empirically from experimental works to predict slagging and fouling issue also found to be dedicated to bituminous coal [10, 11]. For numerical approach, many researchers utilized Computational Fluid Dynamics (CFD) simulations to predict the coal combustion flow and thermal performance. Majedski [12] conducted CFD simulation of a 225 MWe front wall boiler. He developed the model by considering the particle heating, devolatilization, char combustion, turbulent flow, radiative heat transfer and used mixture fraction approach to model the gas phase combustion process. He used Rosin-Rammler law to calculate coal particle size distribution. The aim of the study is to find the location of high erosion hazard inside the boiler and predict location of ash deposition may occur by analysing the velocity, temperature and combustion products distribution.

Since validity of the results is the main concern when dealing with numerical simulation, Jo *et al.,* [13] have conducted mesh sensitivity study and compare the predicted combustion parameters with actual parameters of tangential-fired boiler. There are three sizes ranging between 1.2 million and 5.4 million. They concluded that key performance parameters such as total wall heat absorption and NOx concentration was inappropriate criteria for the mesh sensitivity test. This is because these parameters is sensitive to the overall reaction stoichiometry instead of the mesh fineness. They suggested that the use of a coarse mesh could be acceptable in evaluating the key performance parameters influenced by major operation variables such as air distribution and fuel properties. However, sufficient mesh fineness is required if detailed flow pattern is needed especially for ash deposition analysis.

In recent decades, the utilization of sub-bituminous coal in thermal power plant was accelerated with a new boiler design that enable firing of this type of coal. It is known that coal combustion of sub-bituminous coal is very complex [14, 15]. However, since such type of coal is easily available, most newly-designed boilers were built to fire this coal. Considering all the complexity and difficulty, many researchers had embarked on the study of sub-bituminous coal combustion behaviour both numerically and experimentally. This paper aims to investigate the combustion performance of sub-bituminous coals in full scale power station boiler. This coal is commonly used in Malaysia power plants but not widely explored.

2. Methodology

2.1 Boiler Description

The boiler system under study is a 700 MW boiler with a tangential-firing configuration. The firing equipment consists of 28 coal burners. The burners system provides pulverized coal to the boiler from pulverizers where it has been crushed to consistent sizes. The primary air flow carries the fine coal to the burners for combustion to take place in the boiler furnace. The furnace is rectangular in shape with four burners firing from each corner, thus creating a fireball at the center of the furnace.

The numerical modelling of the boiler combustion process was carried out using an ANSYS-FLUENT 14.5 CFD package assuming steady, turbulent and compressible flow. The research commence with the collection of a boiler design data and configuration. CFD models were built based on the design and validated using operational data from the boiler. The model was then be used to predict the behavior of several coals on combustion characteristics such as flame temperature, O_2 & CO species composition and furnace exit gas temperature (FEGT) with the same boiler setting which were mass flow of air & coal and burner tilting angle.

2.2 Mesh Generation

The geometry and mesh generated for the boiler model is shown in Figure 1. The overall framework of the meshing scheme used in this study is quadrilateral mesh. Fine mesh was constructed in critical regions, such as in the area closed to burners, primary and secondary nozzles and within the winebox. The model was developed based on the actual operating boiler in the power plant. From the drawing obtained, few simplications were made to avoid extreme skewness level that might affect the stability of the calculation. The simplications made however, does not affect the final outcome as the main aim is to observe the flow and combustion temperature of the overall furnace flow domain. The number of mesh constructed is approximately 2.3 million cells. Prior grid dependency study has been undertaken and it is shown that the current mesh is sufficient enough to resolve the flow field, especially in complex regions where flow properties are critical. Comparison of the simulation results with different mesh density is shown in Figure 2. The mesh quantity was reduced by 20% and increased by 20%. It is shown that the differences of the predicted temperature between these varying mesh were negligible.

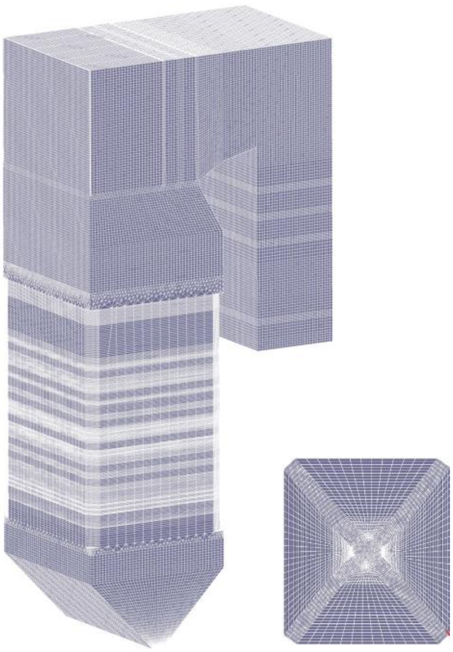


Fig. 1. Mesh generated for the tangential-fired boiler

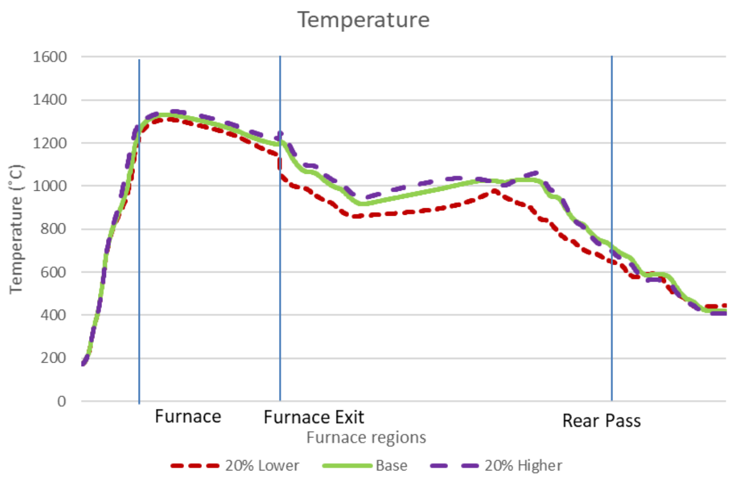


Fig. 2. The variation of predicted temperature along the centreline of the furnace with different mesh quantity

2.3 Model Assumptions

The standard Reynolds Average Navier-Stokes Equation (RANS) is used to solve the continuity, momentum and energy equations. Realizable k-ε model was used as the closure for turbulent model and P1 was selected for radiation model. The combustion equation was assumed assuming non premixed model and the PDF is generated by integration with FG-DVC software. The tracking of coal particles is made available using Discrete Phase Model (DPM) and the coal particles distribution is assumed to follow the Rosin-Rammler distribution.

In this study, 3 different coals were numerically tested, namely Coal A, Coal B and Coal C. These coals are listed among the acceptable coal for firing in the boiler. Table 1 shows the coal properties for these coals.

Table 1
The properties of coals

Coal properties	Coal A	Coal B	Coal C
Calorific Value, kJ/kg	5732.57	6122.24	6495.45
Moisture, %	13.30	5.89	6.55
Volatile matter, %	43.80	41.03	40.98
Fixed carbon, %	41.25	43.69	45.32
Ash, %	1.65	9.40	7.16
C, %	61.80	70.80	73.45
H, %	5.63	5.76	5.76
O, %	31.21	21.90	18.81
N, %	1.09	1.34	1.46
S, %	0.27	0.50	0.53

2.4 Boundary Conditions

The boundary conditions were obtained from the daily operational data at 100% Boiler Maximum Continuous Rate (BMCR). The inlet conditions are the air and coal flows entering the domain from the burner nozzles. Coal flow rate and combustion stoichiometric ratio were set as 60 kg/s and 1.2 respectively. Temperatures of combustion air are set as 345 °C. Pulverized coal size was modelled by a Rosin-Rammler distribution between 75µm and 300µm. The outlet conditions is the flue gas passage at boiler rear pass.

2.5 Validation Result

Validation of result was performed by comparing the predicted temperature with the designed temperature data such as furnace exit gas temperature (FEGT) and rear pass temperature. The comparison between these parameters are shown in Figure 3. It was observed that the predicted FEGT and rear pass temperature show good agreement with the designed data.

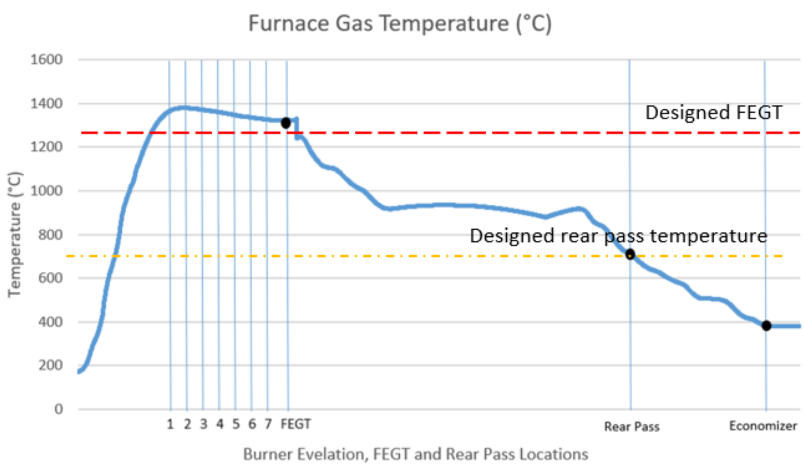


Fig. 3. The comparison between the predicted with the designed temperatures

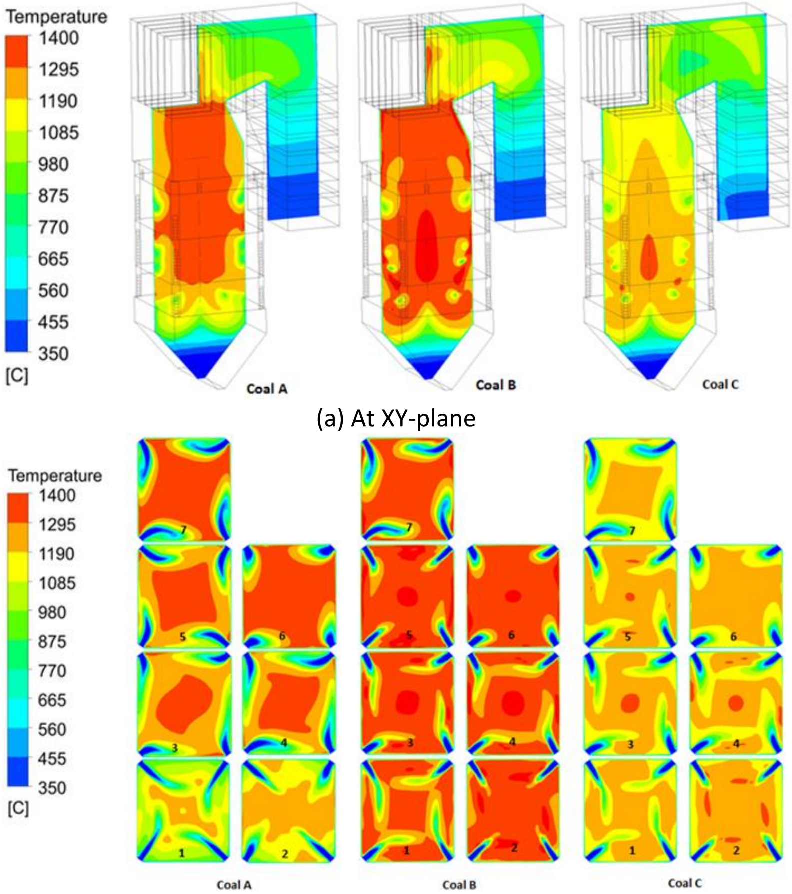
3. Results

3.1 Flame Temperature, Velocity, O_2 and CO Mass Fraction

The flame temperature distribution on the XY plane is shown in Figure 4(a). The temperature colour scale is the same for all cases. Coal A shows evenly distributed flame temperature. The fireball develops along the burner zone with peak temperature at the centre of the furnace. For Coal B, the flame temperature is higher than Coal A with higher temperature predicted at the centre of the furnace and expanded to the furnace wall. This could be attributed by Coal B higher calorific value and fixed carbon compared to Coal A. Higher flame temperature was also observed at the upper region of the furnace as compared to Coal A. This could potentially result in higher ash deposition to the wall or other superheater surfaces [16]. The flame temperature of Coal C is evenly distributed at the centre of the furnace with shorter flame length as compared to Coal A and B. Even though the calorific value of Coal C is higher than Coal B, the predicted temperature for Coal C is lower than the Coal B. Theoretically, coals with higher fixed carbon and calorific value might result in higher temperature during the combustion process [17]. However, other parameter such as fuel ratio could also play significant role in the combustion behaviour [18]. Fuel ratio is the ratio of fixed carbon to volatile matter. Higher ratio indicates the difficulty of the coal to completely combust [10]. Based on the coal properties shown in Table 1, the fuel ratio for Coal A, B and C are 0.94, 1.06 and 1.11 respectively. Coal C has a relatively higher ratio than Coal B, therefore this will lead to a decrease in the energy absorbed in the radiant section.

Figure 4(b) shows the temperature distribution along furnace height at 7 different burner elevations, starting from bottom burner elevation (Elevation 1) to the highest elevation (Elevation 7). General observation shows similar coal jet penetration to the centre of the furnace. When the mixture of coal and air injected from the burners achieve adequate temperature, coal devolatilisation will take place. At the lower burner levels the temperature distribution shows lower values than at the higher levels for Coal A and B. Formation of fireball is also observed from the coal jets from the four corners where the large amount of heat is released indicated by the red regions. It is also interesting to note that the flame jets were deflected at the top burner level for all cases due to the strong swirl momentum of combustion gas as the height of furnace increases.

Figure 5 shows the temperature profile along furnace height for all simulated cases. Steep temperature gradient is observed from the hopper to burner regions, mainly due to initiation of combustion process. Among the 3 coals, Coal B reached the highest gas temperature which is slightly more than 1400 °C. The furnace exit gas temperature (FEGT) for Coal A and B are generally higher than Coal C. The FEGT for Coal A and B is below 1400 °C while Coal C is about 1200 °C. As the combustion gas flow to the rear pass section of the furnace, it can be seen that the temperature starts to drop as more energy is absorbed by the waterwall and superheaters [19, 20]. It is expected that Coal A and B have higher chances for slagging and fouling occurrence due to high downstream area temperature as compared to Coal C.



(a) At XY-plane

(b) At cross section along burner levels

Fig. 4. The flame temperature distribution for Coal A, B and C

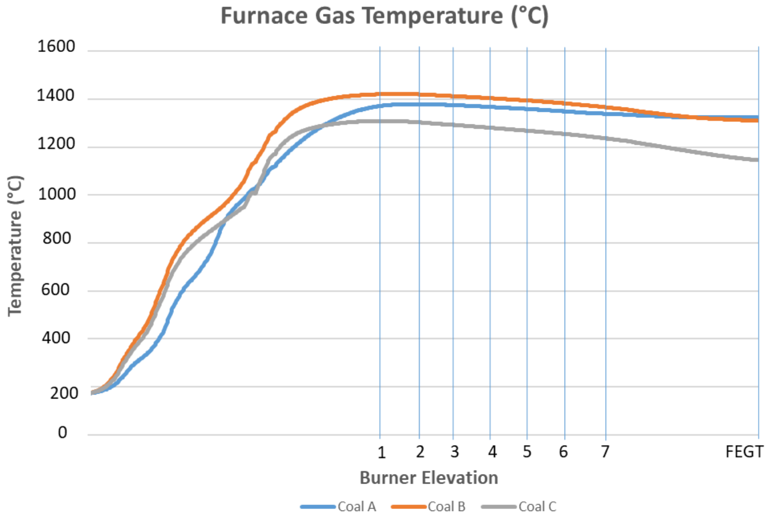
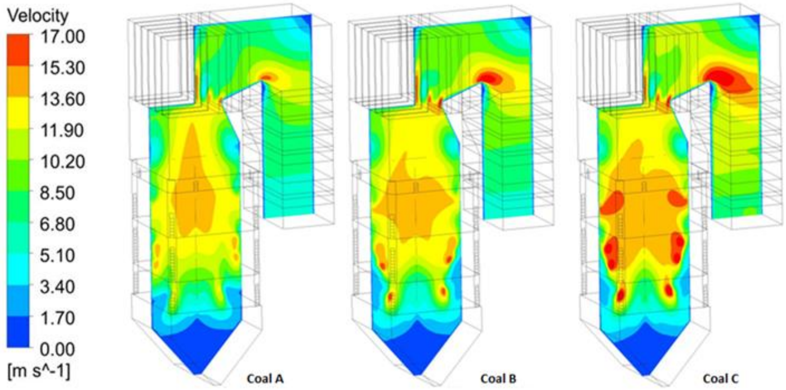
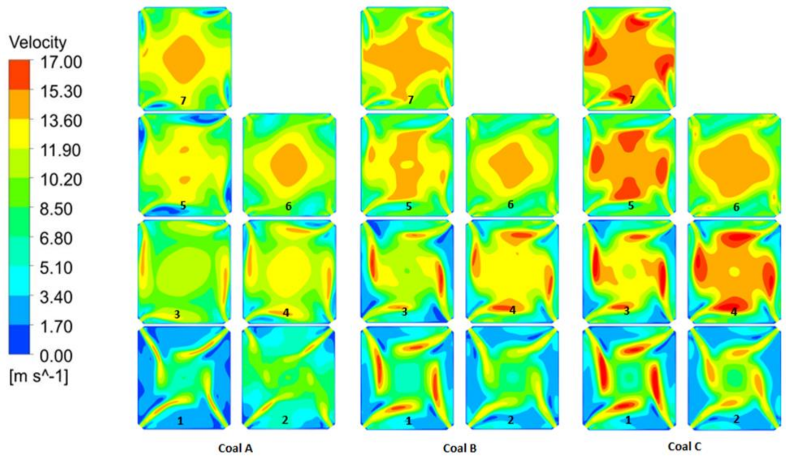


Fig. 5. The predicted furnace exit gas temperature (FEGT) for Coal A, B and C

Figure 6(a) and 6(b) show the contour of velocity magnitude inside the furnace at XY planes and at different furnace elevation respectively. The average combustion gas velocity was predicted to be in the range of 2m/s – 17 m/s. For all cases, it is noted that maximum velocity is achieved in the burner region where jet of coal and air first enter the furnace. This is illustrated by spots of high velocity regions in Figure 6(a). This spot is more obvious for Coal C as the regions get larger compared to other cases. It is interesting to note that different coal properties yield different flame speed and, in this case, Coal C, which possesses the highest calorific value and fixed carbon content produces the highest velocity magnitude. From Figure 6(b), it can be seen in all cases that the fireball start to develop in the burner zone. The fireball gradually becomes larger as elevation increases from the burner 1 to 7 as more flow is added from the burners. It is also noted that as the elevation increases, the velocity magnitude tend to get uniform as heat are dissipated and absorbed by the waterwall and superheaters.



(a) At XY plane



(b) At cross section along burner levels

Fig. 6. The velocity magnitude for Coal A, B and C

Figure 7 illustrates the velocity magnitude along furnace height for different coals. The local velocity is taken at furnace centre and consistent for all cases. Similar trend is expected with high peak velocity predicted at the windbox burner regions for all cases, where coal particle and combustion air are injected.

Figure 8 shows the O_2 mass fraction for Coal A, B and C. O_2 is injected from four corners and is available along the wall above the burner zone. It is rapidly consumed by the combustibles released from coal [21-23]. As a result, O_2 is depleted closer to the wall and completely consumed at the centre of the furnace. For Coal A, the O_2 is consumed before entering the rear pass. For Coal B and C, there is still remaining O_2 at the rear pass area which will exit the area as flue gas. Excess O_2 in flue gas would indicate incomplete combustion in the furnace zone.

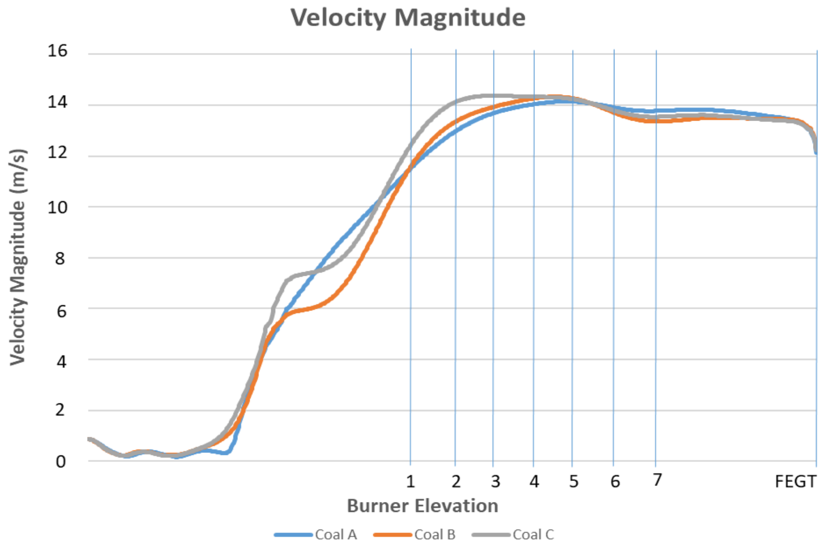


Fig. 7. The peak velocity magnitude for Coal A, B and C

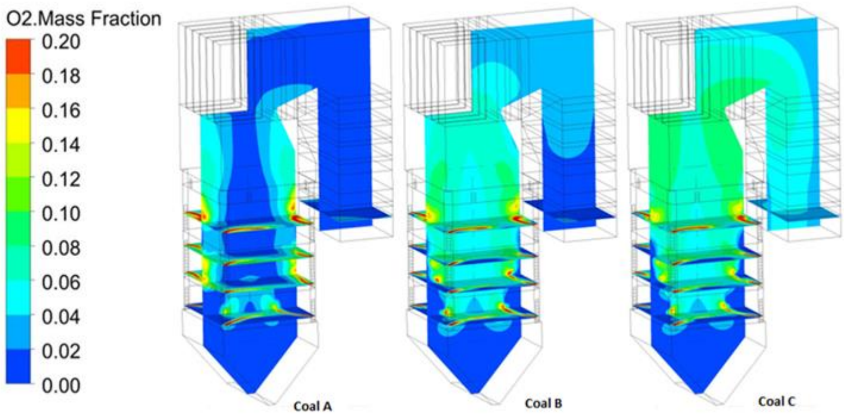


Fig. 8. The O_2 mass fraction for Coal A, B and C

Mass fraction of CO for Coal C is the highest as compared to Coal A and Coal B as shown in Figure 9. Such finding would indicate that ignition delay or incomplete combustion in the furnace zone most probably will occur when consuming this type of coal [24, 25]. The completion of gas reactions is prolonged as indicated by several % of CO remaining above the burner zone. Coal A, which has the maximum flame temperature within the burner zone (refer Figure 4) also has the lowest CO concentration above the burner zone.

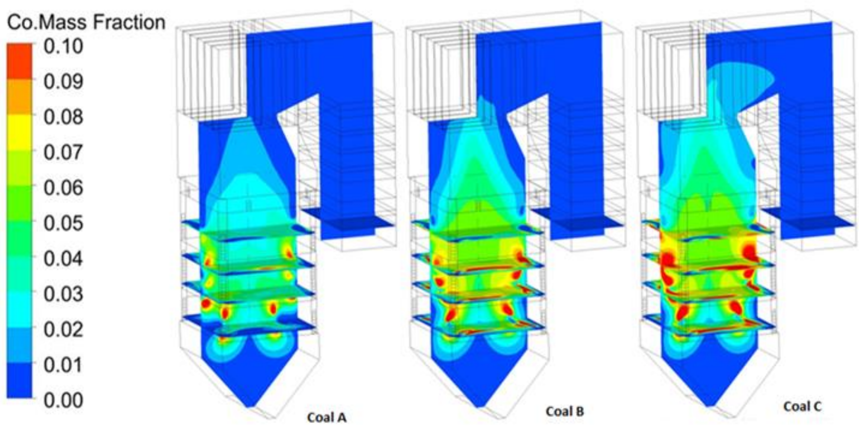


Fig. 9. The CO mass fraction for Coal A, B and C

4. Conclusions

CFD simulation of flow and combustion in a full-scale power station furnace have been carried out to better understand the combustion process inside the boiler when using different types of sub-bituminous coals. Three acceptable coals for firing in the boiler were used and the predicted results show that the temperature distribution, velocity, O_2 and CO species distributions are related to the types of coal. Coal with high calorific value will release more energy during combustion which consequently produce high furnace temperature. In addition, fuel ratio could also play a significant role on the temperature distribution. The distributions of O_2 and CO are closely related to combustion behaviour in the furnace which also has influence on the flue gas compositions. Based on this study, the temperature and velocity profile are in agreement with the expected behaviour of a tangential-fired boiler and the model was validated with the boiler performance data such as furnace exit gas temperature, O_2 and CO %.

The physical and chemical mechanisms inside a boiler is very complex and in order to better understand these processes, this work should continue to simulate with wider range of sub-bituminous coal properties. The effect of varying operating parameters on combustion results should also be investigated. Adjustment on boiler parameters is required to adapt with wide range of coal properties for optimum performance.

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