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Optimisation of Solid Fuel In-furnace Blending for an Opposed-firing Utility Boiler: A Numerical Analysis

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ABSTRACT

Continuous research on the clean and effective use of coal is still necessary as coal will continue to play a key role in global energy supply for the foreseeable future. Hence, in the current study, the optimisation of in-furnace coal blending for one of Malaysia's opposed-firing utility boilers was numerically executed on the basis of hydrodynamics and combustion characteristics. The predicted FEGT from the numerical model was validated against the actual FEGT from the coal-fired power plant, revealing a difference of less than 10 %. Four (4) coal blended cases were tested, which included both bituminous (bit) and sub-bituminous (sub-bit) coals. The findings demonstrate that due to the difference in density between bit and sub-bit coals, the hydrodynamic performance is predicted to significantly improve when sub-bit coal is injected at the bottom burner as opposed to the upper burner. In terms of kinetics, the higher volatile matter (VM) of sub-bit coal in contrast to bit coal has been postulated to release a substantial amount of volatiles and improve the combustibility of bit coal. Furthermore, enhanced oxygen release from sub-bit coal volatiles can aggravate the gas-solid heterogeneous reaction during bit coal char combustion. As a result of the bottom burner's high temperature, it has been discovered that introducing sub-bit coals into those burners speeds up VM release and char combustion, which increases the rate of combustion. Thus, when combustibility rises, the peak temperature position moves downward, reducing the likelihood of delayed combustion and, consequently, the risk of heat exchanger pendant failure and ash deposition. In a furnace with a relatively long coal residence time, a considerable fraction (>20 %) of high gross calorific value (GCV) sub-bit coal (>5800 kcal/kg) is predicted to produce two peak flame temperatures exceeding 1600°C owing to the likelihood of enhanced char which created delayed combustion. Therefore, a furnace condition with a comparatively shorter coal residence time may aid in the rapid evacuation of residual char from the combustion/burner zone and minimise the potential for delayed combustion. Nonetheless, residual char escape may exacerbate the emission problem by releasing considerable unburned carbon. Overall, the current numerical model has the potential to be a reliable and cost-effective tool for investigating the combustion characteristics of coal blends in a power plant boiler.

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1. Introduction

Electricity and heat production are largely responsible for rising carbon dioxide (CO_2) emissions [1]. As the world population has grown, so has the demand for electrical generation, necessitating the use of coal, natural gas, and oil [1]. Coal-fired power plants emit the highest CO_2 per unit of electric generating capacity [1], and despite the increased interest in green fuels [2-4], it is estimated that no other source of electricity will overtake coal until 2035 [1]. As a result, coal will continue to play a key role in global energy supply for the foreseeable future [1, 5]. Continuous research on the clean and effective use of coal is still required and important. An effective strategy must be implemented to decrease CO_2 emissions from coal-fired power plants [6]. One of the measures is to optimise the combustion performance of the coal-fired boiler [6].

The optimisation of combustion performance of large-scale coal utility boilers has been increasingly important for the utility industry in recent years [7]. Efforts are being made to improve thermal efficiency, extend their longevity, and reduce pollutant emissions [7]. Environmental regulations are becoming more stringent, and power generation businesses are being forced to uphold the agreement between efficient and clean combustion [7]. Furthermore, in order to remain economical, coal-fired power plants must overcome the difficulty of non-design, low-quality coal utilisation, which imposes significant operational challenges such as increased water wall slagging and high temperature corrosion [7]. Slagging not only diminishes a furnace's thermal efficiency but also compromises its integrity due to corrosion, erosion, and implications on the bottom tubes [7,8].

Blending multiple types of coal at pulverised coal-fired power plants is becoming increasingly prevalent in several nations to improve combustion performance while also compensating for an ever-increasingly poor quality of coal consumption [5]. Blending coals and using them in coal-fired power plants has numerous advantages [9]. It would be plausible to improve the functionality of coal blends by lowering fuel costs, controlling emission limits and flame instability, presumably due to differences in ignition characteristics of each coal, increasing fuel flexibility, broadening the range of acceptable coals, providing a consistent product from coals of varying quality, enhancing boiler performance, and addressing existing issues such as poor carbon burnout, slagging, and fouling [9]. Because of the prospect of enhancing performance in all of these areas, the combustion of coal blends has been the topic of numerous recent studies [10,11]. Burning blends, on the other hand, may cause unanticipated and unwanted issues in boiler operation, efficiency, corrosion, erosion, flame stability, slagging, fouling, heat adsorption in the furnace, and so forth [9].

Different types of coal can be blended in power plants in a variety of ways, including stockpiles, bins, and conveyors [9]. When the pile is reclaimed, layers of coals are placed in the proper proportions to give the desired composition of the blend [9]. Different coals are sometimes placed in separate stockpiles, and then predefined proportions for blend are taken from each pile using a loader [9]. The coals to be blended are added in the desired ratio to the bins. The bin is filled with different types of coal in batches. In belt blending, two or multiple distinct coals are proportionally blended by volume or weight on a moving belt conveyor [9]. The coals are fed into different bins and blended before being discharged to adjustable speed feeders. The required blend proportion is achieved by varying the speeds of various feeders that feed coal onto a conveyor, which then transports it to raw coal bunkers [9]. These three blendings can be classified as out-furnace blending methods [9]. With this method, after being mixed together, coals of various sorts are concurrently put into the furnace [9].

The in-furnace blending method involves injecting each coal into the boiler from a separate burner with no prior mixing. This method is not widely used in power plants because it is difficult to transport and distribute two coals individually to coal bunkers [9]. Nevertheless, in-furnace blending

has demonstrated greater flexibility in terms of managing the co-firing adjustment between two or more different types of coals [12]. Many studies on the combustion characteristics, emissions, and ash behaviour of blended coals have been conducted using laboratory and pilot scale furnaces such as thermogravimetric analyser (TGA), drop-tube furnace (DTF), and fuel evaluation test facilities to make a realistic assessment of the combustion behaviour of coal blends [9].
Nevertheless, most blending research has concentrated on the combustion characteristics of the out-furnace blending method [11]. Furthermore, only a few research were found in the literature that studied the influence of the blending procedure at a full-scale utility boiler. [9]. For example, Ikeda *et al.,* [13] investigated coal blends in pilot-scale three-stage burners utilising the in-furnace blending method. In three-stage burners, they evaluated the in-furnace blending approach in comparison to the out-of-furnace blending method. Based on operational experience, they successfully burned coal blends utilising the in-furnace blending process, achieving reductions in both unburned carbon and nitrogen oxides (NO_x) emissions [13]. Amidst these research, there is still a necessity to investigate coal-blend phenomena because most work has concentrated on the combustion attributes of the out-furnace blending method, and the fundamental combustion mechanisms resulting from the repercussions of the in-furnace blending method are still poorly defined [13].

Coal is a heterogeneous substance with varying qualities in terms of rank, maceral content, and related impurities [11]. As a result, developing a flawless methodology for predicting the combustion behaviour of coals and coal blends is difficult [11]. It has been recognised that characteristics related to fuel composition (proximate and ultimate analysis data, heating value, etc.) continue to stay additive after blending, whereas many characteristics related to combustion are non-additive [10,11, 13]. That is, they exert reactive and unreactive repercussions [10,11, 13]. For instance, additivity cannot anticipate ignition, combustion and flame stability, slagging, fouling, and NO_x emissions [10-11, 13]. Experimental methods were used to evaluate the combustion performance of coal blends used in pulverised coal-fired boilers [13]. Some empirical indices based on volatile matter composition, fuel ratios, and maceral compositions were also constructed from the experimental data in order to empirically forecast the ignitability, flame stability, and burning of coal blends [13].

Numerical modelling is another technique that has the potential to be a reliable and cost-effective tool in the examination of coal blends. Numerical modelling has proven to be an efficient method for diagnosing and resolving flow and combustion problems [13, 14-18]. It has been widely used to analyse the combustion performance of a single coal and binary-coal blends in bench-pilots and full-scale utility furnaces because it can provide insights into the combustion properties of unfamiliar coals [13]. Shen *et al.,* [13] simulated flow and combustion for binary-coal blends, and the numerical blend modelling was confirmed with experimental data under simplified blast-furnace settings. They demonstrated that the combinatorial impact is caused by interactions between individual coals in terms of particle temperature and volatile matter, and the modelling provides a useful approach for the formulation of coal blends.

At the moment, the three most common combustion technologies used in coal-fired power plants are opposed-fired, tangential-fired, and down-fired. Because of its flame organisation independence, limitless boiler shape, and low gas temperature deviation in the horizontal flue gas pass, opposed-fired boilers are frequently utilised [19]. However, low-load flame stability and NO_x emissions remain the primary challenges in design and operation [19]. As a result, the current study applies comprehensive numerical modelling on one of Malaysia's opposed-fired coal utility boiler models. The current study's main goal is to get fundamental insights into the impact of varied in-furnace blending configurations on combustion performance for a variety of coal types.

2. Physical Setup

The three-dimensional (3D) geometry of a coal-fired boiler shown in Figure 1 was developed using as-built dimensions from the actual coal-fired power plant under study. The boiler has a wall-firing layout with a total of 36 coal burners that are also the primary air (PA) inlets, with 36 secondary air (SA) inlets concentrically located at each burner-PA inlet to allow proper mixing of the incoming coal and air, as well as to provide a dry low NO_x area near the burner region where the incoming SA will provide a recirculation zone for the entering coal and air [8]. Because of the wall-firing layout, each side of a boiler (front and rear walls) has 18 burner-PA inlets and 18 SA inlets situated at three different heights at a burner zone. The tube bundles of superheaters and reheaters were simplified to a few thin walls to reduce computational costs [8], while still accounting for the accuracy of computational works in which heat transfer models were applied to thin walls to simulate the heat transport process between the flue gas and the steam in heat exchanger bundles. The details of heat transfer modelling on the heat exchanger bundles follows the same procedure as Yang *et al.,* [20].

The over-fire air (OFA) inlets are located between the burner zone and the heat exchanger bundles, and they consist of 6 inlets each at the front and rear walls at the same elevation height, as well as another 2 inlets slightly below the 6-inlet sets. Figure 1 displays the computational model and boundary names used on the boiler. As indicated in Figure 1, mills 1-6 deliver coal and PA for each burner-PA inlet elevation (A to F).

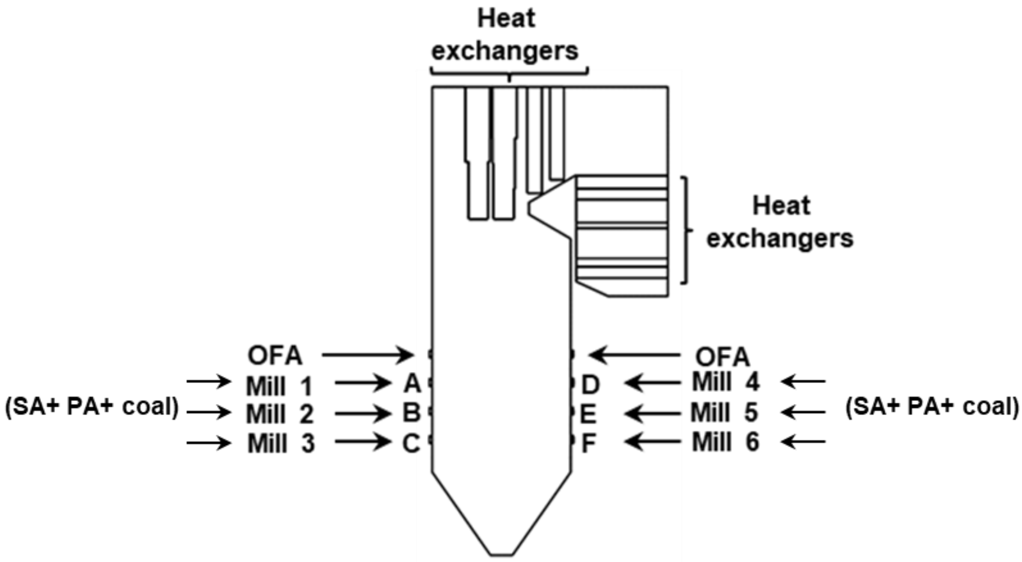


Fig. 1. Computational model of the boiler

In a standard utility coal-fired boiler system, the coal-fired boiler incorporates the piping system and the furnace as one system, with all mills connected to discharge pipes that transport coal particles and PA into the boiler [8]. However, in order to save computational expenses, the piping structure is not included in the computational domain for this study. Fuel oil (FO) inlets are not included as one of the flow inlet boundaries in the present study since the FO is often used during the furnace's startup phase. The present study is a steadily simulated reacting flow assessment in which combustion is supposed to be long past the transitory period of the coal-fired furnace's start-up operation.

3. Numerical Setup

The detailed chemical reaction modelling schemes of coal combustion employed in the current project are similar to those shown in our prior research [8]. The current study's chemical kinetics and combustion models account for the three major stages of the coal combustion process: coal devolatilisation, char conversion/reaction, and volatiles reactions. The volatile composition and rate constants for coal devolatilisation were predicted using the advanced coal network model and determined using our own analytical fuel laboratory's historical coal database. The finite volume technique was used to discretize the governing equations (steady state and compressible). For all setup and numerical processing, ANSYS Fluent V.19 R1 was used. The governing equations were solved using a pressure-based solver. The Semi-Implicit Method for Pressure Linked Equations (SIMPLE) technique was utilised to solve the pressure-velocity coupling. Ferziger *et al.,* [21] provide thorough information on the SIMPLE algorithm's constants and formulations. The Discrete Ordinates (DO) model was utilised to address the radiative heat transfer from the reacting flow. The Shear Stress Transport (SST) $k - w$ model, which was reported to provide good convergence and accuracy in reacting flow simulations [22], was used to resolve turbulent flow.

To determine the size fraction of coal particles, sieve analysis was done on coal samples taken from the actual power plant under study. The size fraction was used to translate the range of coal fineness into the Rosin Rammler distribution, and the curve fit coefficients of the Rosin Rammler distribution were introduced into the CFD numerical code to reflect the variation of coal fineness from the power plant under study. The coal fineness ranged from 75µm and 300µm, and all coal particles were tracked using a Lagrangian system that accounted for turbulent dispersion for 80 000 particles.

Several coal types were chosen for the in-furnace blending analyses based on the actual coal used by the power plant while it was operational. The combination of bituminous and sub-bituminous coals was used to evaluate the viability of using sub-bituminous coal in the present boiler, which was built to burn only bituminous coal. In the beginning, one hundred (100) different coal blends were examined, taking advantage of the coal's additive qualities such its gross calorific value (GCV), total moisture, ash content, volatile matter, and sulphur content. Following that, the accept and reject criteria from the power plant were compared to the additive characteristics' values from all coal blends. All coal blended combinations that fulfilled the reject criteria were eliminated, leaving four (4) coal blended cases. As a result, these four (4) coals blended scenarios were chosen to proceed with the CFD simulation of in-furnace blending.

Table 1 displays the properties of the coals used in the four (4) coal blended scenarios. These coals were utilised by the power plant while it was operating, and they were collected in a small sample and subjected to comprehensive analytical fuel testing to determine its coal properties. These coal characteristics (shown in Table 1) are part of the current numerical study's boundary conditions. Table 2, on the other hand, shows the four (4) coal blended scenarios utilised for the CFD simulation of in-furnace blending.

Referring to Tables 1 and 2, coals B1 and B2 are bituminous, while coals S3 and S4 are sub-bituminous. Case BB is the baseline in which no blending occurred (100 % coal B1). The validation with actual plant data was carried out based on the CFD results from case BB. This is because case BB, or 100 % coal B1, has been regularly used in the power plant under study, and a large amount of plant data from this firing can be used to validate the baseline case. As a result, the power plant operating condition during the firing of coal B1 was appropriately captured by the power plant sensor and transferred as the boundary conditions of the current numerical analysis.

Table 1
Coal types and characteristics

Coal	Proximate analysis, % (TM-Total moisture, VM-Volatile matter, FC-Fixed carbon, AC-Ash content)				Ultimate analysis, % (C-Carbon, H-Hydrogen, N-Nitrogen, O-Oxygen, S-Sulphur)					GCV (kcal/kg)
	TM	VM	FC	AC	C	H	N	O	S	
B1	7.4	25.9	53.0	13.8	83.9	4.7	2.1	8.1	0.8	6232
B2	10.3	30.3	45.8	13.1	81.3	5.6	1.9	10.6	0.7	6169
S3	23.9	35.9	35.5	4.5	74.6	6.1	1.8	16.8	0.7	5100
S4	17.9	38.5	40.7	2.8	75.0	5.5	1.4	18.0	0.1	5835

Table 2
Coal blended cases

Case	Coal types (%)			
	B1	B2	S3	S4
BB	100	-	-	-
1	90	-	10	-
2	80	-	-	20
3	-	90	-	10
4	-	80	-	20

As indicated in Table 3, mills 1-6 deliver coal and PA for each burner-PA inlet elevation. Mill 6 does not emit any coal flow in the burner elevation F since it was used as a standby burner at the time this operational data was collected.

Table 3
Operating conditions for the CFD model validation

Parameter	Operating condition
Mill 1 coal flow (t/h)	32.91
Mill 2 coal flow (t/h)	38.45
Mill 3 coal flow (t/h)	39.45
Mill 4 coal flow (t/h)	39.45
Mill 5 coal flow (t/h)	39.45
Mill 6 coal flow (t/h)	0.00
Main steam temperature (°C)	538
Total OFA flow (t/h)	389.36
Total SA flow (t/h)	1168.07
Mill 1 PA inlet temperature (°C)	78.99
Mill 2 PA inlet temperature (°C)	79.95
Mill 3 PA inlet temperature (°C)	79.83
Mill 4 PA inlet temperature (°C)	79.95
Mill 5 PA inlet temperature (°C)	79.95
Mill 6 PA inlet temperature (°C)	48.89
Mill 1 PA flow (t/h)	73.86
Mill 2 PA flow (t/h)	72.90
Mill 3 PA flow (t/h)	73.85
Mill 4 PA flow (t/h)	73.78
Mill 5 PA flow (t/h)	68.26
Mill 6 PA flow (t/h)	14.92
SA temperature (°C)	333.00

4. Grid-Convergence Analysis and Model Validation

To guarantee that the spatial convergence accuracy is sufficient, the grid independent test is performed. Meshes (elements) are constructed with orthogonal quality and skewness in mind to reflect mesh attributes, which determine the level of spatial discretization errors [8]. The orthogonal and skewness features of all generated meshes assessed in the grid independent test were controlled to ensure that acceptable mesh qualities could be constructed. When the mesh number exceeds 1.89 million, the velocity and temperature profiles in the furnace's centre almost cease to vary. The mesh model is shown in Figure 2.

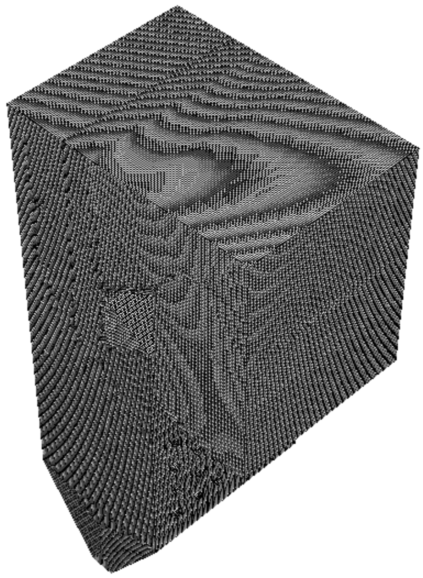


Fig. 2. Mesh model of the boiler (isometric view)

Following the determination of the independent mesh number, a model validation exercise was carried out, which involved comparing the predicted FEGT result from the present model with the actual FEGT from the power plant under study. The predicted FEGT result is based on the average temperature in a plane slightly below the furnace's nose area (below the tube bundles of superheaters and reheaters). Table 4 displays the FEGT results from the CFD model and the actual power plant.

Table 4
Validation based on FEGT results

FEGT (°C)		Percentage difference (%)
Actual	CFD	
1200	1284.81	7.07

Table 4 demonstrates that the predicted results from the overall CFD model were within 10% of the actual FEGT. Therefore, based on the FEGT validation results, the current numerical model's reliability was determined to be acceptable.

5. Results and Discussion

5.1 Standby Burner Elevation Optimisation

As previously demonstrated in Table 3, standby burner elevation certainly present and is frequently employed in the operation of coal-fired power plants. As a result, the standby burner elevation was chosen before the CFD simulation for the aforementioned coal blended cases is run. As soon as the standby burner elevation was chosen, it remains fixed for the duration of the coal blended simulation cases. Based on the coal particle residence time inside the furnace, the optimal standby burner position was chosen. The combustion performance is known to improve when coal particles remain in the furnace region for a longer period of time, particularly in the combustion zone, allowing for a more complete combustion to occur [23]. The CFD findings for the standby burner elevation optimisation are displayed in Figure 3.

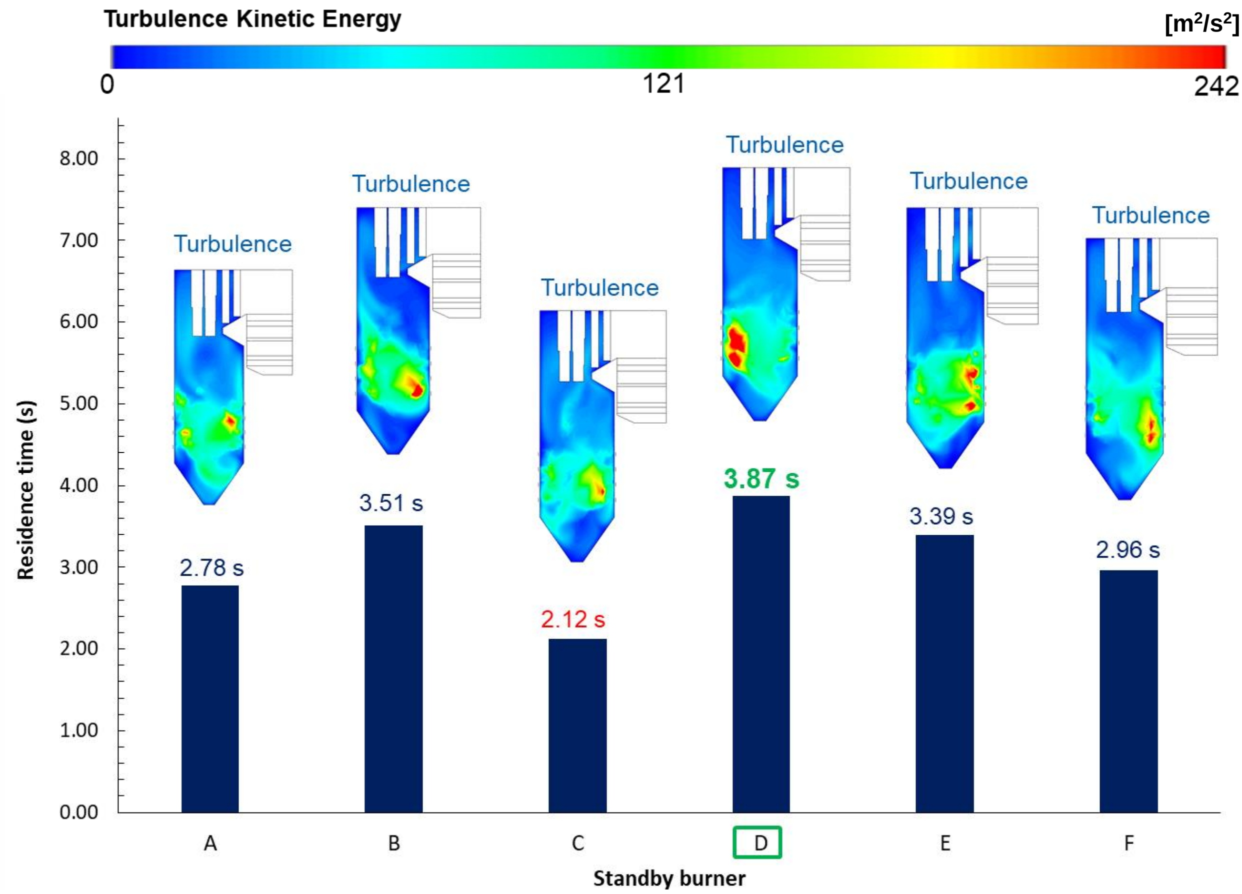


Fig. 3. Predicted turbulence kinetic energy and coal particle residence time in the furnace at varying stand burner positions

Figure 3 depicts a relationship between predicted turbulence and coal particle residence time in the furnace. As the turbulence intensifies, it contributes to an increase in the mixing rate within the furnace. This effect serves to improve the residence time of the coal particle within the furnace. According to Figure 3, using standby burner D generated the most turbulence in the furnace, resulting in the longest coal particle residence time, 3.87 seconds. According to the Coal-fired Power Generation Handbook [23], the coal particle residence time in the furnace should be within 2 to 5 seconds for complete combustion to have taken place. Based on the results in Figure 3, burner elevation D is selected as the standby burner throughout the simulation for coal blending cases.

5.2 Case 1: 90 % B1, 10 % S3

The first step in optimising in-furnace blending is to evaluate predicted turbulence and coal residence time at various burner-coal type configurations, as illustrated in Figure 4. This is done in order to determine which burner-coal arrangement will provide the optimum combustion performance.

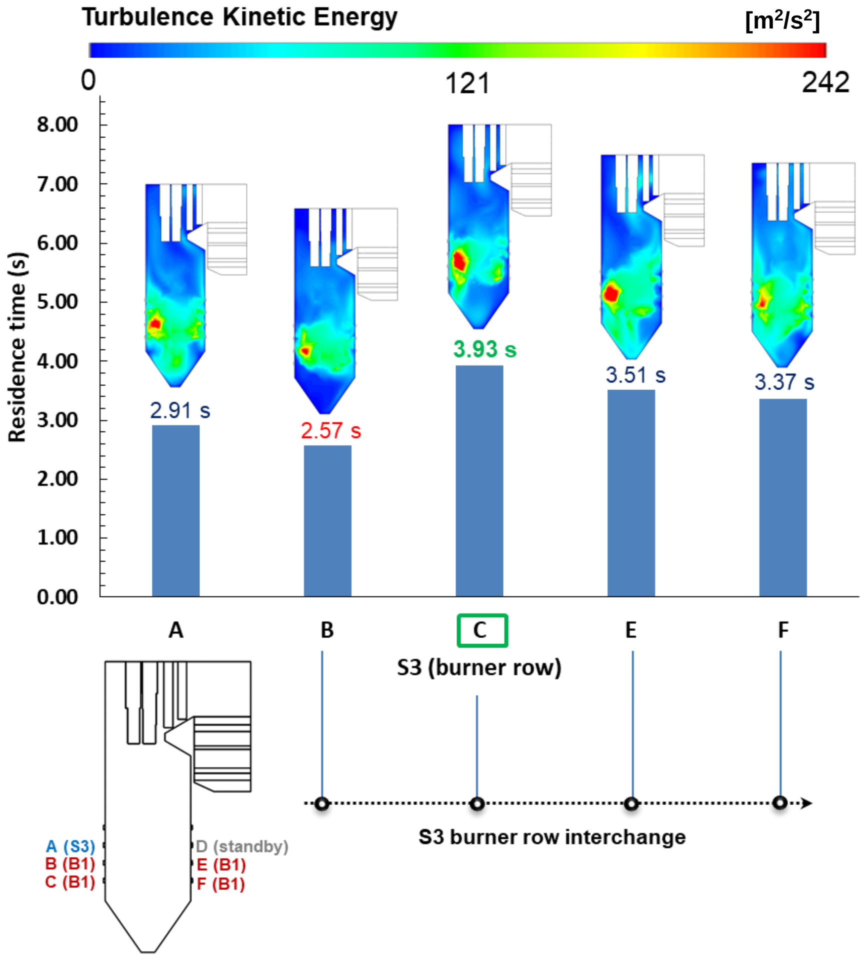


Fig. 4. Predicted turbulence kinetic energy and coal particle residence time in the furnace at varying burner-S3 coal type configurations

Based on the results in Figure 4, it is predicted that using S3 coal at burner elevation/row C will result in the highest turbulence and coal residence time in the furnace of all burner-S3 coal type configurations. The combustion simulation for two cases from Figure 4 was performed based on these results. The first case involves the use of S3 coal in burner row C, which has been expected to provide the longest coal residence time in the furnace. The second case involves the use of S3 coal in burner row B, which has been predicted to result in the shortest coal residence time in the furnace. Figure 5 depicts a comparison of the temperature profiles from these two cases.

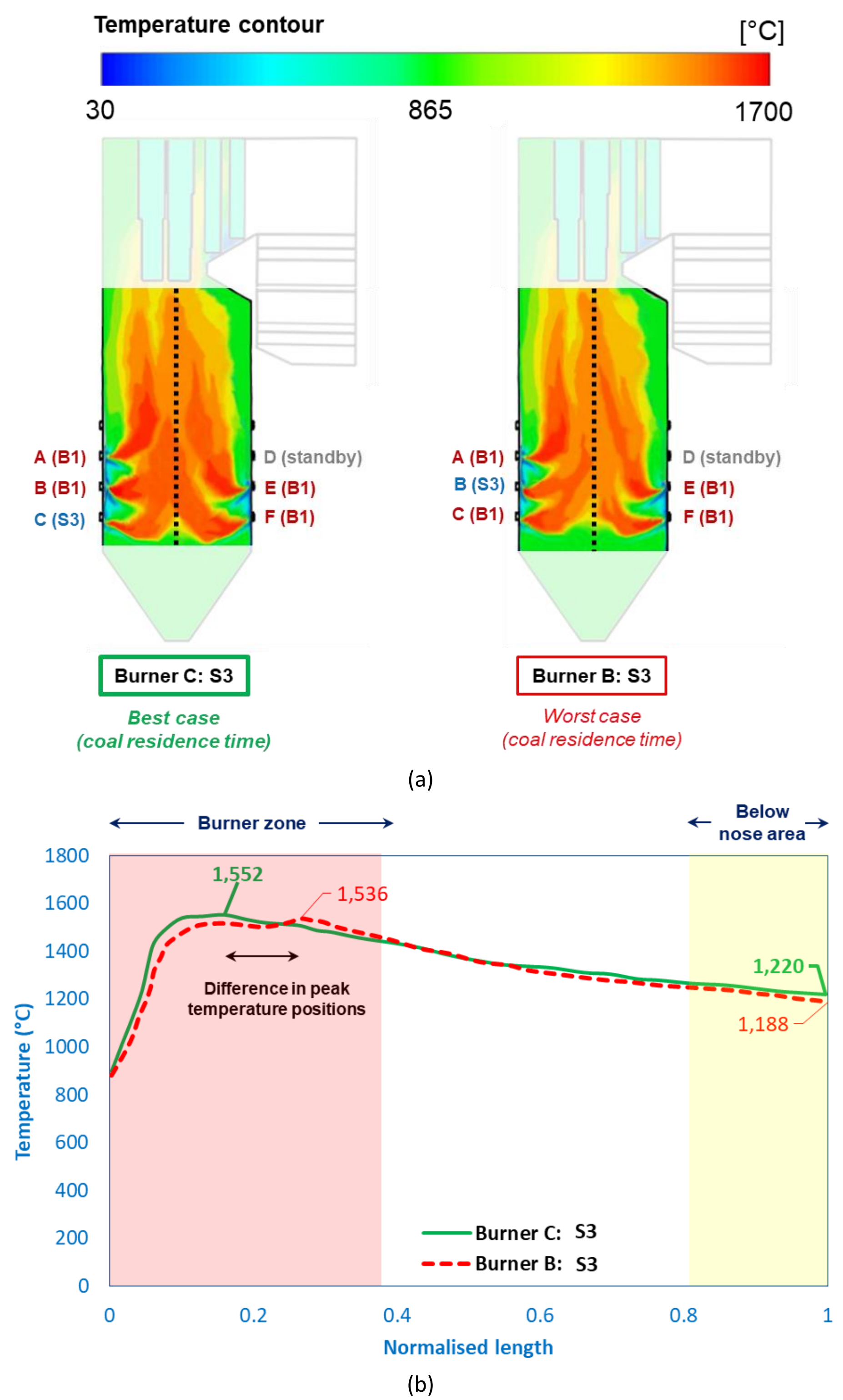


Fig. 5. Temperature profile predicted for Case 1 based on (a) qualitative and (b) quantitative data

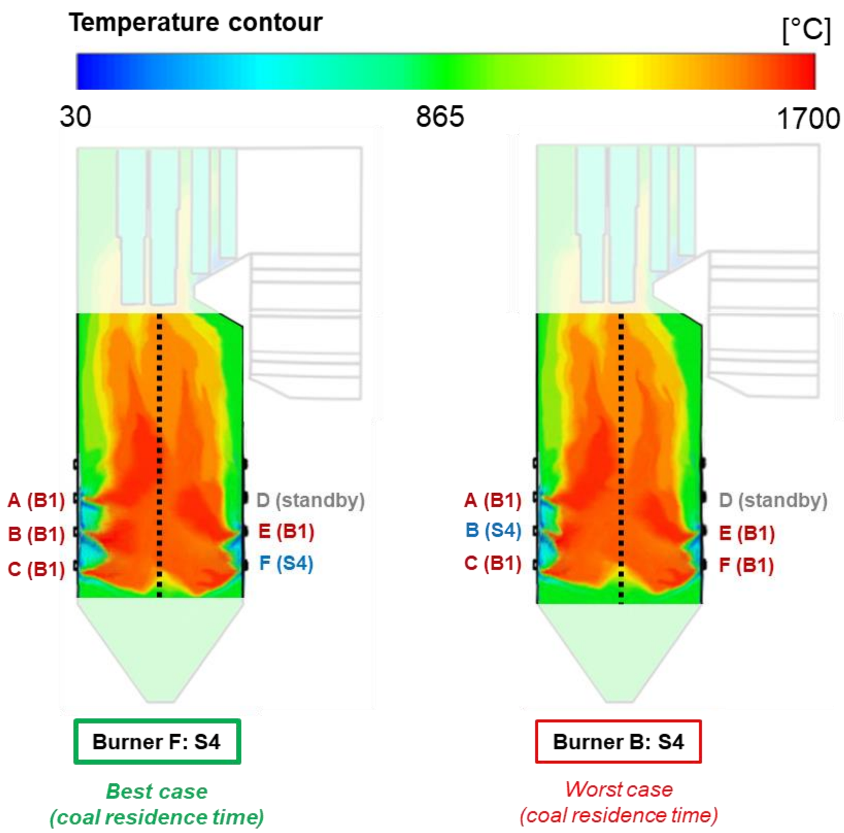
According to Figure 5 (a), the temperature contours for these two cases show only minor variation, especially near the burners. In the Burner C: S3 case, the temperature is slightly higher than in the Burner B: S3 case. Along with the enhanced coal residence time seen in the Burner C: S3 case due to the hydrodynamics interaction between coal, air, and the resulting flue gas, which allows for a more complete combustion, another important factor that could contribute to the temperature increase is the kinetics interaction. Table 1 shows that the VM of S3 coal, which is the sub-bituminous rank, is greater. It can be postulated that a considerable release of volatiles from S3 coal during the devolatilisation stage improves the combustibility of B1 coal, which has lesser VM despite having a greater GCV.

The shorter time required to achieve volatile combustion from S3 coal helps to accelerate volatile and char combustion from B1 coal. Furthermore, higher oxygen releases from S3 coal volatiles can exacerbate the gas-solid heterogeneous reaction during B1 coal char combustion [23,24]. As a result, despite the fact that the time scale of devolatilisation is much shorter than the time scale of subsequent char combustion [23], the synergistic impact of kinetics from S3 and B1 coals aids in increasing the combustion rate of the coal blends. B1 coal, which has benefited from S3 coal's higher combustibility, proceeds to have a higher rate of volatiles and char combustion. As a significant amount of porous char particle is burnt by surface reactions of oxidising species such as oxygen [23], the higher FC (char) from the B1 coal serves to further enhance the overall combustion temperature. The bottom location of the burner, which used S3 coal, promotes the overall combustion rate since it allows for a faster rate of volatiles release and char combustion to occur due to the temperature condition in the bottom burner.

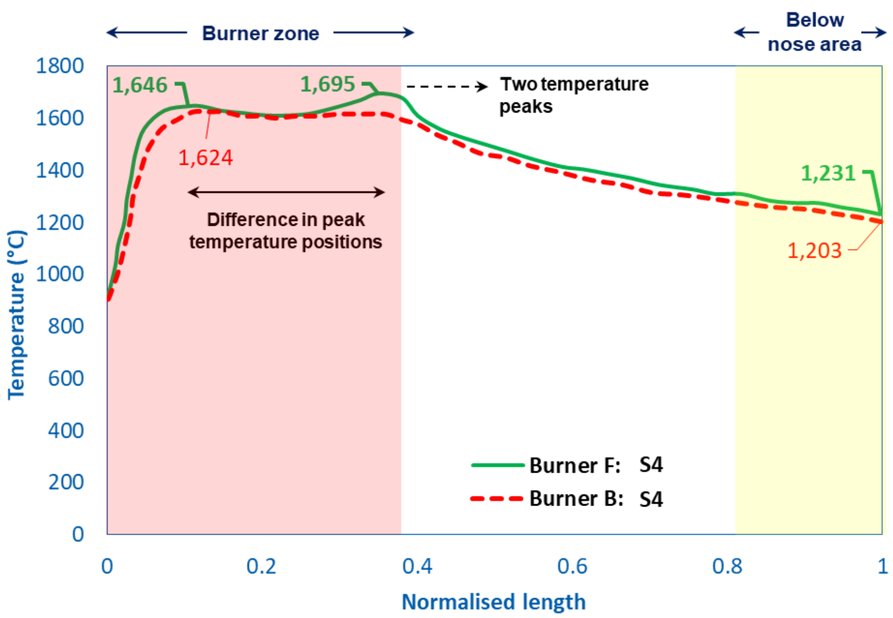
Figure 5 (b) demonstrates the improved combustibility given by the Burner C: S3 case. Figure 5 depicts the temperature profiles along the centreline after it was placed in the furnace (b). The peak temperature position in the Burner C: S3 case is further downstream than in the Burner B: S3 case, indicating an increase in combustibility. The lower the peak flame temperature position in the furnace's burner zone, the lower the risk of delayed combustion. The delayed combustion can jeopardise the integrity of heat exchanger pendants and increase the likelihood of slagging and fouling. Burner C: S3 case has a peak flame temperature that is 1 % higher than Burner B: S3 case, demonstrating an increase in combustion rate.

5.3 Case 2: 80 % B1, 20 % S4

For the purpose of simplicity, the examination of predicted turbulence and coal residence time at various burner-coal type configurations in Case 2 is not examined in length, as it was in Case 1. According to the coal residence time assessment, employing S4 coal at burner elevation/row F will result in the highest turbulence and coal residence time in the furnace of all burner-S4 coal type configurations in Case 2. Based on these findings, combustion simulations for two cases were run. The first case comprises the usage of S4 coal in burner row F, which is predicted to provide the furnace with the longest coal residence time. The second case involves using S4 coal in burner row B, which is expected to result in the shortest coal residence time in the furnace. Figure 6 compares the temperature profiles from these two cases.



(a)



(b)

Fig. 6. Temperature profile predicted for Case 2 based on (a) qualitative and (b) quantitative data

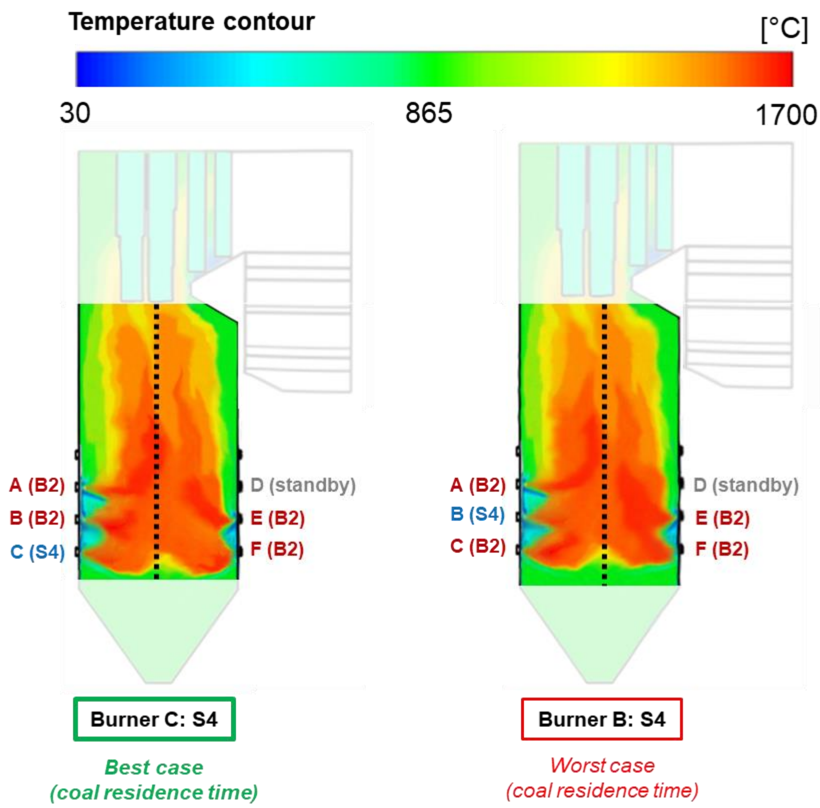
The temperature contours for these two cases, as shown in Figure 6, show a greater overall temperature than Case 1 with an increase in the burner zone temperature of around 80 to 150°C. The rise in burner zone temperature is attributed to a 20 % fraction of high GCV sub-bituminous coal (>5800 kcal/kg) in Case 2. As a result, the higher portion of sub-bituminous high GCV coal in Case 2 against Case 1 is expected to increase the total heat content of the coal [24], resulting in a higher combustion temperature. As indicated in Table 1, the GCV of S4 coal (5835 kcal/kg) used in Case 2 is larger than that of S3 coal (5100 kcal/kg) used in Case 1.

The temperature is much higher in the Burner F: S4 case than in the Burner B: S4 example. Furthermore, the Burner F: S4 case is expected to produce two peak flame temperatures that exceed 1600°C. While the increased coal residence time exhibited in the Burner F: S4 case aids in the increase in combustion temperature, the kinetic interaction between B1 and S4 coal is the most critical component that could contribute to the large temperature increase. S4 coal has higher VM and FC than S3 coal, which contributes directly to the increase in heating value [23]. As previously stated, FC serves as the primary heat source during combustion, with a large quantity of porous char particle being burned by surface reactions of oxidising species [23]. High VM, on the other hand, promotes combustibility due to the ease with which fuel can be ignited [23]. It is possible that there is a delayed combustion as a result of the increased char (FC) from S4 coal, with residual char escaping from the first zone high combustion reaction (first peak temperature) and undertaking secondary combustion reaction (second peak temperature) with the excess oxidiser from OFA and flue gas.

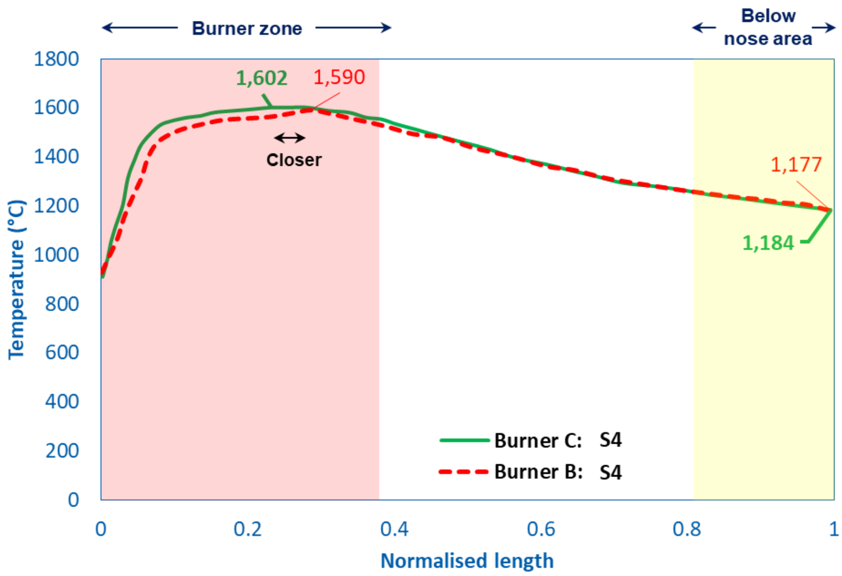
While the hydrodynamic performance of Burner F: S4 is superior to that of Burner B: S4, the absence of delayed combustion in the Burner B: S4 case makes it more suitable for use in actual power plant operation. The contradictory findings can be explained by the char oxidation time, which can take seconds as opposed to the devolatilisation process, which typically takes only a few hundred milliseconds [23]. As a result, the lower coal residence time in the Burner B: S4 case may contribute to the rapid evacuation of residual char from the combustion/burner zone. As a result, the residual char combustion that passes through the OFA does not have enough time to complete its process since the char exits faster. However, the escape of residual char may contribute to emission issue due to the discharge of high unburned carbon. This finding is corroborated by prior research, which revealed that increasing the amount of sub-bituminous coal above a specific threshold increases the unburned carbon fraction significantly [10].

5.4 Case 3: 90 % B2, 10 % S4

In Case 3, employing S4 coal at burner elevation/row C will result in the highest turbulence and coal residence time in the furnace of all burner-S4 coal type configurations in Case 3. Similar to prior cases, combustion simulations for two situations, namely the Burner C: S4 case (highest coal residence time) and the Burner B: S4 case (shortest coal residence time), were run. Figure 7 depicts a comparison of the temperature profiles from these two scenarios.



(a)



(b)

Fig. 7. Temperature profile predicted for Case 3 based on (a) qualitative and (b) quantitative data

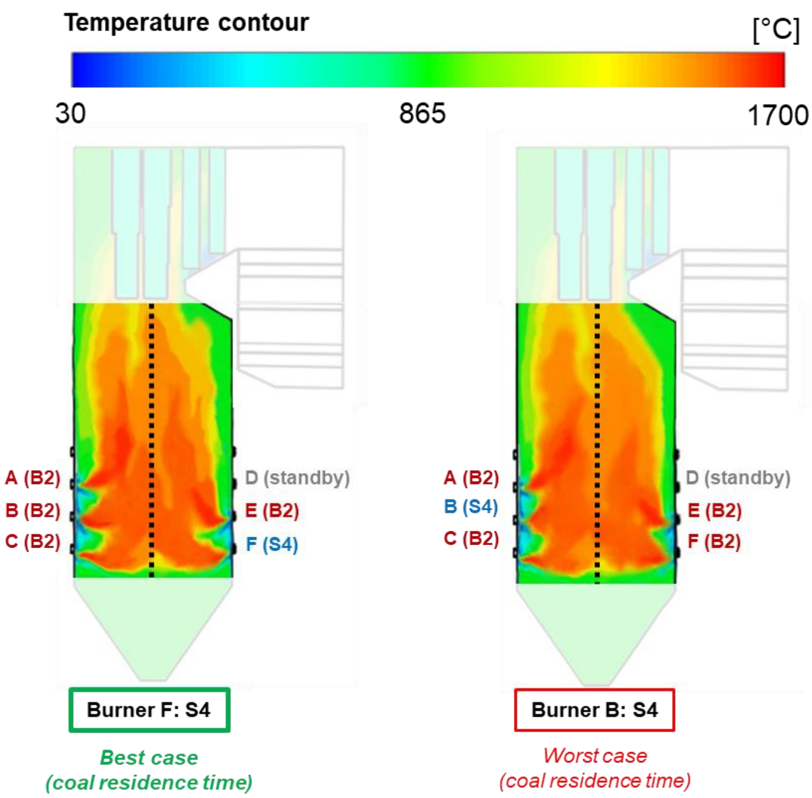
As compared to Cases 1 and 2, the temperature contour for the best and worst coal residence time in Case 3 has relatively identical features, as shown in Figure 7 (a). The minor variation in temperature contour for these two cases is further corroborated by the qualitative data in Figure 7 (b), which shows nearly identical temperature profiles for these two instances. Even the peak flame temperature placement and magnitude have been predicted to be almost same in these two scenarios, with less than 1 % variation in both peak temperature positioning and magnitude parameters.

The compatibility of the coal types is believed to be the primary cause of the temperature profile's minor variation. According to Table 1, important coal properties such as GCV, FC, and VM are relatively close in values for both B2 and S4 as compared to Case 1 (B1 and S3) and Case 2 (B2 and S4) (B1 and S4). Even if these coal properties are additive in nature while flame stability is not, the impact of coal characteristics on the generated flame can still be linked.

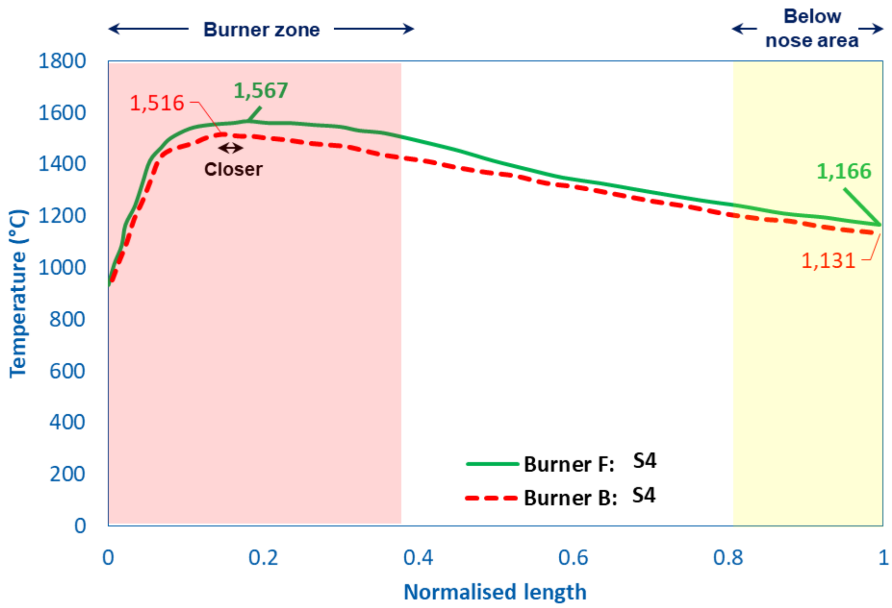
5.5 Case 4: 80 % B2, 20 % S4

The percentage of S4 coal was increased from 10 % in Case 3 to 20 % in Case 4. In Case 4, the optimal burner-S4 coal type configuration for generating the longest coal residence time is when S4 coal is used at burner elevation/row F. Despite the fact that the coal types used in Case 4 are the same as in Case 3, there is a difference in the selection of burner-S4 coal that can deliver the maximum coal residence time, where Case 3 predicted burner row C and Case 4 predicted burner row F. Nonetheless, both of these burners are located at the bottom, demonstrating the capacity of the bottom burner to improve hydrodynamic performance when sub-bituminous coal was introduced into the stated burner.

It has been reported that the higher the rank of coal, the greater the amount of purities and the greater the density of the coal [23]. As a result, S4 coal, which is a sub-bituminous rank coal, has a lower density than B2 coal, which is a bituminous rank coal. Due to the disruption of high density coal (bituminous) at the upper burners, the injection of lower density coal (sub-bituminous) at the bottom burner has been postulated to reduce its tendency to escape faster out of the furnace. As a result, the coal residence time will be substantially longer, allowing for more thorough coal combustion.
Similar to previous cases, combustion simulations were performed for two scenarios: the Burner F: S4 case (longest coal residence time) and the Burner B: S4 case (shortest coal residence time). The temperature profiles from these two situations are compared in Figure 8.



(a)



(b)

Fig. 8. Temperature profile predicted for Case 4 based on (a) qualitative and (b) quantitative data

As seen in Figure 8, the temperature profiles for Burner F: S4 and Burner B: S4 are nearly identical. However, in terms of overall temperature magnitude, Burner F: S4 is predicted to generate a higher temperature than Burner B: S4. However, when compared to Case 3, which used the same coal types despite the difference in proportion, the overall temperature in Case 4 is lower. This is explained by the decrease in B2 coal percentage from 90 % in Case 3 to 80 % in Case 4. B2 coal, which has a greater FC than S4 coal, predominantly adds to the overall heat content of the coal blended. As a result, reducing the amount of B2 coal will reduce the combustion temperature in the furnace.

Another interesting discovery in Figure 8 is the temperature behaviour near the end of the burner zone, which is approaching the OFA area. The gradient of the temperature profile appears to drop significantly slower in Burner F: S4 than in Burner B: S4. It is possible that the longer coal residence time in Burner F: S4 causes the char oxidation process to occur at a faster rate, as the char residence time in the furnace is significantly longer. As a result, the zone with high combustion rate appears to become broader in the furnace, as shown in Figure 8. In the case of Burner B: S4, which has a shorter coal residence time in the furnace, the coal escapes faster out of the furnace, preventing the char oxidation process from proceeding more completely.

The position of the peak temperature differs when comparing the temperature profiles from Case 3 and Case 4 in Figures 7 and 8, respectively. When compared to Case 3, the peak temperature appears to be further downstream in the burner zone in Case 4. This is owing to the increased combustibility caused by the increased amount of S4 coal in Case 4, which has a relatively high VM. As previously discussed, significant volatile release from sub-bituminous coal (S4) during the devolatilisation stage enhances the combustibility of bituminous coal (B2), which has a lower VM despite having a higher GCV. Hence, the larger percentage of S4 coal in Case 4 produces more VM, which increases the devolatilisation rate and the overall char oxidation process, allowing for a shorter time to reach peak flame temperature in the furnace.

6. Conclusions

The optimisation of in-furnace coal blending for one of Malaysia's opposed-firing utility boilers was numerically executed on the basis of hydrodynamics and combustion characteristics. The predicted FEGT from the numerical model was validated against the actual FEGT from the coal-fired power plant where the current boiler is situated, demonstrating a difference of less than 10 %. As a result of the validation, the current numerical model has the potential to be a reliable and cost-effective tool for examining the combustion properties of coal blends in an actual power plant boiler.

In order to move forward with the numerical simulation of in-furnace blending, the one hundred (100) different coal blends that were investigated by taking advantage of the coal's additive qualities were reduced into only four (4) coal blended cases based on the information of accept and reject criteria of the coal characteristics from the power plant under study. In the aforesaid four (4) coal blended scenarios, four (4) coal types were used, including the bituminous coals B1 and B2 and the sub-bituminous coals S3 and S4. The current research provided the following key findings based on the four (4) coal blended cases that were numerically tested:

i. The hydrodynamic performance of the coal blend particles is expected to improve significantly when sub-bituminous coal is introduced at the bottom burner rather than the upper burner. The density of coal has been discovered to play a significant role in hydrodynamic performance, with the injection of lower density coal (sub-bituminous) at the bottom burner being postulated to reduce its tendency to escape faster out of the furnace due to the disruption of high density coal (bituminous) at the upper burners. As a result, the coal residence time will be significantly longer, allowing for more thorough coal combustion.
ii. It has been predicted that injecting sub-bituminous coal, particularly at bottom burners, will increase the combustion rate of bituminous coal. The higher VM of sub-bituminous coal in comparison to bituminous coal has been postulated to release a significant amount of volatiles during the devolatilisation stage, improving the combustibility of bituminous coal. The shorter time required for volatile combustion from sub-bituminous coals aids in the acceleration of volatile and char combustion from bituminous coals. Furthermore, increased oxygen release from sub-bituminous coal volatiles can aggravate the gas-solid heterogeneous reaction during bituminous coal char combustion. As a result, the synergistic effect of kinetics from sub-bituminous and bituminous coals contributes to an increase in the combustion rate of coal blends.
iii. Because of the high-temperature condition in the bottom burner, the bottom location of the burner that used sub-bituminous coal has been found to promote the overall combustion rate since it allows for a faster rate of volatiles release and char combustion to occur. Overall, when the combustibility increases, the peak temperature position moves downstream, lowering the risk of delayed combustion and, as a result, the possibility of heat exchanger pendant failure and ash deposition.
iv. In a furnace with a relatively long coal residence time, a considerable fraction (>20 percent) of high GCV sub-bituminous coal (>5800 kcal/kg) is predicted to produce two peak flame temperatures exceeding 1600°C. Owing to the likelihood of enhanced char (FC) from the high GCV sub-bituminous coal, the presence of secondary peak flame temperature near the OFA zone has been expected. As a result of the increased char (FC), residual char has been hypothesised to escape from the first zone high combustion

reaction (first peak temperature) and engage in secondary combustion reaction (second peak temperature) with excess oxidiser from OFA and flue gas.

v. Therefore, in the case of a coal blend containing bituminous and high GCV sub-bituminous coal, a furnace condition with a comparatively shorter coal residence time may aid in the rapid evacuation of residual char from the combustion/burner zone. As a result, because the char escapes faster, the residual char combustion that passes through the OFA does not have enough time to complete its process, minimising the potential for delayed combustion near the OFA zone. Nonetheless, residual char escape may add to the emission problem due to the discharge of significant unburned carbon.

vi. Based on the CFD results, it was discovered that the compatibility of the coal types is the principal reason of the modest fluctuation in the temperature profile between furnaces with the highest and lowest coal residence time. Even if major coal qualities like GCV, FC, and VM are additive, whereas flame stability is not, the impact of coal characteristics on the generated flame can still be correlated.

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