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Oil Palm Wastes Co-firing in an Opposed Firing 500 MW Utility Boiler: A Numerical Analysis

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ABSTRACT

Malaysia is rich in palm oil plantations, where oil palm wastes (OPWs) are one of the readily accessible biomass resources. OPWs has the potential to be used as a fuel for electricity generation. Hence, the evaluation of OPWs co-firing for one of Malaysia's 500 MW utility boilers was executed numerically. Three types of OPWs were tested including empty fruit bunches (EFB), palm kernel shell (PKS), and palm mesocarp fibres (PMF). The predicted furnace exit gas temperature (FEGT) from the numerical model was validated against the actual FEGT from the power plant where the current boiler is situated, revealing a difference of less than 10%. The nose area temperature was predicted to exceed the cap of 1200°C in OPWs co-firing cases due to higher volatile matter (VM) in OPWs than the baseline of pure coal case, leading to higher levels of volatile release. When co-firing with OPWs, the predicted unburned carbon (UBC) at the boiler's outlet is lower because OPWs-coal blends contain less fixed carbon (FC) than the pure coal blend. UBC levels were anticipated to be lower than the loss of ignition (LOI) limit in all cases, highlighting its positive impact on carbon reduction. Slightly lowered mill performance was observed as a result of the calculated OPWs fuel flow surpassing the normal operation in the power plant to make up for the low gross calorific value (GCV) of OPWs while meeting the required load from the boiler. OPWs co-firing was predicted to emit lower carbon monoxide (CO) and carbon dioxide (CO_2) than baseline coal due to lower FC. Nonetheless, higher thermal nitrogen oxides (NO_x) were predicted due to the higher flame temperature created by OPWs co-firing. Even so, it is recommended that the ash mineral composition be included in future numerical studies since the ash minerals may have an effect on the emitted NO_x.

1. Introduction

Presently, the electricity industry is responsible for about 40% of global carbon dioxide (CO_2) emissions, and electricity demand is expected to grow by more than 50% by 2040 [1-2]. Due to the huge reserves and affordability of coal, coal-fired thermal power plants produce a significant share

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of the world's primary electricity [2-6]. Since coal has a high carbon content, coal-fired thermal power plants generate more CO_2 than any other form of power generation [7-8], and they are one of the main anthropogenic CO_2 emission sources [2, 4, 9], contributing for 30.4% of global CO_2 emissions in 2018 [10]. The reduction of greenhouse gas (GHG) emissions is essential for addressing climate change triggered by global warming, and the reduction of CO_2 emissions is now a global consensus [7, 9-13]. The desire to achieve a low-carbon society is widely discussed, and coal-fired utilities are under increasing pressure to decarbonise [5].

At the United Nations Climate Change Conference (COP26), more than 40 countries pledged to abandon coal [2]. Amidst the excitement surrounding the low-carbon transition, the current global energy crisis has resulted in a renewed rush for coal, showing that the rapid shift to renewable resources may be much more challenging than expected [2]. One remedy for this issue is to progressively phase out coal to allow time for zero-carbon technology to take root [2]. As a result, decreasing carbon emissions from existing coal-fired power plants is essential for lessening the carbon apex and creating a carbon-neutral society while targeting towards zero-carbon technologies and for the supply chain to mature [9-10].

Hence, numerous strategies are being developed to decrease CO_2 emissions from the above said power plants, such as ultra-supercritical technology [10], integrated gasification combined cycle (IGCC) [10], double reheat technology [10], carbon capture and storage (CCS) [10], oxy-fuel combustion [7], carbon capture and storage [7], and the use of low-carbon/carbon-neutral fuels [10-11]. When it comes to the use of low-carbon/carbon-neutral fuels, hydrogen is anticipated to play a significant part in the future formation of a low-carbon society [9, 11-13, 15]. Nevertheless, due to its high volatility [11], hydrogen storage and transportation remain complicated [13, 16]. Biomass and biogas are also alluring carbon-neutral fuels for co-firing [5, 14], but seasonal fluctuations in feedstock supply pose major challenges [5].

Malaysia has an advantage in this regard due to the abundance of palm oil plantations [17], where oil palm wastes (OPWs) are one of the readily accessible biomass resources [6, 18]. Solid waste from palm oil plantations, such as empty fruit bunches (EFB), palm kernel shell (PKS), and palm mesocarp fibres (PMF), has the potential to be used as a fuel to generate electricity [6, 18]. The use of OPWs in a coal-fired power plant can significantly reduce GHG emissions [6]. Furthermore, using OPWs as fuel in coal-fired power plants could mitigate one of the negative effects of palm oil plantations, which is the massive production of agricultural waste [6, 19]. Plus, the majority of newly built coal-fired power plants in some European countries, Japan, and China are largely co-fired, with biomass accounting for 10%-20% of calorie output [6]. Therefore, with efficient planning of the OPWs supply chain to achieve the co-firing scales required [6], there will be a significant business opportunity for OPWs co-firing.

However, a few co-firing repercussions must be identified and clearly understood in terms of OPWs co-firing suitability in existing coal-fired power plants. Nowadays, to remain economically viable, coal-fired power plants must overcome the challenge of non-design, low-quality coal usage, which incurs major operational issues such as greater water wall slagging and high temperature corrosion [20]. Therefore, OPWs co-firing may result in unexpected and undesirable problems with boiler operation, efficiency, corrosion, erosion, flame stability, slagging, fouling, heat adsorption in the furnace, and so on [21].

In coal-fired power plants, the co-firing technique involves injecting different types of solid fuels into the boiler from a different burner with no prior mixing. Since it is challenging to transport and disseminate two solid fuels separately to bunkers, this method is not widely employed in power plants [21]. Nonetheless, co-firing has shown greater ability to manage co-firing adjustment between two or more different types of solid fuels [22]. However, the majority of solid fuels blending research has focused on the combustion characteristics of the out-furnace blending strategy, in which various types of solid fuels were pre-mixed before entering the boiler [23]. Hence, there is a need to evaluate co-firing strategy since most research has focused on the combustion aspects of the out-furnace blending procedure, and the underlying combustion mechanisms resulting from the OPWs co-firing strategy are still vaguely defined and limited to academic studies [6, 24].

Coal is a heterogeneous substance with varying qualities such as rank, maceral content, and impurities [23]. As a result, constructing an ideal methodology for predicting the combustion behaviour of coals and OPWs co-firing is challenging [23]. It has been established that fuel composition characteristics (proximate and ultimate analysis data, heating value, etc.) remain additive after blending, whereas many combustion characteristics are non-additive [23-24]. That is, they have both reactive and unreactive consequences [23-24]. Additivity, for example, cannot predict ignition, flame stability, slagging, fouling, and nitrogen oxides (NO_x) emissions [23-24]. Experimental techniques were used to assess the combustion performance of various types of solid fuel blends used in pulverised coal-fired boilers [24]. Several empirical indices based on volatile matter constituents, fuel ratios, and maceral compositions were also built from the experimental results in order to empirically predict the slagging, fouling, ignitability, flame stability, and burning of coal-OPWs [25].

Another approach that has the potential to be a dependable and cost-effective strategy in the investigation of OPWs co-firing is numerical modelling (computational fluid dynamics). Numerical modelling has been shown to be an effective technique for diagnosing and resolving flow and combustion issues [24, 26-31]. As it can provide insights into the combustion properties of unfamiliar solid fuel blends [6, 24], such as OPWs co-firing, it has been widely used to examine the combustion performance of a single coal and multiple solid fuel blends in bench-pilots and full-scale utility furnaces. Lee *et al.* [24] simulated combustion and flow for a variety of solid fuel blends, and the numerical modelling was validated using experimental data from a drop-tube furnace. They revealed that the combinatorial impact is caused by particle temperature and volatile matter interactions between individual solid fuels, and the modelling offers an effective strategy for the implementation of multiple solid fuel blends.

Aziz *et al.* [6] implemented the OPWs co-firing with coal in a utility coal-fired boiler model, using PKS as the OPW type. While the assessment has provided significant findings on the predicted co-firing behaviour in the aspects of emissions and thermal behaviour, the validation aspect of the said assessment is vague with no actual power plant operational data involved. In broad sense, the combustion characteristics, heating surface temperatures, and flue gas components from pilot-scale tests differ from actual power plant data [32-33], and the said operating data differs even between power plants. Pilot-scale test data is frequently obtained from shorter test durations, which differs from the real operating procedure in power plants, in continuous mode of operation and longer combustion period. As a result, creating numerical models based on data from pilot-scale experiments will not provide a comprehensive insight of actual OPWs co-firing in a utility boiler.

To create a credible OPWs co-firing numerical model, extensive data collection activities at the actual coal-fired utility boiler, as well as numerical procedures that closely follow the actual coal-fired utility boiler operations, are highly desired. Another reason for using actual data is the complicated geometry of coal-fired utility boilers, which affects the solid phase flow behaviour and alters particle movement and fluid dynamics within the boiler [34]. Particle and flow dynamics have a large impact on the subsequent thermal behaviour [34].

To address the stated gaps, the present study collects relevant power plant data from one of Malaysia's 500 MW opposed-fired coal-fired power plants, allowing the actual plant data to be appropriately defined and transformed into a reliable OPWs co-firing numerical model. The validation was carried out using a single coal case as a baseline. The numerical model used in this research was integrated with the solid fuel combustion model, which included the kinetics of devolatilisation, char conversion/reaction, and volatiles reactions. The current study employed three types of OPWs including EFB, PKS, and PMF. The primary objective of the current research is to gain fundamental insights into the operational impacts of various types of OPWs co-firing in a utility boiler.

2. Physical Setup

The three-dimensional (3D) configuration of a coal-fired boiler as shown in Figure 1 was created using as-built dimensions from the actual coal-fired power plant under consideration. The boiler has a wall-firing design with 36 coal burners that are also the primary air (PA) inlets, with 36 secondary air (SA) inlets circumferentially positioned at each burner-PA inlet to enable better mixing of the incoming coal and air, as well as to provide a dry low NO_x region closer to the burner area where the incoming SA creates a recirculation zone for the incoming coal and air [35-36]. Each side of a boiler (front and rear walls) has each 18 burner-PA inlets and 18 SA inlets located at three different heights at a burner zone due to the wall-firing layout. To reduce computational costs, the tube bundles of superheaters and reheaters were simplified to a few thin walls [35-36]. The accuracy of computational works considered, heat transfer models' implementation to thin walls to replicate the heat transport process between the flue gas and the steam within the heat exchanger bundles. The heat transfer modelling on the heat exchanger bundles is done in the same way as Yang *et al.* [37].

The over-fire air (OFA) inlets are positioned between the burner zone and the heat exchanger bundles, and they are made up of six inlets at the front and rear walls with the same elevation height. The computational model and boundary names used on the boiler are depicted in Figure 1. Mills 1-6, as shown in Figure 1, supply coal and PA for each burner-PA inlet elevation (A to F).

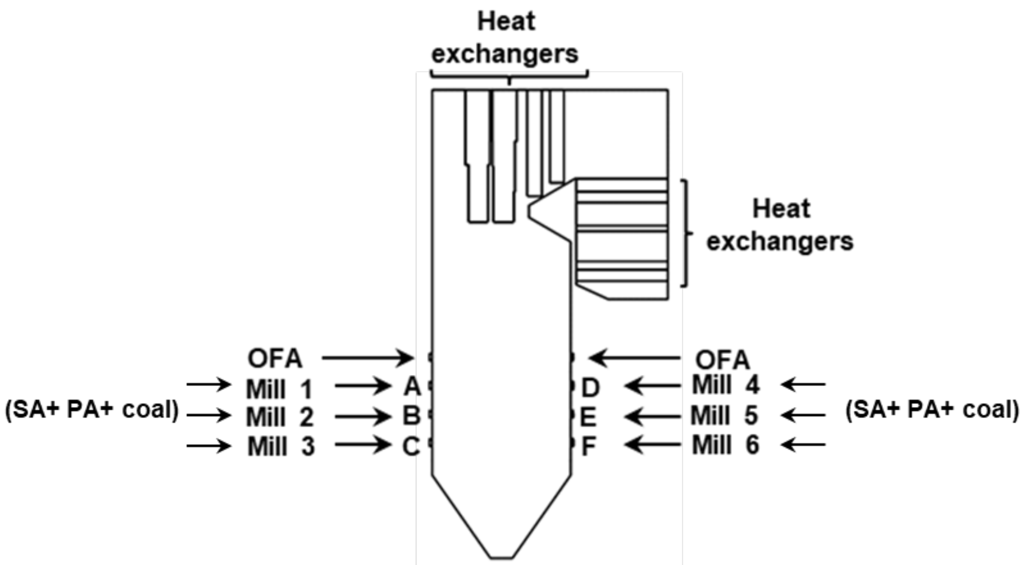

Fig. 1. Computational model of the boiler

In a common utility coal-fired boiler framework, the coal-fired boiler integrates the piping structure and the furnace as one system, with all mills connected to discharge pipes that deliver coal particles and PA into the boiler [35-36]. However, in order to save computational costs, the piping structure is not part of the computational domain for this study. Fuel oil (FO) inlets are not considered as one of the flow inlet boundaries in this study because the FO is frequently used during the furnace's startup phase. The current study is a steadily simulated reacting flow assessment in which combustion is assumed 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 solid fuel combustion used in this research work are similar to those demonstrated in our previous research [35-36]. The chemical kinetics and combustion models used in this study account for the three main stages of solid fuel combustion: devolatilisation, char conversion/reaction, and volatiles reactions. The volatile composition and rate constants for solid fuel devolatilisation were predicted using the advanced solid fuel network model and ascertained using the historical solid fuel database from our own analytical laboratory. The governing equations were discretised using the finite volume technique (steady state and compressible). ANSYS Fluent V.19 R1 was employed for all setup and numerical processing. A pressure-based solver was used to solve the governing equations. To resolve the pressure-velocity coupling, the Semi-Implicit Method for Pressure Linked Equations (SIMPLE) technique was used. Ferziger *et al.* [38] go into great detail about the SIMPLE algorithm's constants and formulations. To address the radiative heat transfer from the reacting flow, the Discrete Ordinates (DO) model was used. To resolve turbulent flow, the Shear Stress Transport (SST) k - w model was utilised, which has been shown to provide good convergence and accuracy in reacting flow simulations [39].

Sieve analysis was performed on coal samples taken from the actual power plant under study to determine the size fraction of coal particles. The size fraction was used to translate the range of coal fineness into the Rosin Rammler distribution, and the Rosin Rammler distribution curve fit coefficients were introduced into the numerical code to reflect the variation of coal fineness from the power plant under study. The fineness of the coal ranged between 75µm and 300µm, and all solid fuel particles were tracked with a Lagrangian system that accounted for turbulent dispersion for 80,000 particles. It is a well-known fact that the pulverised biomass will have larger particle sizes after passing through the conventional coal-fired utility pulverised mill due to the difference in density, Hardgrove Grindability Index (HGI), and terminal velocity [40]. The fineness of OPWs is therefore assumed to be in the range of 75µm for this research, as required by the power plant. The impact of HGI is excluded in this co-firing research and will be investigated further in the future.

A post-processing method was used to simulate NO_x production. To begin, combustion simulations were used to derive temperature, major gas composition, and velocity distributions. The reactions of thermal NO_x and NO_x reduction by char were then incorporated based on the combustion computation. Only NO_x-related species were computed, but flow, turbulence, other major gas compositions such as oxygen, CO_2, carbon monoxide (CO), and hydrogen, energy, as well as radiation equations were not solved.

The bituminous coal was chosen for this study because the current boiler was designed to only burn bituminous coal. Table 1 displays the properties of the solid fuels (coal and OPWs) used in the simulations. The said bituminous coal was used by the power plant while it was operating, and it was collected in a small sample and subjected to extensive analytical fuel testing to determine its coal properties. The properties of OPWs were provided by one of Malaysia's major OPW suppliers. These solid fuel characteristics (shown in Table 1) are part of the numerical study's boundary conditions. Table 2 depicts the four (4) solid fuel co-firing scenarios used in the simulation. The OPWs co-firing ratios were determined based on a calorific percentage (cal. %).

Table 1
Solid fuel types and characteristics

Solid fuel	Proximate analysis, wt. %, dry basis (db) (VM-Volatile matter, FC-Fixed carbon, AC-Ash content)			Ultimate analysis, wt. %, db (C-Carbon, H-Hydrogen, N-Nitrogen, O-Oxygen, S-Sulphur)					GCV- Gross Calorific Value, db (kcal/kg)
	VM	FC	AC	C	H	N	O	S	
Coal (B1)	25.4	59.5	15.1	73.68	4.53	1.65	4.57	0.50	6678
EFB	78.5	17.3	4.3	44.07	5.52	0.41	45.73	0.46	5067
PKS	80.9	16.8	2.4	49.13	5.42	0.48	42.45	0.41	4852
PMF	79.8	14.9	5.4	45.51	5.03	0.54	43.61	0.42	4876

Table 2
Co-firing cases

Case	Fuel type for the burner row						Capacity (MW)
	A (20 cal.%)	B (20.cal%)	C (20.cal%)	D (20.cal%)	E (20.cal%)	F (20.cal%)	
Baseline	B1	B1	B1	Standby	B1	B1	500
B1-EFB	EFB	B1	B1		B1	B1	
B1-PKS	PKS	B1	B1		B1	B1	
B1-PMF	PMF	B1	B1		B1	B1	

According to Tables 1 and 2, coal B1 is bituminous, whereas EFB, PKS, and PMF are OPWs. The baseline scenario involves no co-firing (100% coal B1). The validation with actual plant data was carried out based on the CFD results from the aforementioned baseline case. This is because the baseline case, or 100% coal B1, has been used frequently in the power plant under study, and a large amount of plant data from this firing can be utilised to validate the baseline case. Therefore, the power plant operating condition during the firing of coal B1 was properly captured by the power plant sensor and transferred as the boundary conditions of the current numerical analysis. Mills 1-6 deliver coal and PA for each burner-PA inlet elevation, as shown in Table 3. Mill 4 emits no coal flow at the burner elevation D because it was used as a standby burner.

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)	0.00
Mill 5 coal flow (t/h)	39.45
Mill 6 coal flow (t/h)	39.45
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 assure that the spatial convergence accuracy is sufficient, the grid independent test is performed. Meshes (elements) are built with orthogonal quality and skewness in mind to reflect mesh attributes that influence the level of spatial discretisation errors [35-36]. To ensure that acceptable mesh qualities could be constructed, the orthogonal and skewness features of all generated meshes in the grid independent test were controlled. When the mesh number exceeds 1.89 million, the velocity and temperature profiles in the furnace's centre nearly stop changing. Figure 2 depicts the mesh model.

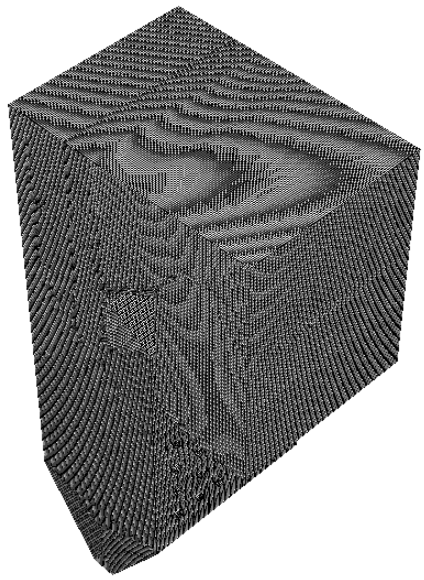

Fig. 2. Mesh model of the boiler (isometric view)

After determining the independent mesh number, a model validation exercise was performed, which involved comparing the predicted furnace exit gas temperature (FEGT) result from the current model to the actual FEGT from the power plant under study. The predicted FEGT value is based on the average temperature in a plane slightly below the nose area of the furnace (below the tube bundles of superheaters and reheaters). The FEGT results from the CFD model and the actual power plant are shown in Table 4. Table 4 shows that the overall CFD model predicted results were within 10% of the actual FEGT. As a result, the current numerical model's reliability was determined to be acceptable based on the FEGT validation results.

Table 4
Validation based on FEGT results

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

5. Results and Discussion
5.1 Temperature Results

Figure 3 depicts the predicted temperature contour of the boiler model as well as the nose area temperature for each case. Since OPWs have a higher VM than baseline coal, the high combustion temperature zones in the boiler with OPWs co-firing are much larger than in the boiler with pure coal firing. Previous research has shown that the VM plays an important role in the early combustion phenomenon and the oxidation of large amounts of volatiles [17, 36].

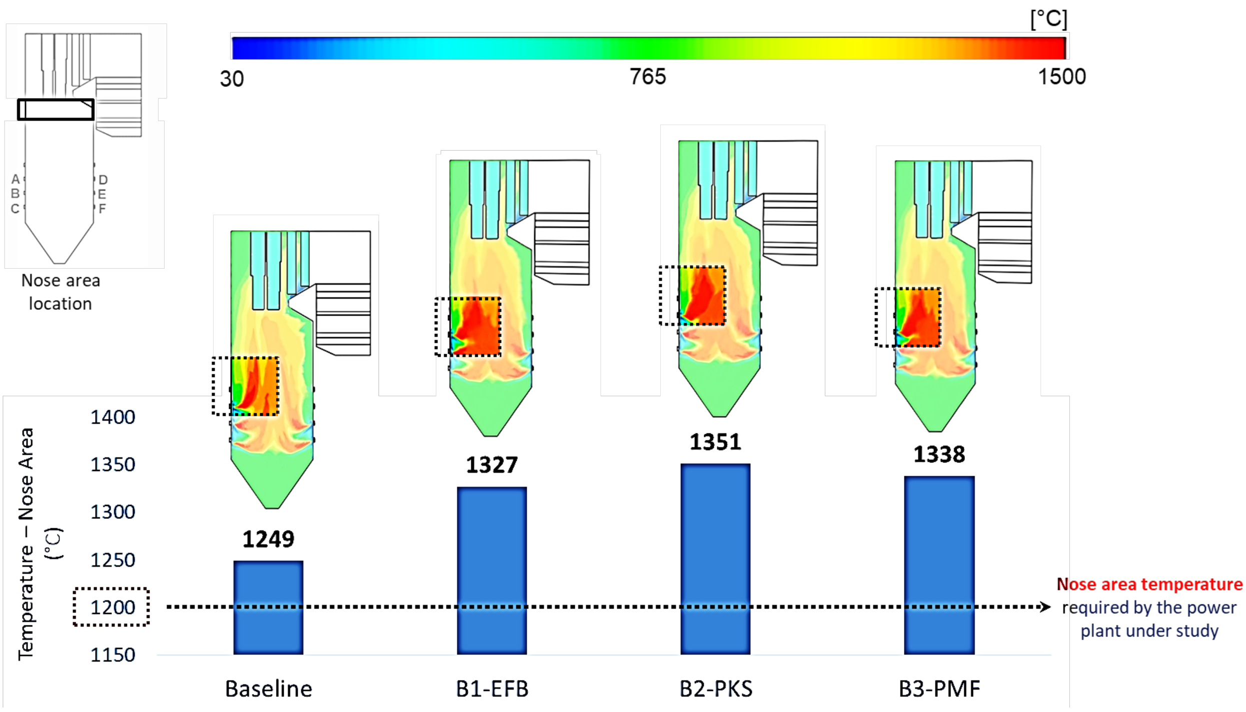

Fig. 3. Predicted temperature results within the boiler model

The predicted nose area temperature, which exceeded 1200°C in all OPWs co-firing cases, is the highlight of these findings. The power plant under consideration requires an approximately 1200°C at the nose area region to avoid ash deposition occurrences, with the nose area temperature not exceeding the initial deformation temperature (IDT) of the solid fuel blends. As previously stated, the power plant under study was intended to burn primarily bituminous coals, a low VM solid fuel [36]. As a result, the boiler configuration and operating conditions were primarily designed to ensure that bituminous coals could be fired while maintaining a nose area of roughly 1200°C.

Co-firing OPWs fuel, which has a high VM, could change the kinetics time scale of devolatilisation, which is already known to be shorter than the time scale of successive char combustion [36]. The synergistic impact of coal and OPW kinetics aids in raising the combustion rate of solid fuel blends,B1 coal, which has prospered from OPW's higher combustibility, proceeds to have a greater rate of volatile release and char combustion.

5.2 Unburned Carbon (UBC) Results

Excessive UBC in fly ash is undesirable from the standpoint of power plant operation. It represents a noticeable fuel loss, lowering overall plant efficiency [41]. The concrete industry is the largest market for fly ash (additive for cement) [41]. According to ASTM standard 618, one of the criteria for such an application is that the UBC or loss on ignition (LOI) limit must be less than 6% [41]. Therefore, power plant places a lot of importance on UBC amount because it affects their profits. UBC levels above the LOI limit reduced plant efficiency, and fly ash could not be sold to the concrete industry. As seen in Table 5, the predicted UBC levels at the boiler's outlet are reduced when co-firing with OPWs because the OPWs-coal blends contain less FC than the pure coal blend.

Table 5
Predicted UBC levels

Case	CFD (%)	LOI limit (%)
Baseline	3.52	
B1-EFB	2.03	<6
B1-PKS	1.97	
B1-PMF	1.94	

5.3 OPWs Fuel Flow and Mill Capacity

In order to achieve the required load from the boiler, the fuel flow into the boiler was primarily determined by its calorific output. The required load for this utility boiler is 500 MW. As shown in Figure 1, the pulverised solid fuel will be transported from the mill to the boiler. Table 2 shows that in all OPWs co-firing cases, 20 cal.% of the OPWs will be injected into the boiler, accounting for the usage of one mill (in this case Mill 1/burner row A). Figure 4 depicts the calculated OPWs fuel flow for each OPWs co-firing case.

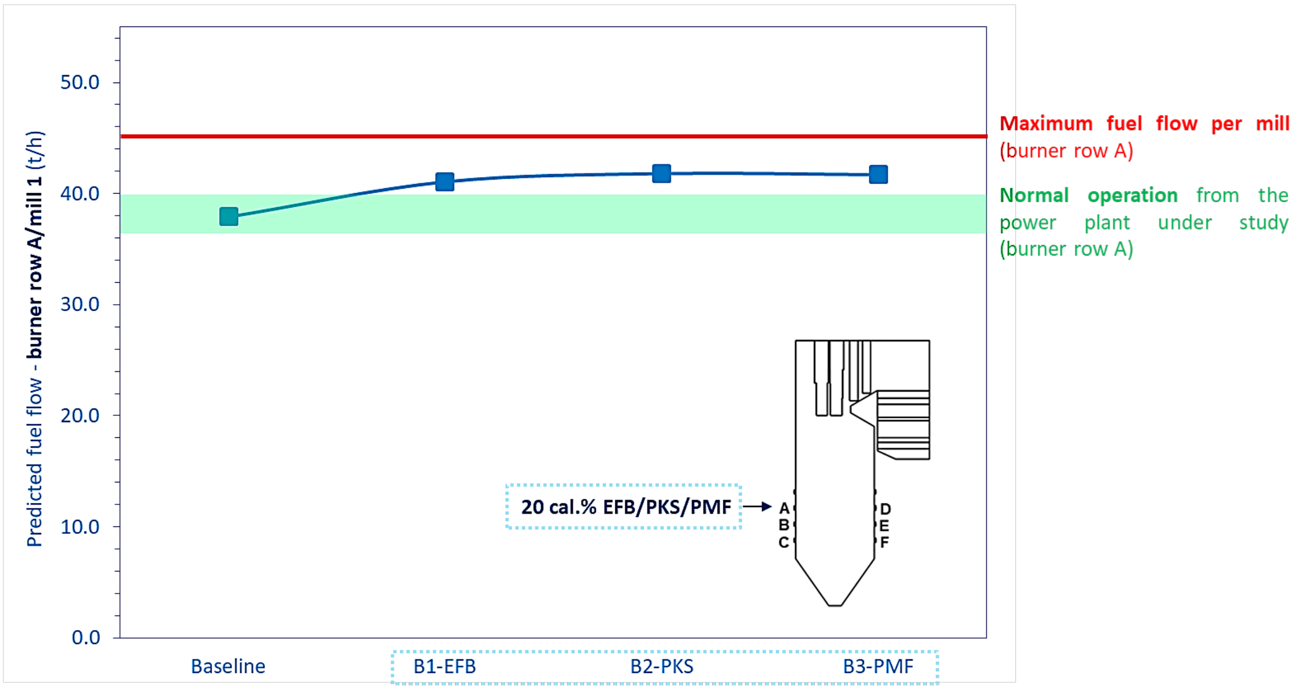

Fig. 4. Calculated OPWs fuel flow per mill (burner row A)

Figure 4 shows that the OPWs fuel flow is slightly higher than the normal operation of the power plant under consideration. This is due to OPWs having a lower GCV than B1 coal, as shown in Table 1. As seen in the baseline case (pure coal firing), the fuel flow at burner row A is within normal operation due to the use of B1 coal at burner row A. The slight increase in OPWs fuel flow corresponds to lower GCV of OPWs when compared to B1 coal. As a result, a higher OPWs fuel flow is required to achieve the utility boiler's required load. Nonetheless, as shown by the red line in Figure 4, the predicted OPWs fuel flow is still lower than the maximum allowable fuel flow per mill.

5.4 Predicted CO, CO_2, and NO_x

Tables 6, 7, and 9 show the predicted CO_2, CO, and NO_x at the boiler's outlet, respectively. OPWs have lower FC than coal, resulting in lower CO and CO_2 emissions when coal is co-fired with OPWs. However, because ash mineral compositions are not taken into account, even though OPWs contain less N than the baseline coal, OPWs co-firing cases are expected to produce more NO_x than the baseline coal due to the higher flame temperature generated, which results in an increase in thermal NO_x, as stated in the Zeldovich mechanism [6]. Except for the predicted NO_x, the predicted CO emissions do not exceed the specified emission limit required by the power plant under study.

Table 6
Predicted CO levels

Case	CFD (mg/m^3)	Limit (mg/m^3)
Baseline	197.35	<200
B1-EFB	149.41	
B1-PKS	147.86	
B1-PMF	147.11	

Table 7
Predicted CO_2 levels

Case	CFD (%)	Limit (%)
Baseline	14.05	N/A
B1-EFB	9.53	
B1-PKS	8.82	
B1-PMF	8.45	

Table 8
Predicted NO_x levels

Case	CFD (mg/m^3)	Limit (mg/m^3)
Baseline	574	<600
B1-EFB	671	
B1-PKS	695	
B1-PMF	673	

6. Conclusions and Recommendations

The assessment of OPWs co-firing for one of Malaysia's 500 MW utility boilers was numerically carried out. Three types of OPWs tested including EFB, PKS, and PMF. The predicted FEGT from the numerical model was validated against the actual FEGT from the coal-fired power plant where the current boiler is located, revealing a discrepancy of less than 10%. As a result of the validation, the numerical model has the capability to be a reliable and cost-effective tool for analysing the combustion performance of multiple solid fuel blends in an actual power plant boiler. The current study yielded the following key findings based on numerically tested OPWs co-firing cases:

- The nose area temperature was anticipated to exceed the cap of 1200°C in OPWs co-firing cases due to the higher VM in OPWs than the baseline pure coal case, resulting in a higher rate of volatile release. It is suggested to co-fire OPWs in a boiler designed to burn sub-bituminous coal rather than the bituminous-fuelled boiler used in this study because the VM and FC of OPWs are more comparable with common sub-bituminous coals.
- When co-firing with OPWs, the predicted UBC levels at the boiler's outlet are lower because OPWs-coal blends contain less FC than pure coal blends. Furthermore, UBC levels are expected to be lower than the LOI limit in all cases, demonstrating its positive impact in terms of carbon reduction.
- Slightly reduced mill performance was discovered as a result of the calculated OPWs fuel flow exceeding the normal operation in the power plant under study to compensate for the low GCV of OPWs while achieving the required load from the boiler. As a result of the potential increase in fuel consumption caused by OPW's low calorific value, the cost of operating the power plant that used OPWs co-firing may be higher.
- OPWs co-firing is expected to emit less CO and CO_2 than baseline coal due to lower FC. Nonetheless, higher thermal NO_x was predicted due to the higher flame temperature generated by OPWs co-firing. However, it is recommended that the ash mineral compositions to be included in future numerical studies because the ash minerals may influence the emitted NO_x.

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