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A Numerical Model for Ash Deposition Based on Actual Operating Conditions of a 700 MW Coal-Fired Power Plant: Validation Feedback Loop via Structural Similarity Indexes (SSIMs)

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ABSTRACT

The combustion of coals will result in significant ash-related issues, which will ultimately lead to the efficiency loss of coal-fired utility boilers. While there have been numerous attempts to predict ash deposition dynamics using numerical approaches, the majority of these models were constructed using experimental data from pilot-scale furnaces and without integration with combustion models. Therefore, the current study collects meaningful power plant data from ash sampling activities at one of Malaysia's 700 MW sub-critical coal-fired power plants, enabling the ash deposition behavior in a real coal-fired utility boiler to be adequately captured and converted into a reliable ash deposition numerical model. The validation feedback loop of the ash deposition model was run using in-situ measurement data (ash sampling picture) and the actual power plant operating conditions during the ash sampling activities. The image processing algorithm was used to determine the degree of similarity between the actual ash sampling image and the predicted ash deposition image from the numerical model. Prior to the validation feedback loop, the overall numerical model (solver, combustion, turbulence, radiation) was successfully validated with the FEGT from the actual power plant, revealing a difference of less than 5 %. The current study found that the baseline ash deposition model (created from experimental data) underestimates the quantity of ash deposition gathered. The validation feedback loop of the baseline ash deposition model successfully established a new set of impaction efficiency constants, which increased the similarity of the images between the actual and predicted ash depositions. The current study's drawback, however, is mostly in the validation basis, which is largely qualitative in nature. Although the Structural Similarity Index (SSIM) value is useful for comparing the similarity of images between actual and predicted ash depositions, a more quantitative measurement that can provide extra meaningful data points and higher accuracy on the deposited ash is preferable. However, based on this modified version of the ash deposition model, the agreement is found to be satisfactory in terms of gaining a rudimentary insight of the ash deposition behavior in a coal-fired boiler.

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1. Introduction

Coal is an important energy source in Malaysia, accounting for over 20 % of the country's total energy supply as of 2019 [1]. The burning of coals, however, will result in major ash-related concerns such as erosion, corrosion, slagging, and fouling, which will eventually lead to a loss in the efficiency of the coal-fired utility boiler, potentially resulting in an unplanned shutdown [2]. Despite modifications in coal-fired boiler design to raise boiler capacity and the use of routine soot blowing systems to mitigate the consequences of slagging and fouling, unforeseen issues still take place at various locations in which the cleaning system is unreachable or the bonding between the deposits and the walls is too powerful for the cleaning system to be efficient [2]. Furthermore, the issue of ash deposition complicates combustion tuning processes in coal-fired power plants [3]. The ash deposition behavior, which is dependent on the manner of occurrence and the composition of inorganics, is critical in boiler design and coal type selection [2].

There have been various endeavours to comprehend the ash deposition mechanisms and forecast the ash deposition behavior during the coal-fired combustion process. Traditional approaches, like ash viscosity, ash fusibility, and slagging and fouling indices calculated from ash compositions and temperatures, are utilized to forecast ash deposition behavior [2]. Over the last few decades, numerous researchers have sought to build various numerical models employing high fidelity Computational Fluid Dynamics (CFD) approaches to address the inadequacies of conventional techniques in estimating ash deposition rates [2]. Nonetheless, only a few models have been satisfactorily developed since determining the sticking efficiency of deposit surfaces and particles, which are regulated by numerous mechanisms, is complicated [2]. Major mechanisms include thermophoresis, inertial impaction, condensation, chemical reaction, eddy diffusion, and some others [2]. As a result, various critical elements should be considered when estimating deposition behavior, such as particle impacting and sticking, particle composition and size distribution, deposit characteristics, transport mechanism, and operating conditions [2]. The incorporation of all of these important mechanisms will help provide a better understanding of the ash deposition process by providing reasonable descriptions of the ash transport, particle impacting, sticking, and growth processes [2]. The ash deposition numerical model can also extract a lot of information, such as the deposit growth rate, ash formation process, particle impaction rate and sticking propensity, particle transport and fluid dynamics, deposit structure, heat transfer through ash deposit, and the impact of deposition on operation conditions, to name a few [2].

While numerous ash deposition numerical models have been produced over the years, the majority of these models were built on the validation feedback loop using experimental data from bench and pilot-scale furnaces [2,4]. In general, the combustion circumstances, heating surface temperatures, and flue gas constituents from bench or pilot-scale tests differ from those in actual utility boilers [4,5]. The data from bench or pilot-scale tests is frequently obtained from test durations that are insufficient for persistent ash deposition, which is a long-term process [4]. As a result, developing ash deposition numerical models based on pilot-scale experiment data will not provide an in-depth understanding of actual ash deposition in a utility boiler. That being said, thorough ash sampling activities at the actual coal-fired utility boiler, as well as a validation feedback loop of the ash deposition numerical model that closely follows the actual coal-fired utility boiler operations, are highly desired in order to establish a credible ash deposition numerical model.

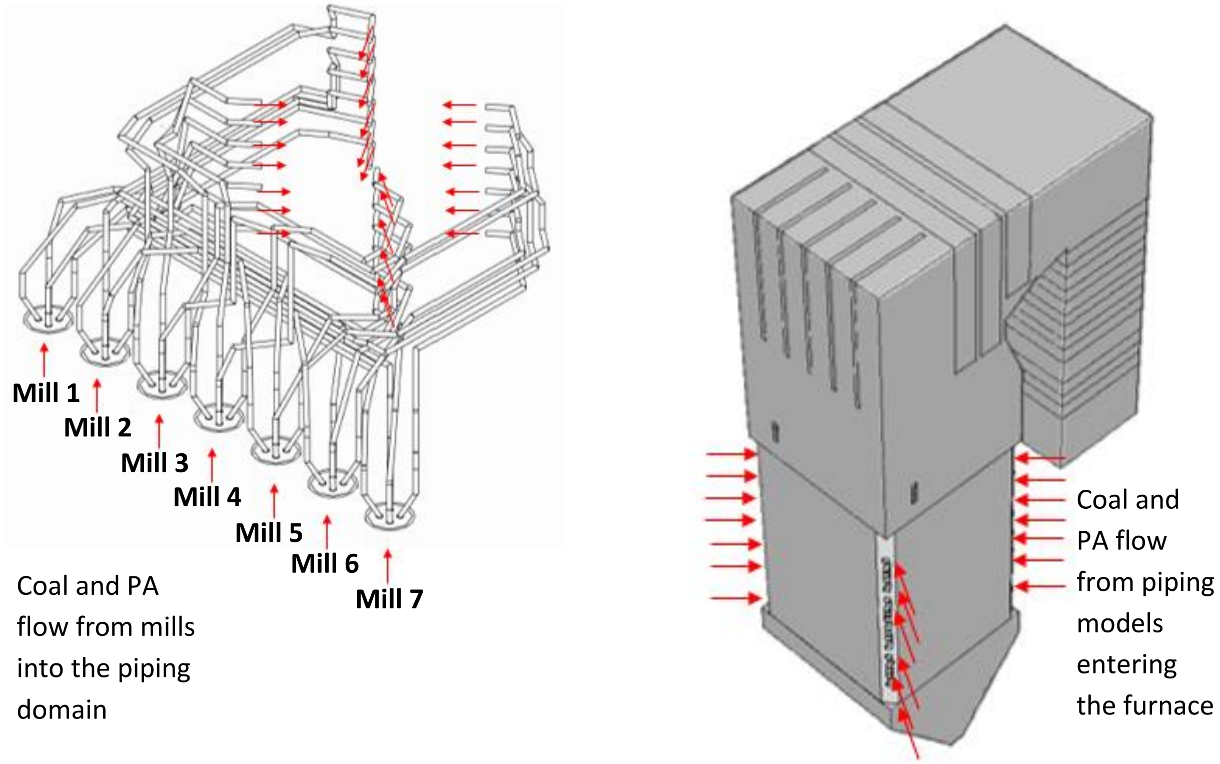
Another reason to use actual power plant data to construct the ash deposition model is the complex geometry of coal-utility boilers, which impacts the solid phase flow pattern and changes particle movement and fluid dynamics within the boiler [2]. Changes in particle and flow dynamics have a significant impact on the subsequent ash build-up and deposition rate [2]. Furthermore, the majority of ash deposition models created to date have not included any combustion or particle rebound/removal models to predict deposition behavior in actual utility boilers [2]. The ash deposition build-up process in a boiler varies with the conditions within the boiler [2]. Temperature and gas flow changes may have a major impact on ash deposition within the utility boiler system [2]. A prediction of ash deposition under different boiler operating conditions cannot be accurately portrayed without integration with combustion and particle rebound/removal models [2].

To fill the aforementioned gaps, the current study gathers meaningful power plant data from ash sampling activities in one of Malaysia's 700 MW sub-critical coal-fired power plants, so that the ash deposition behavior in a real coal-fired utility boiler can be adequately captured and converted into a reliable ash deposition numerical model. Having stated that, the current numerical analysis takes a holistic approach to develop the ash deposition numerical model based on actual coal-fired power plant data. For the ash sampling activities, in-situ measurements were carried out at the actual coal-fired power plant using the ash deposition probe (ADP). The validation feedback loop of the ash deposition numerical model was run based on in-situ measurement data (ash sampling picture) and the actual power plant operating condition during the ash sampling activities. In this first attempt to develop the said model, the image processing code is used to calculate the similarity of the ash sampling picture with the ash deposition predicted by the model, where the validation feedback loop is executed for various particle impaction efficiencies until the Structural Similarity Index (SSIM) value achieves 0.8, indicating reasonable similarity between these two pictures. The current study's ash deposition numerical model was also integrated with the combustion model, which includes the coal combustion process (coal devolatilization, char conversion/reaction, volatiles reactions) in order to establish a reliable ash deposition numerical model based on the numerical procedure that closely follows the actual power plant operating conditions.

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 700 MW coal-fired power plant under study. The computational domain of a coal-fired boiler integrates the piping system and the furnace as one whole system to account for the coal mass imbalance when the coal enters the furnace in order to appropriately follow the actual power plant operating conditions. In the actual system, each mill is linked to four outlet pipes that transfer coal particles into the furnace via burner sets. The system is set up so that each mill supplies coal to four burners situated at the same furnace elevation. Hence, the current computational domain is based on the exact geometry of a coal-fired utility boiler's piping-furnace system.

The boiler features a tangential-firing layout with a total of 28 coal burners, resulting in 28 pipes supplying primary air (PA) and coal to the furnace. To reduce computational costs, the tube bundles of superheaters and reheaters were simplified to a few thin walls, 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.



(a) (b)

Fig. 1. The computing domain of the coal-fired boiler system under study, which incorporates (a) the piping and (b) the furnace models

Figure 2 depicts the boundary names used on the furnace. Because of the tangential-firing layout, four sets of burners and oxidizer inlets are placed at each furnace's corner to create a fireball in the furnace's center. As a result, there are a total of 28 coal + PA inlets (burners) connected to the piping systems, with 7 coal + PA inlets in each corner. The secondary air (SA) contains a total of 52 inlets, with 13 in each corner. Each SA inlet is located near the coal + PA inlet to enable proper mixing of the incoming coal and air, as well as to offer 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. Fuel oil (FO) inlets are not included as one of the flow inlet boundaries in the current study because the FO is frequently used during the furnace's startup phase. The current study is a steadily simulated reacting flow analysis in which combustion is assumed to be far past the transitory period of the coal-fired furnace's start-up operation.

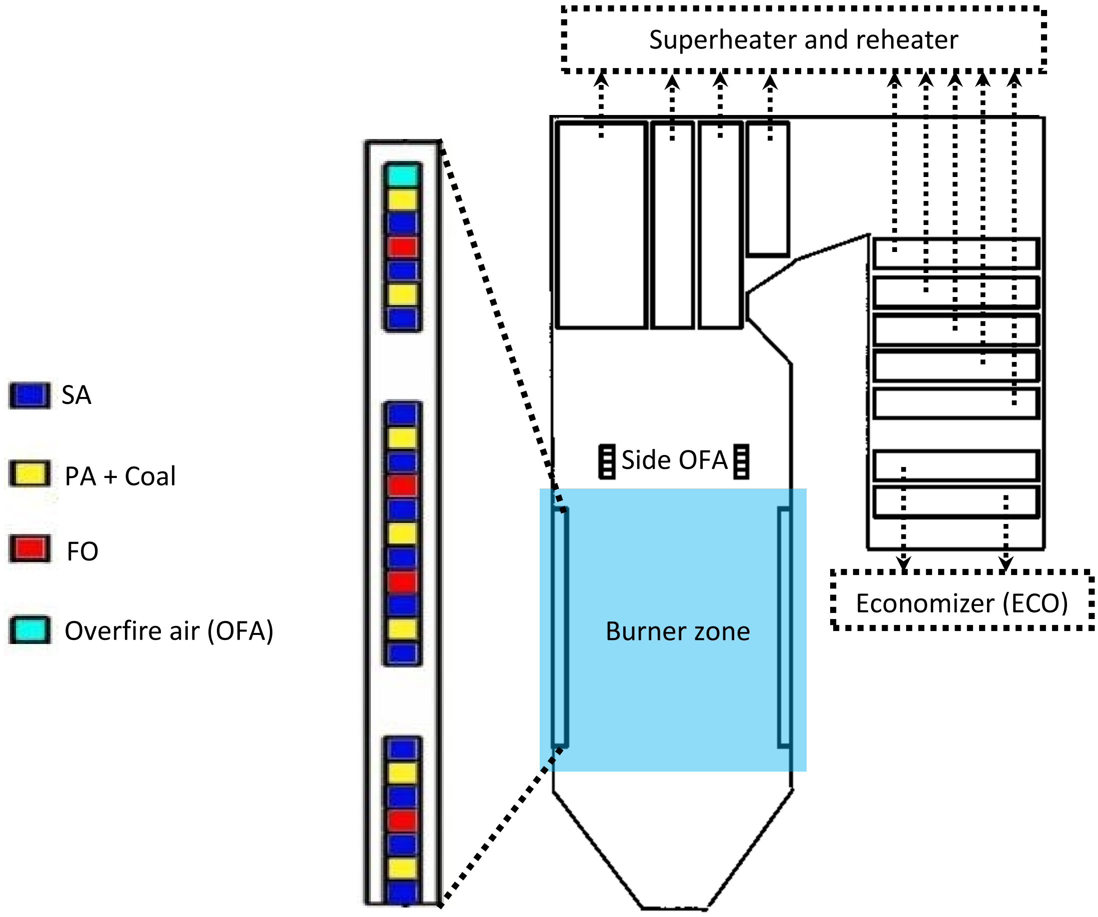


Fig. 2. Boundary inlets on the furnace domain

3. Numerical Setup

The governing equations (steady state and compressible) are discretized using the finite volume technique and a commercial CFD software, ANSYS Fluent V.19 R1. ANSYS Fluent V.19 R1 is used for all setup and numerical processing. Previous research on non-reacting and reacting flow simulations has already demonstrated ANSYS Fluent's capabilities [6-10]. The pressure-based solver is used to solve the governing equations.

To solve the pressure-velocity coupling, the Semi-Implicit Method for Pressure Linked Equations (SIMPLE) technique was used. Ferziger *et al.,* [11] explains detailed information on the constants and formulations used in the SIMPLE algorithm. To address the radiative heat transfer from the reacting flow, the Discrete Ordinates (DO) model was used. Turbulence was resolved using the Shear Stress Transport (SST) $k-w$ model, which was found to provide good convergence and accuracy in reacting flow simulations [12].

The sieve analysis was performed on coal samples taken from the actual power plant under study to measure the size fraction of coal particles. The range of coal fineness was translated into the Rosin Rammler distribution based on the size fraction, and the curve fit coefficients of the Rosin Rammler distribution were inserted into the CFD numerical code to reflect the variation of coal fineness from the power plant under study. The coal fineness ranged between 75μm and 300μm, and all coal particles were tracked using a Lagrangian scheme that took turbulent dispersion into account for 80,000 particles.

The chemical kinetics and combustion models used in the current study account for the three main stages of the coal combustion process, which are coal devolatilization, char conversion/reaction, and volatiles reactions. The composition of the volatiles and the rate constants for coal devolatilization were determined using the advanced coal network model and the coal database from our own analytical fuel laboratory. The detailed chemical reactions of the coal combustion method used in the current investigation are as shown in references [13,14].

The coal used by the power plant while it was in operation was gathered in a small sample and subjected to extensive analytical fuel testing to evaluate its coal properties. These coal properties (given in Table 1) are part of the boundary conditions for the current numerical study.

Table 1
Coal properties

Proximate analysis (%)				Ultimate analysis (%)					Calorific value (kcal/kg)
Total moisture (TM)	Volatile matter (VM)	Fixed carbon (FC)	Ash content (AC)	Carbon (C)	Hydrogen (H)	Nitrogen (N)	Oxygen (O)	Sulphur (S)	
15.5	40.3	42.5	4.4	71.7	4.5	1.2	17.3	0.4	5890

As the current study used a series of simulations based on power plant data to develop a reliable ash deposition numerical model, changes in power plant operating conditions during the 30-minute ash sampling activities were properly recorded and transferred as the boundary conditions of the current numerical analysis. Because the sensor data from the power plant under study is collected at 5-minute intervals, there are a total of six sets of operating conditions during the 30-minute ash sampling activities. Figure 3 depicts the interconnection of the plant operating conditions and the numerical procedure.

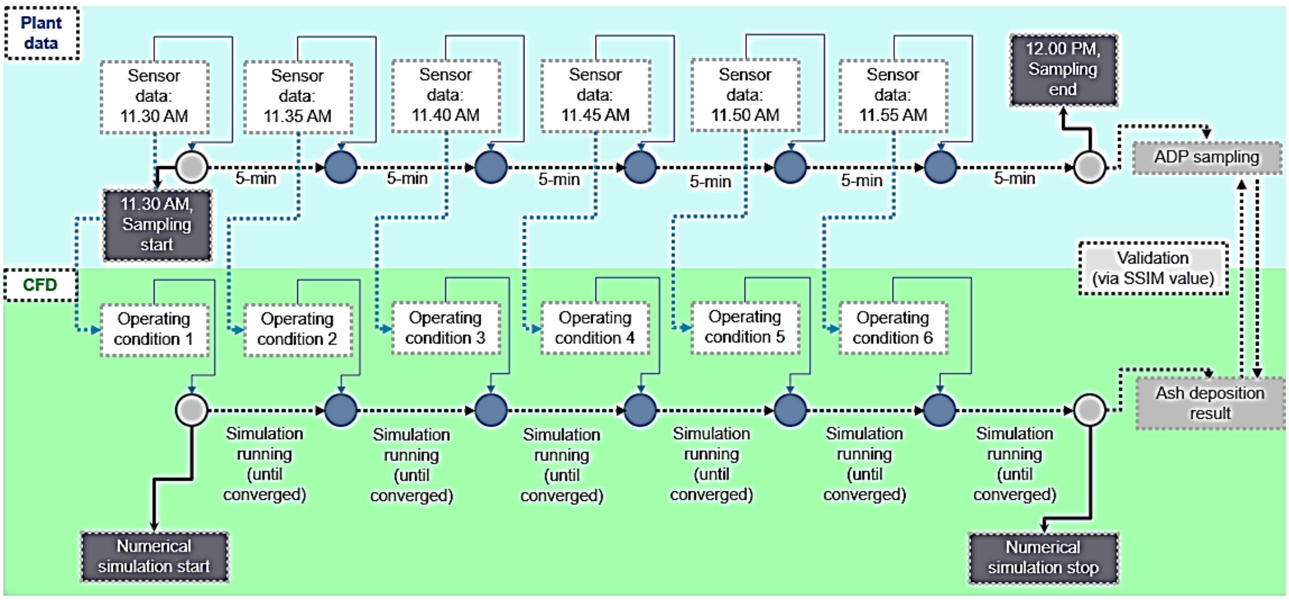


Fig. 3. Interrelationship of the plant operating conditions and the numerical procedure

As shown in Figure 3, there are six sets of operating conditions that were applied to the numerical procedure to account for the variation in operating conditions during the 30-minute ash sampling activities. Table 2 displays a list of operating conditions acquired from power plant data during ash sampling activities. All of the parameters listed under each set of operating conditions were actual plant data collected from existing sensors. These parameters were used as the boundary conditions for the CFD numerical model.

Table 2
Operating conditions implemented in the numerical model

Parameter	Operating condition based on the plant sensor data (11.30 AM to 12.00 PM – a period of ash sampling activities)					
	1	2	3	4	5	6
Mill 1 coal flow (t/h)	54.57587	53.02468	56.65992	49.84946	55.51388	56.61481
Mill 2 coal flow (t/h)	53.04163	52.80275	56.16094	48.92973	54.16047	55.09808
Mill 3 coal flow (t/h)	53.82602	52.65963	55.91112	48.83189	54.73964	55.6409
Mill 4 coal flow (t/h)	0	0	1.186759	41.11998	54.34443	55.27924
Mill 5 coal flow (t/h)	54.04679	51.90032	42.69234	35.67288	0.114188	0
Mill 6 coal flow (t/h)	54.16156	53.03918	56.2757	48.93466	54.6759	56.04873
Mill 7 coal flow (t/h)	53.92819	53.07055	55.68604	48.59481	53.45578	54.83458
Main steam temperature (°C)	539.2317	537.5927	534.3448	536.5581	537.3227	543.6648
Total SA flow (kNm3/h)	1307.673	1268.725	1248.913	1208.633	1242.785	1266.893
Total PA flow (kNm3/h)	670.773	663.1491	751.3834	752.8989	757.6177	770.6742
Mill 1 PA inlet temperature (°C)	243.9396	243.838	242.8547	243.6377	237.9737	244.5732
Mill 2 PA inlet temperature (°C)	237.717	238.5899	239.3994	236.7574	227.6044	234.158
Mill 3 PA inlet temperature (°C)	264.056	262.4175	262.4526	264.2888	262.9257	260.9603
Mill 4 PA inlet temperature (°C)	40.83481	40.81853	78.1622	236.7992	297.6551	300.9321
Mill 5 PA inlet temperature (°C)	254.005	207.6707	170.7705	153.0822	157.045	105.6459
Mill 6 PA inlet temperature (°C)	239.5107	240.4643	241.0569	239.8106	229.4787	238.0857
Mill 7 PA inlet temperature (°C)	223.7148	225.5335	224.1664	221.9375	212.9409	223.8471
Mill 1 PA inlet pressure (kPa)	6.854506	6.859916	6.903182	6.547427	6.668105	6.933839
Mill 2 PA inlet pressure (kPa)	4.749764	4.697245	4.805223	4.533242	4.504772	4.716075
Mill 3 PA inlet pressure (kPa)	7.408967	7.548942	7.449836	7.370863	7.403826	7.511089
Mill 4 PA inlet pressure (kPa)	-0.18523	-0.15776	2.018828	5.482043	7.06123	7.445631
Mill 5 PA inlet pressure (kPa)	7.615616	7.455385	6.1688	4.948228	4.193171	3.658432
Mill 6 PA inlet pressure (kPa)	2.311307	2.575751	3.072151	2.958676	3.29997	3.753843
Mill 7 PA inlet pressure (kPa)	7.490765	7.35921	7.392587	7.203446	7.157698	7.420597
SA temperature (°C)	353.2419	353.0377	353.1483	353.8906	354.0603	353.875

In Table 2, all mill parameters are represented as the boundary inlets for the piping system that connects to the furnace domain. There is an interchange of mill operation during the 30-minute sampling activities, demonstrating the quick changes in operating conditions throughout the coal-fired power plant operation. The furnace wall conditions (water wall, superheater wall, reheater wall, economizer wall) are based on the assumptions mentioned in references [13,14].

The baseline ash deposition numerical model used in this study was built by Baxter *et al.,* [2]. The ash deposition rate used in this model is shown in Eq. (1).

$$I_i(\rho_i, X_i) = q_i \eta_{Ii} \eta_{Ci} \tag{1}$$

where q_i is the particle mass flux, η_{Ci} is the sticking probability, ρ_i is the particle density, X_i is the particle size, and η_{Ii} is the particle impaction efficiency. The particle impaction efficiency is expressed in Eq. (2).

$$\eta_{Ii} = \frac{1}{1+\frac{b}{St_{eff}-a}+\frac{c}{(St_{eff}-a)^2}+\frac{d}{(St_{eff}-a)^3}} \quad (2)$$

where St_{eff} represents the Stokes number, also known as the ratio of the particle residence time to the flow time around an obstacle. The constant values of *a, b, c,* and *d* are given in Table 3. Detail information on the constants and formulations utilized in the model can be found in Yongtie *et al.,* [2].

Table 3
Constant values for the impaction efficiency

Reference	a	b	c	d
Baxter *et al.,* [2]	0.1425	1.28	0.00215	0.00587

As inertial impaction is a key contributor to the ash deposition, most prior studies depict the inertial impaction process via two main parameters, which are the sticking probability (η_{Ci}) and the particle impaction efficiency (η_{Ii}) [2]. In the current study, η_{Ii} denotes the particle collision and is defined as the ratio of the number of ash particles colliding on the ADP surface to the total number of ash particles travelling through areas around the probe. The 3D geometry of ADP was constructed and introduced into the furnace domain to mimic the actual ash sampling method. The location of the probe is the same as it was during the ash sampling activities, which was at one of the peep holes near the heat exchanger pendants. The ash deposition numerical model was created using the User Defined Function (UDF), and it was then used as the wall boundary condition on the surface of the probe to capture the ash deposition process. Figure 4 depicts the position of the probe within the furnace domain.

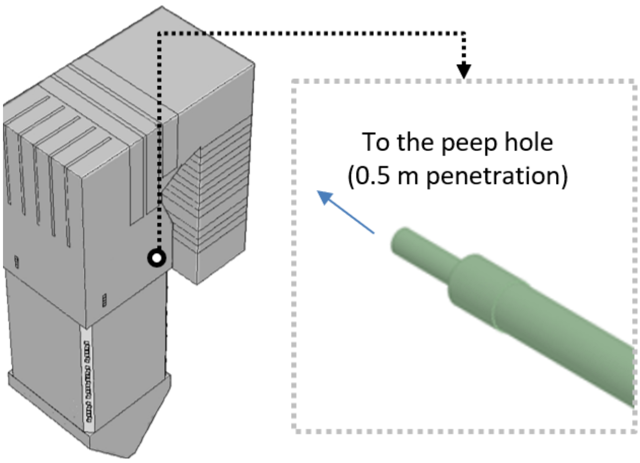
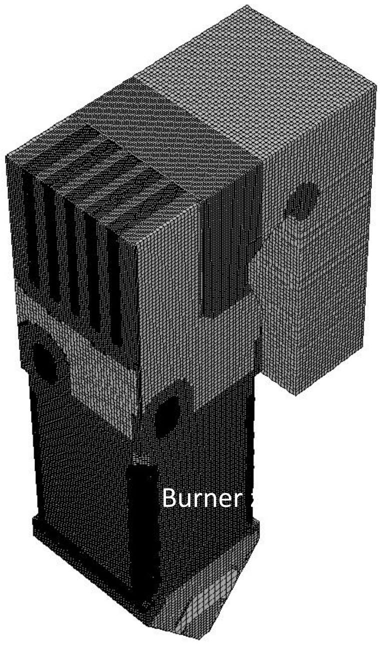


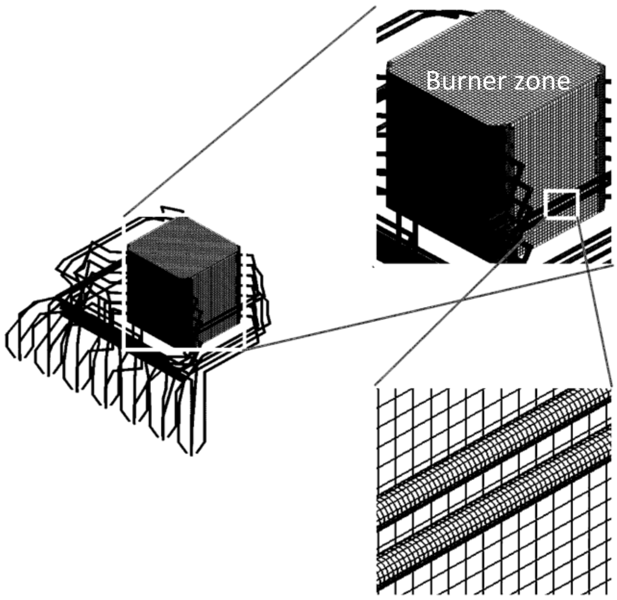
Fig. 4. The location of the ADP in the furnace domain

The validation feedback loop is executed by modifying the impaction efficiency constant values in Table 3. The grid convergence analysis, as well as the validation towards the overall numerical model (solver, turbulence, combustion, and radiation) based on the actual furnace exit gas temperature (FEGT) acquired during the ash sampling activities, were performed prior to the validation feedback loop of the ash deposition model. In the following sections, the results are presented and discussed.

4. Grid-Convergence Analysis and Model Validation

The grid independent test is used to ensure that the spatial convergence accuracy is satisfactory. Meshes (elements) are built with orthogonal quality and skewness taken into account to reflect mesh qualities, as mesh qualities affect the extent of spatial discretization errors [15]. To guarantee that acceptable mesh qualities can be constructed, the orthogonal and skewness characteristics of all generated meshes examined in the grid independent test were controlled. As the mesh number exceeds 2.59 million, the velocity and temperature profiles in the central of the furnace almost cease to vary. The piping domain was also subjected to a grid independent test, in which the coal flow velocity at the exit of each pipe practically ceases to vary when the mesh number exceeds 3.57 million. As a result, for the furnace and piping models, 2.59 million and 3.57 million meshes are chosen, respectively. Figure 5 depicts the mesh models.





(a) (b)

Fig. 5. Mesh models of (a) the furnace and (b) the piping system tangentially connected to the burner zone of the furnace

Following the determination of the independent mesh number, a model validation exercise was performed by comparing the predicted FEGT result from the current model with the actual FEGT during the ash sampling activities. The predicted FEGT result is based on the average temperature in a plane placed 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
Validation based on FEGT results

FEGT (°C)		Percentage difference (%)
Actual	CFD	
1154.26	1204.79	4.38

Table 4 shows that the predicted results from the overall CFD model were in reasonable agreement with the actual FEGT, with less than 5 % discrepancy. Therefore, based on the validation results from the FEGT, the reliability of the current numerical model was assessed to be satisfactory in terms of the implemented solver, as well as the combustion, turbulence, and radiation models. The validation feedback loop of the ash deposition model was conducted once the above-mentioned models had received appropriate validation.

5. Results and Discussion: Validation Feedback Loop of the Ash Deposition Model

The validation feedback loop in the current study was performed based on the alteration of constants in Table 3, which indicates the impaction efficiency. The SSIM value was used to verify the resemblance between the actual ash deposition picture and the predicted ash deposition. Figure 6 depicts a qualitative representation of the validation feedback loop.

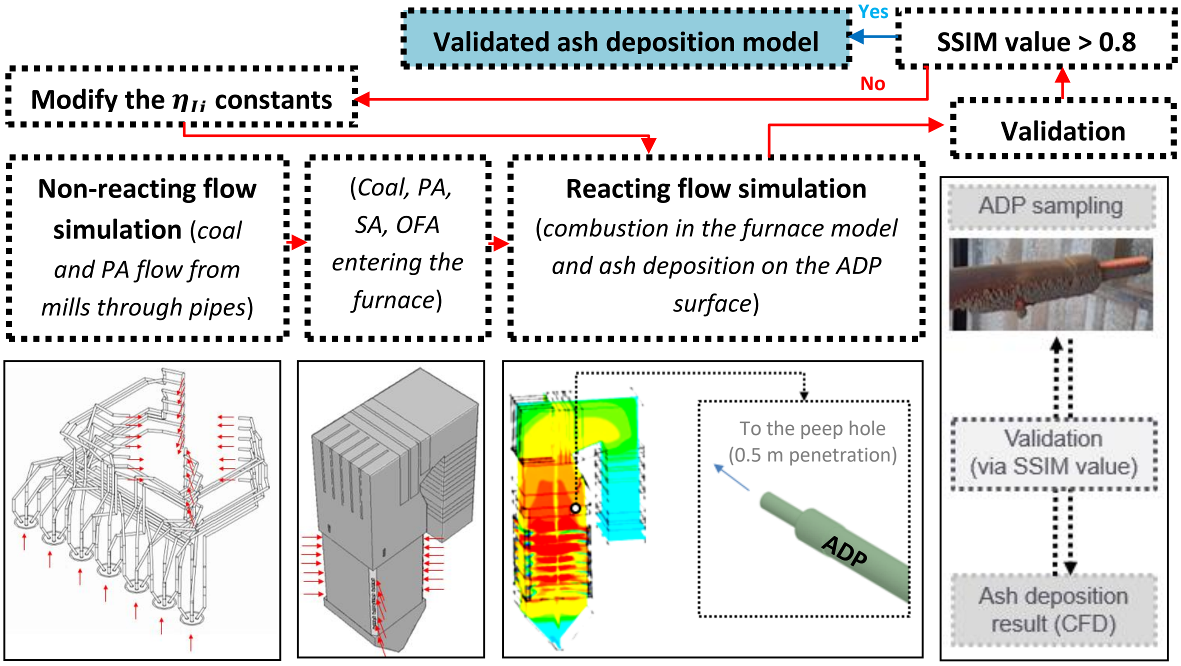


Fig. 6. Qualitative representation of the validation feedback loop

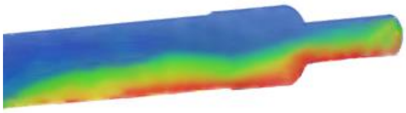
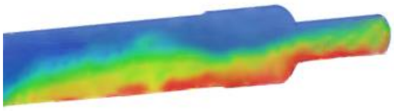
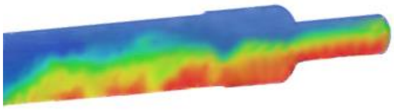
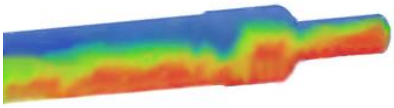
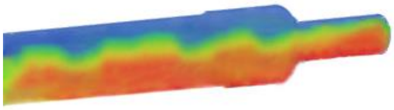
The criteria for the SSIM value to be more than 0.8 is the primary validation premise employed in the current work, where an SSIM value near to 1 indicates high resemblance between two figures. Using the MATLAB software, the SSIM value between two figures was determined. Figure 7 shows a cleaned-up version of the actual ADP sample image that was used to guarantee that an appropriate SSIM value could be measured.

(a) (b)

Fig. 7. Images of (a) the original ADP sampling and (b) the cleaned-up version

The η_{Ii} constants were modified based on the multiplier applied to the constants, as indicated in Table 5. Table 5's "Baxter" represents the original set of constants stated in Table 3. The validation feedback loop employs the following multipliers: 1.00 (original), 0.90, 0.85, 0.70, and 0.50, where the lower the multiplier value, the higher the impaction efficiency. Table 5 shows the qualitative findings of the predicted ash deposition on the ADP surface for each multiplier case, as well as the SSIM value for each case.

Table 5
Constant values for the impaction efficiency

Multiplier	Ash deposition prediction result (ADP) Deposition thickness [m] 	SSIM
(**1.00**)(Baxter)		0.78
(**0.90**)(Baxter)		0.79
(**0.85**)(Baxter)		0.83
(**0.70**)(Baxter)		0.79
(**0.50**)(Baxter)		0.80

According to the findings in Table 5, a multiplier of 0.85 results in an SSIM value more than 0.8, indicating a strong resemblance with the actual ADP sample image. It is also clear that the original ash deposition model established by Baxter *et al.,* [2] is insufficient to accurately capture ash deposition in a coal-fired power plant. The original model drastically underestimated particle impaction efficiency, resulting in less ash deposition, which does not adequately reflect the actual ash deposition behavior in a 700 MW coal-fired power plant. It is also crucial to note that, even when employing a proper numerical approach based on actual power plant operating conditions, the original model cannot accurately describe ash deposition behavior.

The primary cause is the development of the original ash deposition model, which is based on the experimental setup. Small-scale experimental setups have many limitations when it comes for simulating actual power plant operating conditions. Because particle transport is heavily influenced by the flow pattern of the gas-solid phase, the complex geometry of an actual boiler, as well as the relatively extreme conditions within the actual furnace as opposed to small-scale experimental setups, will produce a significant difference in terms of gas-solid phase flow dynamics. As a result, correlating the η_{Ii} constants based on the results of small-scale experimental setups is insufficient for real-world utility boiler applications. Therefore, the impaction efficiency constants must be correlated using a holistic numerical technique that follows the actual power plant conditions, as is done in the current study.

The validation feedback loop used in this work was successful in increasing the similarity between the collected ash deposition from the model prediction and the actual ash deposition sample. The improved version of the ash deposition model has been properly tuned based on the SSIM value by adjusting the impaction efficiency constants. The current study's drawback, however, is mostly in the validation basis, which is largely qualitative in nature. Although the SSIM value is beneficial for comparing the similarity of images between actual and predicted ash depositions, a more quantitative measurement that can provide more meaningful data points and higher precision on the deposited ash is preferable. However, based on this modified version of the ash deposition model, the agreement is found to be satisfactory in terms of gaining a rudimentary insight of the ash deposition behavior in a coal-fired boiler.

6. Conclusions and Future Works

The current work has effectively produced a modified version of the ash deposition numerical model that has been properly tuned based on the validation feedback loop of coal-fired utility boiler simulations. In the current study, a holistic numerical procedure was used that is based on the actual power plant operating conditions and is further backed by in-situ data collection (ash sampling operations) from the power plant under study.

Prior to the validation feedback loop of the ash deposition model, the overall numerical model (solver, combustion, turbulence, radiation) was successfully validated with the FEGT from the actual power plant, revealing a difference of less than 5 %. The validation feedback loop of the ash deposition model established a new set of impaction efficiency constants, which increased the similarity of the images between the actual and predicted ash depositions. The current research yielded the following important insights

i. The baseline/original ash deposition model used in the current study understates the quantity of ash deposition collected. Thus, correlations of impaction efficiency constants based on small-scale experimental setups are insufficient to describe the highly variable gas-solid phase dynamics in a realistic coal-fired utility furnace.
ii. To ensure the successful establishment of a reliable ash deposition numerical model that can properly predict the ash deposition behavior in a coal-fired power plant, a holistic numerical procedure that properly follows the actual power plant operating conditions, furnace geometry, as well as solid in-situ measurement data must be used.
iii. Based on the current study's modified version of the ash deposition numerical model, the agreement is found to be satisfactory in terms of gaining a rudimentary understanding of the ash deposition behavior in a coal-fired boiler.
iv. The current study's shortcoming is mostly in the validation basis, which is largely qualitative-centric. Although the SSIM value is beneficial for comparing the similarity of images between actual and predicted ash depositions, a more quantitative measurement that provides more meaningful data points and higher precision on the deposited ash is preferable. Therefore, the thickness of the ash deposition from the ash sampling activities will be the primary validation basis in future study.

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