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Characteristics of combustion and ash deposition for pulverized coal combustion under various thermal loads: An experimental study in an 80 kWth combustion system

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Abstract Load-following operations of coal power plants are required to cope with the variability in power generation from renewable energy sources. This study aimed to optimize combustion in coal-fired power plants at low loads by analyzing combustion efficiency, NO_x emissions, and ash deposition in a boiler. An experiment was conducted by varying the heat input in a bench-scale combustion system. The combustion performance, in terms of the CO concentration in combustion gas and unburned carbon content in ash, degraded during low-load operation. Consequently, the fuel ratio was found to be a key factor for determining the combustion efficiency during low-load operation. The nitrogen content of the fuel was dominant in terms of the NO conversion ratio. The inconsistency in the ash deposition tendency suggested that it was affected more by the composition of minerals than by the amount of ash or total feed rate of ash in coal.

1. Introduction

With an increase in the supply of renewable energy, the proportion of coal-fired power plants, which plays the role of base load, is expected to decrease gradually. For electricity generation, wind and solar power are the most widely used renewable energy sources. However, they have a critical defect in that their power production is not constant; it varies significantly depending on the weather and season, which makes responding to immediate power demands difficult [1, 2]. Therefore, to compensate for this limitation, it is important to secure certain measures, such as energy storage systems or power sources, for peak loads. Further, some existing coal power plants need to change their roles from base loads to load-following power production [3-6]. This is one approach to ensuring that existing coal power plants contribute to mitigating carbon emission [7-9].

The load-following operation of coal power plants can be quantitatively evaluated using three technical indicators: minimum load, ramp rate, and start-up time [10]. Fernandez et al. [11] performed simulation analysis for a 600 MW supercritical thermal power plant that combined sliding pressure boiler control and steam control. Zheng et al. [12] reported a low-load operation of up to 700 MW for a 1000 MW boiler, which is 70 % of the load. NO_x emissions could be reduced by lowering the oxidizer ratio in the main combustion zone during low-load operation. Tsumura et al. [13] showed that the minimum load and NO_x emissions could be lowered by modifying the burner in a 7 kW test furnace. Sun et al. [14] suggested a method to lower the minimum load by using a thermal energy storage method based on the drying of low-rank coal. Brouwer et al. [15] evaluated the economics and operation performance for the load-following operation of coal power plants in terms of mitigating CO_2 emission and suggested that more flexibility was required for achieving low-carbon scenarios. Avagianos et al. [16] simulated a coal-fired power plant with a 367 MW capacity; the simulation was purposed to theoretically estimate the heat transfer coefficient from 100 % to 35 % load. They investigated the load-following operation up to 40 % based on the fuel input and evaluated the economic feasibility and operating performance. Han et al. [17] modeled a 1000 MW_e-class coal-fired power plant using thermodynamic analysis. They investigated the effects of the load-following operation on energy efficiency and the environment. Simulation results showed that the total environmental impact potential increased by approximately 90 % because of the reduction in the plant thermal and NO_x removal efficiencies during partial or low-load operation. Using pre-dried lignite, they obtained a net efficiency of 33.3 % at 35 % load and verified this result via comparison with the computational fluid dynamics model. Simulation of the system showed that the novel system could significantly reduce CO_2 emissions from power plants using low-rank coal. Eslick et al. [18] modeled a 245 MW_e subcritical coal-fired power plant using the Institute for the Design of Advanced Energy Systems Integrated Platform (IDAES). This model improved the performance of partial-load operation by predicting the quality of steam throughout the plant using flow rate, temperature, and pressure. Thus, the minimum operating load was found to decrease from 90 MW to 50 MW. Haijiao et al. [19] conducted a study to lower the minimum load for a 600 MW coal-fired power plant. The simulation was performed by modeling the entire power plant. They found that the minimum load reduced to 210 MW by extracting the reheat steam when operating at 50 % load.

Among the three indicators, minimum load is the most important one because it is directly related to the available flexibility capacity and combustion performance. Under partial-load operating conditions, there may be differences in the combustion characteristics from the existing combustion conditions, mostly in a negative way. The temperature in the combustion chamber decreases with a decrease in the amount of heat input, which increases combustion instability. The heat transfer efficiency may also decrease because of the temperature decrease in the furnace and change in the composition and flow rate of the flue gas. Frequent changes in combustion temperature can cause fatigue and corrosion of boiler tubes [20, 21]. During low-load operation, the possibility of low-temperature corrosion owing to low flue gas temperature increases, which may cause direct problems in the facility [20, 22]. If the flue gas temperature decreases, the efficiency of environmental facilities also decreases, and there is a possibility that the emission of environmental substances will increase [23]. Furthermore, the decrease in flue gas temperature may exhibit different characteristics in the slagging and fouling phenomena that continuously cause operational disturbances in existing power plants and the occurrence of clinkers, which may cause direct damage to the facility [24]. Several studies have been conducted on the load-following operation of coal power plants and their suitability for responding to energy transitions [11-17, 25].

In a real-scale power plants where a variety of coals are used, problems with combustion stability or ash deposition may occur during low-load operation, depending on the fuel used. However, there is a notable lack of experimental investigations into coal combustion under low loads. To address this gap, our study explores the inherent characteristics of coal combustion at low loads compared to standard or rated loads and to elucidate any distinct differences arising from the type of fuel used. Using a bench-scale test combustion furnace, we conducted rigorous experiments across a range of load conditions. By testing a variety of fuel types, we aimed to unravel the specific attributes presented by each fuel.

In this study, combustion experiments were performed with various loads for six types of coal in an 80 kW_{th} combustion system. The combustion and ash deposition characteristics were evaluated based on the load and fuel characteristics. Combustion stability is closely related to the fuel ratio of coal, and ash deposition is not always proportional to the ash content of coal.

2. Experimental approach

2.1 Test furnace and data measurement methods

A cylindrical furnace with a single down-firing burner, having a capacity of 80 kW_{th}, was used as the pulverized coal combustion system for the experiment. Its schematic is shown in Fig. 1. The diameter and height of the furnace were 600 and

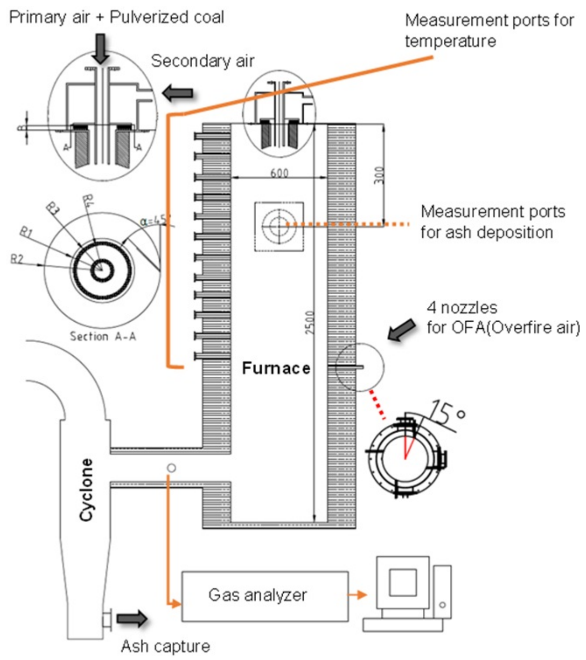


Fig. 1. Schematic of bench-scale furnace (80 kW_{th}) and tangential vane swirl-type coal burner.

2500 mm, respectively, and it was divided into five stages of equal height. Each stage had ports for the measurements of ash deposition, temperature, and gas composition. Overfired air (OFA) was divided into four ports at a 15° angle at the lower part of the third stage of the furnace, and it was supplied after preheating. In this experiment, the temperature at the center and the flue gas composition were measured at 12 points along the exit direction. To investigate the ash deposition characteristics, real-time measurements were performed using devices composed of a probe and load cells. Each device was installed on the side of the first furnace stage (y = 755 mm). A tangential vane swirl-type coal burner was used to supply primary and secondary combustion air. The primary combustion air and pulverized coal entered the burner simultaneously and flowed into the combustion furnace. Then, the secondary combustion air was influenced by the swirl to create a swirling flow such that the pulverized coal flowing into the combustion furnace would be properly mixed with the air. The swirl number, defined by Beer [26], was set as 0.84. A KCV-KT20 feeder from K-tron was used for feeding pulverized coals and was tested for quantitative feeding before experiments.

2.2 Fuel

Table 1 presents the results of the proximate and ultimate analyses of the coal used in the experiment. One bituminous and five sub-bituminous coal samples were used. The bituminous TRAFIGURA coal had a high fixed carbon content and low moisture content. The fixed carbon contents of the remaining five sub-bituminous coals were in the range 33.2-43.2 %, and the SAMSUNG-CNT coal with the lowest fixed carbon content had the highest moisture content of 26.74 %. It had the lowest ash content of 3.7 %, while TRAFIGURA contained the highest ash-content of 15.3 %. Based on the ash content, the coals used in this experiment can be classified into three high-ash and three low-ash coals. The moisture contents of the former category (TRAFIGURA, GLENCORE-A, AVRA) were relatively low (8.4-16.1 %). AVRA-AL, SAMSUNG-CNT, and BAYAN-L had similar fuel nitrogen contents of 0.8, 0.8, and 0.9 %, respectively, whereas the nitrogen contents of the three other coals were higher, ranging from 1.3 to 1.6 %. TRAFIGURA coal had the highest calorific value of 27.6 MJ/kg, while that of AVRA coal was the lowest at 23.0 MJ/kg. Table 1 also lists the fuel ratio for each fuel, which is the ratio of the fixed carbon content to volatile content in the fuel. This is an important fuel characteristic that affects stable combustion when the load is reduced. AVRA-AL coal, which is a sub-bituminous coal, had a fuel ratio of 1.8, which was higher than that of TRAFIGURA coal (1.4). Owing to the low volatile matter content of AVRA-AL coal, its fuel ratio was calculated to be high, even though its fixed carbon content was low. The SAMSUNC-CNT coal had the lowest fuel ratio of 0.9 (< 1) as it contained a large amount of volatile matter and less fixed carbon.

Table 1. Compositions and heating value of the fuels used.

Fuels	Proximate analysis (as received basis wt%)				LHV (MJ/kg)	Fuel ratio
	M	VM	FC	Ash		
AVRA-AL	16.1	24.3	44.6	15.0	23.0	1.8
TRAFIGURA	8.4	31.4	44.9	15.3	27.6	1.4
GLENCORE-A	12.6	30.6	42.9	14.0	26.2	1.4
GLENCORE-AM	19.6	31.1	43.2	6.1	25.9	1.4
BAYAN-L	25.8	33.4	34.4	6.5	24.3	1.0
SAMSUNG-CNT	26.7	36.4	33.2	3.7	26.5	0.9

Fuels	Ultimate analysis (as received basis wt %)				
	C	H	O	N	S
AVRA-AL	53.0	2.7	11.9	0.8	0.5
TRAFIGURA	63.9	4.1	6.0	1.6	0.7
GLENCORE-A	59.1	3.6	8.8	1.4	0.6
GLENCORE-AM	56.1	3.1	13.5	1.3	0.3
BAYAN-L	48.3	3.0	15.4	0.9	0.3
SAMSUNG-CNT	51.5	3.3	13.7	0.8	0.3

2.3 Experimental conditions

Before starting the experiment, the furnace was preheated for roughly 27 hours. Each experimental session took 3 hours, ensuring adequate time for temperature stabilization. This duration also guarantees sufficient time for measurement of ash deposition.

The experiment was conducted by changing the load across the range 50–125 % (40, 60, 80, 100 kW) for each type of coal. The oxidizer was supplied through the primary and secondary combustion air and the OFA entered through the burner. The amounts of air in each case are listed in Table 2. For 100 % load, a ratio of 10:65:25 was set for the primary, secondary, and OFA flowrates; an excess air ratio of 20 % was set. Considering the combustion furnace and swirl number of the burner used in the experiment, the excess air ratio and flowrates ratio can be set such that the NO_x emissions are reduced to the maximum extent [26]. The flow rate of the secondary combustion air changed when the load was varied.

In this study, although the experiments were not iteratively conducted for reproducibility validation, several methodologies were employed to maintain the accuracy of the measurement data. There is potential for the oxidizing agent's flow rate to be significantly influenced by external noise. To address this issue, pre-experimental combustion calculations were executed to predict an O_2 concentration range of 3 to 4 % at the furnace exit. The experimental data was compared with these theoretical expectations, ensuring minimal deviation in the measurement data. For temperature readings at the center of the furnace, a probe with an R-type thermocouple inside and a cooling water system was used. This arrangement effectively addresses and mitigates soot-related problems. Data acquisition at individual measurement points ceased when O_2 concentrations approached zero or reached their observed minimum,

Table 2. Flowrates of air streams for various fuels and heat inputs.

Heat input (% of the designed value)	Primary (Nm^3/h)	Secondary (Nm^3/h)	Overfire (Nm^3/h)	Primary (Nm^3/h)	Secondary (Nm^3/h)	Overfire (Nm^3/h)
	AVRA-AL			TRAFIGURA		
125	11.2	72.8	28.0	11.3	73.2	28.2
100	10.6	55.1	23.8	10.7	79.4	0
75	10.1	39.6	17.5	10.2	57.4	0
50	9.6	23.3	11.9	9.7	35.4	0
	GLENCORE-A			GLENCORE-AM		
125	11.2	73.1	28.1	11.1	72.2	27.8
100	10.7	56.8	22.5	10.6	56.1	22.2
75	10.1	40.4	16.9	10.0	40.0	16.6
50	9.6	24.1	11.2	9.5	23.8	11.1
	BAYAN-L			SAMSUNG-CNT		
125	11.2	72.5	27.9	11.2	72.5	27.9
100	10.6	56.3	22.3	10.6	56.4	22.3
75	10.1	40.1	16.7	10.1	40.2	16.7
50	9.6	23.9	11.2	9.6	23.9	11.1

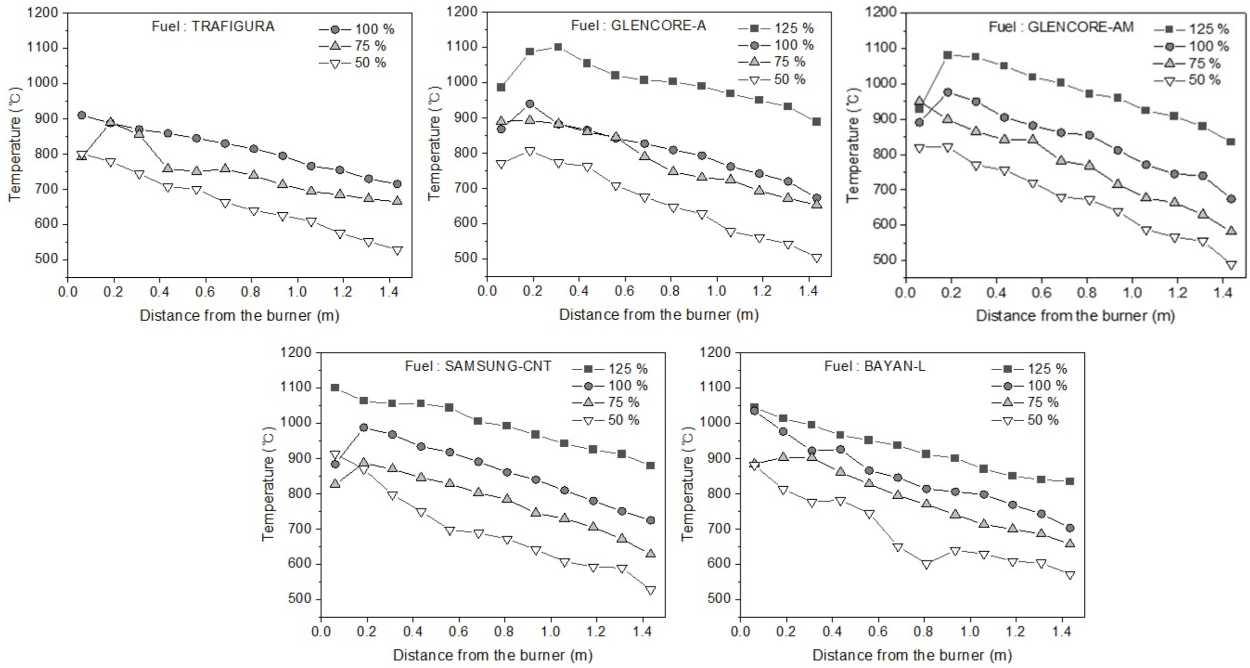


Fig. 2. Axial temperature distribution (center temperature) in the furnace for various thermal loads and fuels.

primarily corresponding to the flame zone. This strategy was implemented to reduce the impact of ambient air during the measurement process. Typically, each data collection interval persisted for 5 to 10 minutes. After each measurement session, an air compressor was used to cleanse the probe, ensuring the removal of ash residues.

3. Results and discussion

3.1 Combustion characteristics for various loads and fuels

Fig. 2 shows the axial temperature distribution for various loads measured at the cross-sectional center of the furnace. The maximum temperature was -1100 °C at 125 % thermal load; however, it dropped to -800 °C at 50 % heat input, which shows a difference of -300 °C. As the load decreased, the heat capacity of the flue gas also decreased, causing an increase in the temperature deviation inside the furnace. The maximum temperature of GLENCORE-A was obtained at y = 0.3 m from the burner, and GLENCORE-AM was at y = 0.2 both at 125 % thermal input. Conversely, the results for SAMSUNG-CNT and BAYAN-L coal showed that their peak temperatures were ob-

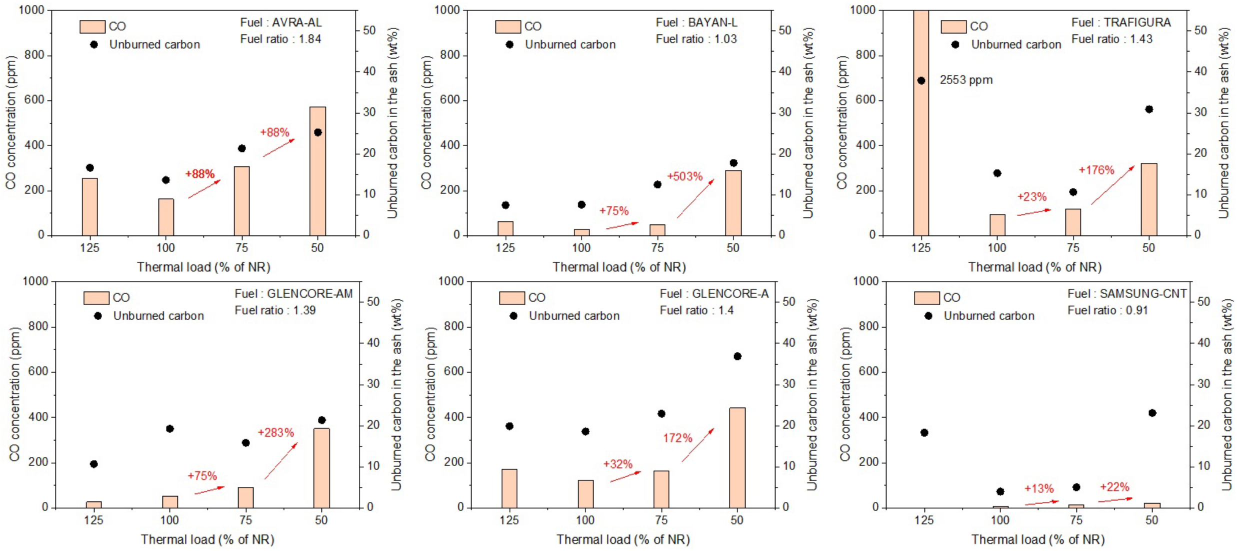


Fig. 3. CO concentration in the combustion gas and unburned carbon content in the ash for various thermal loads and fuels.

tained near the nozzle of the burner. These results indicate that the main combustion zone differed depending on the fuel ratio. It was directly related to the fuel ratio, which was 1.4 and 1.39 for GLENCORE-A and GLENCORE-AM, respectively, and 0.91 and 1.03 for SAMSUNG-CNT and BAYAN-L, respectively. Thus, high-volatile coals reached the maximum temperature quickly because of the rapid homogeneous reaction of the volatiles. This resulted in the maximum temperature being achieved closer to the burner nozzle (i.e., the root of the flame). Conversely, in the case of low-volatile coal, the combustion reaction was lower, and thus, the maximum temperature point moved further from the burner nozzle; this means that the combustion rate is low.

Fig. 3 shows the CO concentration measured at the exit of the furnace and the content of unburned carbon in the ash collected from the cyclone. At 100 % heat input (design condition), the measured CO concentration ranged from less than 1 ppm to a maximum of 162 ppm for various coals. The coal with the lowest CO concentration was SAMSUNG-CNT, and that with the highest was AVRA-AL. At 50 % heat input, the measured CO concentration was within the range 22–573 ppm. The CO concentrations of all coals increased when the load was lowered. When the heat input decreased from 100 to 75 %, the CO concentration increased from 13 to 88 %. When the heat input decreased from 75 to 50 %, the CO concentration increased from 22 to 503 %. Among the various coals, the CO concentration of SAMSUNG-CNT increased the least while that of BAYAN-L increased the most. The unburnt carbon content of the ash captured from the cyclone was between 4 and 19 %, and the value increased from 18 to 37 % as the heat input increased from 50 %. The same tendency was observed with a decrease in the CO concentration. For a reduced heat input, most oxidizers are controlled by the secondary combustion air. It mixes the fuel with the air under the influence of a swirl. Therefore, as the heat input decreases, the fuel and air

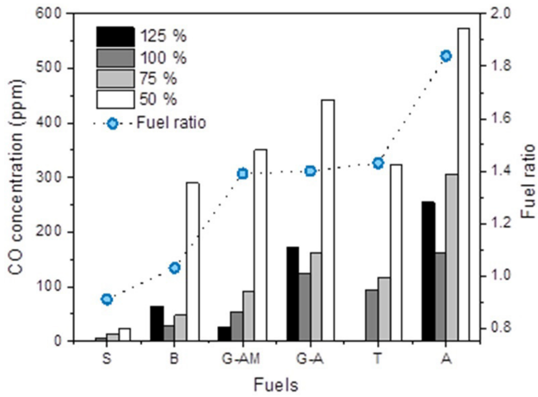


Fig. 4. Correlation of fuel ratio with combustion performance for various thermal loads.

are not appropriately mixed, and thus, the combustibility decreases. However, in this study, there were exceptions where CO increased at the 125 % heat input. This was because sufficient time for char combustion was not secured in the furnace used in the experiment. This also led to an increase in the amount of unburned carbon. As TRAFIGURA, with a fuel ratio of 1.43, was the only bituminous coal with the highest ash and fixed carbon content among coals, the time required for its combustion reaction was longer than that required for the other coals. Thus, the problem of insufficient combustion time was further highlighted in this case. Consequently, the CO concentration was measured to be 2553 ppm, and the combustion did not occur in a stable manner.

Thus, it can be concluded that the characteristics of the fuel significantly affected the combustion characteristics under various thermal loads, as indicated by the experimental results for the six coals tested in this study. Fig. 4 shows the CO concentrations for various fuel ratios. The CO concentration showed a proportional trend with respect to the fuel ratio for all thermal loads (50–125 %). Notably, the CO concentrations were high for the coals with high ash contents. The ash contents of G-AM (GLENCORE-AM) and G-A (GLENCORE-A) were 6.09 wt% and 13.95 wt%, respectively, even though their fuel ratios were very similar. For all heat inputs, G-A, which had a higher ash content than G-AM, had a higher CO concentration and unburned carbon content. The CO concentration and unburned carbon content was hypothesized to increase as the oxidation reaction of the char was delayed. This is because the contact with oxygen of the ash layer surrounding the char was disturbed during the char combustion process. However, further investigation is required to determine the precise reason for this finding.

In was found that combustion instability increased during low-load operation, which resulted in decreased combustibility. This phenomenon was more pronounced for coals with high fuel ratios, which indicates that using coals with low fuel ratios would be more advantageous in low-load operations. In addition, it may be necessary to use a burner with highly swirled combustion air to improve flame stability during low-load operation.

3.2 NO_x emission for various loads and fuels

As shown in Fig. 5, we measure the NO and CO concentrations at the furnace exit for various coals to determine the relationship between NO formation and combustion performance for various thermal loads. All measured NO concentrations were compensated by 6 % O_2 concentration in the flue gas. For 100 % heat input, the NO concentration ranged from 135 to 519 ppm, depending on the fuel. The values decreased to 20-281 ppm when the thermal input was reduced to 50 % load. Most results confirmed that the NO concentration decreased at lower loads. This can be partially attributed to the low temperature that affects thermal NO_x; however, in most cases, it is related to the conversion of fuel nitrogen in the combustion environment. In some cases, the NO concentration decreased as the CO concentration increased at 125 % load. As NO and CO have a trade-off relationship, an increase in the CO concentration seemed to affect the NO concentration, which is evidently shown by most coals in Fig. 5. For AVRA-AL, the NO concentration was significantly lowered because of the effect of CO, despite it having the highest nitrogen content among the coals. To reflect the difference in the nitrogen content among the fuels, the NO_x conversion ratio can be defined using Eq. (1). It can be defined as the ratio between the experimentally measured and theoretical NO concentrations. The theoretical value of NO concentration assumes that the entire fuel nitrogen has been converted to NO.

$$NO_x\ conversion\, ratio = \frac{C_{NO}}{\left(\dfrac{22.41\times\dfrac{FN}{30}}{V_{dry}}\right)\times 10^6}, \tag{1}$$

where C_{NO} (ppm) is the NO concentration at the furnace exit, FN (kg/kg) is the nitrogen content in the fuel, and $V_{dry}[Nm^3/kg]$ is the volumetric amount of flue gas produced per kilogram of fuel. In the previous subsection, we deduced that the fuel ratio and CO concentration in the combustion gas have a linear relationship.

Fig. 6 shows the effects of the fuel ratio and fuel nitrogen content on the NO conversion ratio and NO concentration. Fig. 6(a) evidently shows that the fuel ratio does not appear to be closely correlated with the NO conversion ratio. In Fig. 6(b), data are rearranged according to fuel N, and this shows that the nitrogen content is not constant in the very small range of

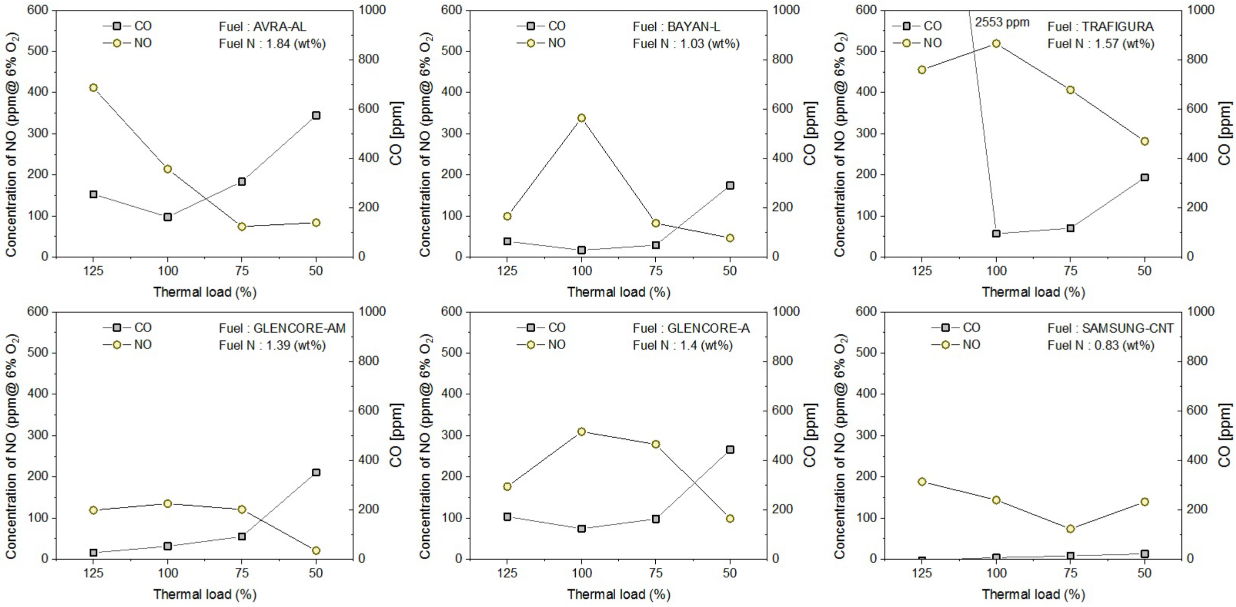
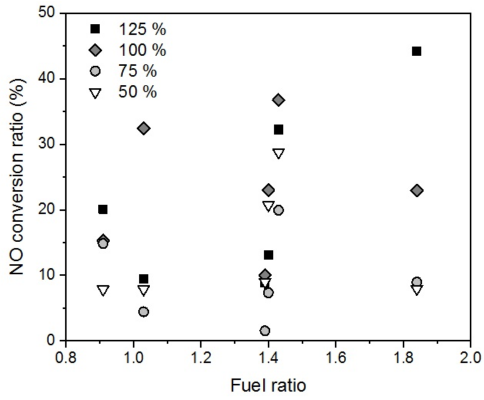
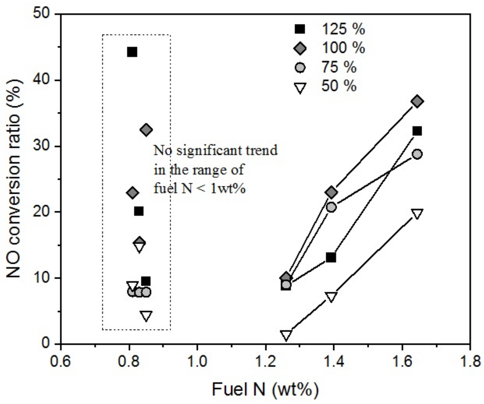


Fig. 5. Concentrations of the NO and CO for various fuels and thermal loads.

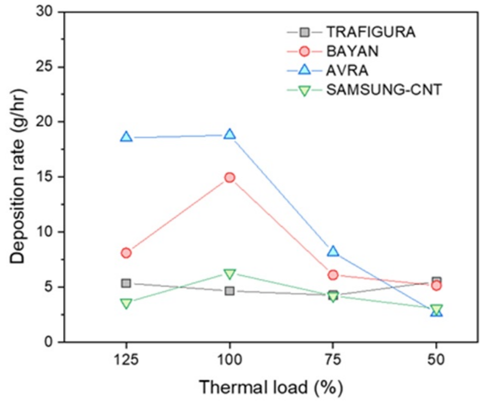


(a)

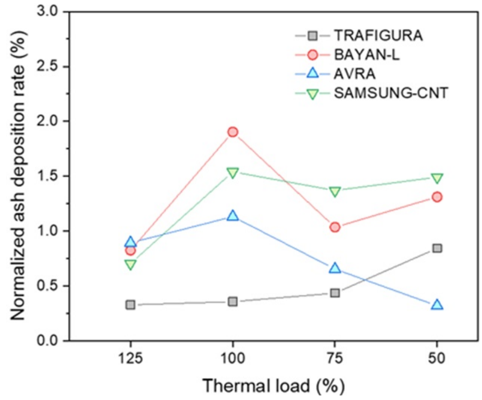


(b)

Fig. 6. Effects of (a) fuel ratio; (b) fuel nitrogen content on the NO_x conversion ratio.



(a)



(b)

Fig. 7. (a) Deposition; (b) normalized ash deposition rates for various fuels and thermal loads.

0.9 % or less. It is presumed that the NO conversion ratio was affected by the CO concentration when the same fuel N was used. When the fuel nitrogen content was 1.2 % or more, the NO conversion ratio increased depending on the nitrogen content. Therefore, it can be surmised that the NO concentration is closely related to the nitrogen content in the fuels while the NO reduction, related to the CO concentration (related to fuel ratio), may have a limited impact.

3.3 Ash deposition characteristics

Under partial-load conditions, we expect that the ash deposition would decrease because of the consequent low ash input and low temperature; however, the low gas velocity could result in its increase. To eliminate the effects of low ash input under low-load conditions, the tendency of ash deposition for various thermal loads was investigated by normalizing the measured ash deposition rate. The normalized ash deposition rate is defined as

$$\begin{aligned}&Normalized\ ash\ deposition\ rate[\%]\\&=\frac{Mass\ of\ deposited\ ash\ on\ the\ probe[g/hr]}{Total\ ash\ input\ for\ a\ case[g/hr]}\times 100\end{aligned} \qquad (2)$$

Fig. 7 shows the experimental results of the ash deposition and normalized rates for various thermal loads and coals. Fig. 7(a) shows a pattern in which the deposition rate decreased with a decrease in the load. This trend was evident for AVRA-AL, which had the lowest deposition rate at 50 % load. It was confirmed that the deposition rate decreased owing to load change, as expected; this decrease was attributed to the decreased ash input under a low thermal load. However, despite AVRA-AL having a high ash content among the coals (Table 1), its deposition rate was the lowest at low loads, even lower than that of SAMSUNG-CNT, which had the lowest amount of ash. TRAFIGURA, which had the highest ash content, also showed a similar decreasing pattern in response to load decrease; however, the amount of deposition was considerably smaller. In contrast, Fig. 7(b) shows a different pattern for the normalized deposition rate; for most coals, the rate is the lowest at maximum load (125 %). In the case of TRAFIGURA, the normalized deposition rate increased with a decrease in the ash flow rate. For SAMSUNG-CNT, the normalized deposition rate was relatively high as well, and at 125 % load, it reached the lowest value. These results allow us to conclude that, in most cases, the increased flow rate of fuel ash to a combustion system can increase ash deposition; however, this is not true in all cases. According to Piotr [24], ash deposition is caused by various factors such as flue gas velocity, furnace cross-sectional area, temperature, and ash composition. The viscosity determined by the ash composition and temperature is the most critical factor affecting ash deposition. Therefore, this study suggests that ash deposition increased at low load because the ash composition of some coals had high viscosity, which increased significantly under low-temperature conditions. Comprehensively, normalized ash deposition also showed a decreasing trend for low-load cases; however, in some cases, it did not, because other operating conditions such as the furnace temperature and chemical composition of the ash could have significantly affected it.

4. Conclusions

The combustion and ash deposition characteristics of six types of coal were investigated by varying the load inside an 80 kW_{th}-scale furnace. The combustion was found to become unstable with a decrease in the heat input. In addition, we found that the fuel ratio was an important characteristic that affected combustion stability. Thus, increasing the proportion of low-fuel-ratio coals can be more advantageous for low-load operation. Meanwhile, the NO concentration in the combustion gas at low thermal loads decreased. This was found to be closely related to the fuel nitrogen content and combustion efficiency. Finally, the ash deposition rate decreased at low thermal loads because of the low temperature of the furnace. However, in the case of normalized ash deposition, there was no clear trend for the various thermal loads. Rather than the thermal load, the chemical composition of ash appears to be a more important parameter that determines the normalized ash deposition rate. This study provides initial insights into combustion-related challenges under load-following operations and a potential index for optimizing combustion.

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