JURNAL REKAYASA PROSES

VOLUME 19, NUMBER 1, 2025, 31–41

RESEARCH ARTICLE

Thermogravimetric analysis of Indonesian low-rank coal: Optimization of drying temperature and kinetic modeling

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Received 05 December 2024; revised 01 February 2025; accepted 04 February 2025

OBJECTIVES Drying high-moisture of low rank coal in the mining sector is essential for increasing energy efficiency and ensuring stability in its use as an energy source. This study aims to determine the optimal drying temperature and kinetic parameters for Indonesian low rank coal (i.e., lignite and sub-bituminous) using thermogravimetric analysis (TGA) under both isothermal and non-isothermal conditions. METHODS Coal samples were tested at three heating rates (5, 10, and 20 °C/min) and three fixed temperatures (150, 200, and 250 °C). Several drying kinetics models, including the Newton, Henderson and Pabis, Logarithmic, and Page models, were used to evaluate the drying characteristics of both coal types. RESULTS The results indicate that the Page model provided the best fit, with the highest R^2 value and the lowest χ^2 value, making it the most accurate model for describing coal drying rates under various conditions. The optimal drying temperature for lignite was 83.04°C, with an activation energy of 3224.04 J/mol, while for sub-bituminous coal, the optimal temperature was 109.65°C with an activation energy of 17972.83 J/mol. CONCLUSIONS These findings support the optimization of the drying process in the industry, particularly for efficiently reducing coal moisture content without compromising energy quality.

KEYWORDS low rank coal; moisture; drying; thermogravimetric, kinetic

1. INTRODUCTION

Indonesia is globally recognized for its abundant natural resources, including a significant coal reserve. According to the BP (2021), Indonesia possessed a total coal reserves of 34.86 billion tons in 2020, with accounted for 3.2% of global reserves. Notably, approximately 70% of these reserves consist of low-rank coal (LRC), such as lignite and sub-bituminous types. More recent data from Geological Agency of Minister of Energy and Mineral Resources of Republic of Indonesia (2024) in 2023 reported that Indonesia's low-rank coal resources amounted to 66.27 billion tons, with reserves of 23.7 billion tons.

Low-rank coal required as a power generation but characterized LRC by high moisture content, typically ranging between 17% and 45%, and a relatively low calorific value (Fatia Umar et al. 2024). These properties pose significant challenges for its utilization. High moisture content reduces energy density, increases transportation costs, decreases combustion efficiency, and adversely impacts grinding mill performance during coal preparation. For instance, the Rembang Steam Power Plant (PLTU) reported annual losses of approximately 30 billion rupiahs due to the use of high-moisture coal, translating to an energy loss of 300 billion kcal or around 50,000 tons of coal (Mangestiono 2014). During combustion, 20%–25% of the heat is consumed to evaporate water, significantly reducing power generation efficiency (Rao et al. 2015).

As an alternative, coal drying presents a promising solution to these challenges. Pre-drying technologies can improve power plant efficiency by 4%–6% and reduce CO_2 emissions by 30% (Agraniotis et al. 2012). Additionally, drying

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enhances the calorific value of low-rank coal, optimizing its utilization and mitigating environmental impacts associated with inefficient combustion. Recognizing these benefits in achieving global energy goals-efficiency, environmental sustainability, and economic viability-various drying technologies have been developed, including rotary dryers (3,700 kJ/kg H_2O), rotary tube dryers (2,950-3,100 kJ/kg H_2O), chamber dryers (3,150 kJ/kg H_2O), pneumatic dryers (3,100 kJ/kg H_2O), fluid bed dryer (3,100-4,000 kJ/kg H_2O), fleissner process (130-1,750 kJ/kg H_2O), and fluidized bed superheated steam drying with heat recovery (450 kJ/kg H_2O) (Karthikeyan et al. 2009). These technologies require varying amounts of energy to remove 1 kg of H_2O, making it crucial to determine the optimal operating temperature for maximum efficiency and to prevent the re-adsorption of H_2O after drying.

This development aligns with Indonesia's government policies on mineral and coal downstreaming, which focus on optimizing mining outputs and increasing resource value. In response, various industries in Indonesia are developing coal drying technologies to enhance the efficiency and sustainability of the national energy supply. Recent studies have explored the kinetics of coal drying using advanced technologies (Sun et al. 2024). For instance, Zhang et al. (2023) investigated low-rank coal drying in a thermal vibration separation fluidized bed, demonstrating that increasing gas velocity and vibration frequency initially decreased and then increased the activation energy required for drying. Similarly, Paswan et al. (2023) examined the drying process of coal slurry in a natural draft tray dryer, highlighting the effects of temperature and material properties on drying rates.

Understanding the drying kinetics of low-rank coal is essential for developing efficient and energy-effective drying technologies, and Thermogravimetric Analysis (TGA) has emerged as a fundamental tool in this field. By enabling precise monitoring of material weight changes under controlled heating conditions both isothermal and non-isothermal TGA provides critical insights into the thermal behavior of materials, including moisture loss rates and the energy required for drying. This capability makes TGA particularly valuable for modelling drying kinetics, where mathematical models such as Newton, Henderson and Pabis, Logarithmic, and Page have been widely applied to porous materials like coal (Kumar Mishra and Mohanty 2021; Rueda-Ordóñez and Tannous 2018). The porous nature of low-rank coals, such as lignite and subbituminous coal, plays a significant role in their drying behavior. Compared to higher-rank coals, these coals exhibit higher porosity, which is often correlated with higher moisture content, influencing drying kinetics (Wang et al. 2018; Usman et al. 2022). Unlike conventional bulk material testing, TGA offers a more controlled and detailed analysis, allowing researchers to better understand drying mechanisms and extract accurate kinetic parameters.

The application of mathematical models to describe biomass drying behavior has been widely conducted using the Newton, Henderson and Pabis, Logarithmic, and Page models, yielding varying results. The Newton model, as the simplest approach, only considers an exponential drying rate constant (Karmakar 2021). The Henderson and Pabis model, developed as an extension of the Newton model, incorporates a correction factor to improve accuracy. Although it offers better performance than the Newton model, it still has limitations in representing the final drying stages (Cai and Chen 2008). Further modifications were introduced in the Logarithmic model by adding additional parameters, making it more accurate and adaptable to various drying conditions (Chen et al. 2012). Among these models, the Page model generally provides the most accurate results in characterizing biomass drying, particularly under non-isothermal conditions, such as in the drying of wheat straw and corn cobs (Cai and Chen 2008). Nevertheless, the accuracy of each model depends on the type of biomass being dried, the drying conditions applied (isothermal or non-isothermal), and the analytical methods used.

Isothermal and non-isothermal TGA analyses provide complementary insights into coal drying behavior. Isothermal TGA helps evaluate steady-state drying behavior and activation energy at constant temperatures, offering a detailed understanding of thermal stability and moisture release rates. In contrast, non-isothermal TGA simulates real-world drying conditions, where temperature dynamically fluctuates, revealing the interplay between temperature gradients and drying rates. By integrating both approaches, researchers can bridge the gap between laboratory-scale experimentation and industrial applications, paving the way for more efficient coal drying technologies and enhancing operational design strategies.

Given the critical role of coal drying in enhancing the quality of low-rank coal and supporting Indonesia's coal down-streaming initiatives, this study aims to identify the optimal drying temperature and compare various drying models to determine which best describes the drying characteristics of Indonesian lignite and sub-bituminous coal under both isothermal and non-isothermal conditions. The comparison of these models is essential for identifying the most accurate and reliable model that can predict coal drying behavior under different conditions, which is key for optimizing drying processes in industrial applications. By selecting the most accurate model, this study not only contributes to improved model predictability but also aligns with global efforts to improve energy efficiency and sustainability. The findings are expected to support the development of more efficient drying equipment, optimal operational parameters, and energy-efficient coal utilization, while ensuring significant moisture reduction, maintaining coal quality, and ensuring thermal stability for future applications.

2. RESEARCH METHODOLOGY

2.1 Drying experiments procedure using thermogravimetric analysis

The lignite and sub-bituminous coal samples used in this study were obtained from a coal mining site in Kalimantan. Sampling was conducted randomly from various locations within the mine to ensure the representativeness of the samples. After collection, the coal samples were air-dried at room temperature for 24 hours to remove surface moisture. Following the drying process, the samples were crushed using a crusher to reduce the particle size to less than 4 mm. To ensure consistency in particle size, the crushed samples were sieved to obtain a fraction size between 0.5 and 1 mm. Finally, homogenization was carried out by shaking the samples in a sealed container to ensure a uniform composition across all samples.

Thermogravimetric analysis (TGA) was conducted using a Linseis STA PT1000 instrument, equipped with a high-precision balance and furnace, at the Laboratory of Analytical Instrumentation, Universitas Gadjah Mada (UGM). To ensure accuracy in temperature measurements and weight change detection, the TGA was calibrated using standard materials with known thermal properties. Calibration was performed with high-purity reference standards to verify temperature accuracy, and baseline corrections were applied before analysis. Additionally, the instrument's sensitivity was calibrated using materials with known moisture content to confirm its ability to accurately measure mass loss during the drying process.

The coal samples were placed in a platinum crucible of TGA and heated from room temperature to 250°C at varying heating rates of 5, 10, and 20°C/min in a nitrogen atmosphere for nonisothermal analysis. The use of low heating rates in this study was intended to capture detailed mass change phenomena in coal samples across the operating temperature range, providing a more precise understanding of thermal decomposition and moisture release. Slower heating rates (5°C/min) are generally employed for energy savings and better control over the drying process, while higher rates (20°C/min) are used in larger systems where faster drying times are required to increase throughput. Similar heating rates have been employed in previous studies to investigate biomass and coal combustion phenomena (Junga et al. 2017), further validating the approach used in this research.

Additionally, isothermal analysis was performed at constant temperatures of 150, 200, and 250°C for 30 minutes. These temperatures align with those used in common drying methods, such as rotary and fluidized-bed dryers, which operate in a range that balances efficient moisture removal with the prevention of thermal degradation of the coal. The selected isothermal temperatures, all above 150°C, were chosen to ensure the complete removal of both surface moisture and inherent moisture while preventing water re-adsorption (Li et al. 2009). The operating temperature is restricted to 250°C to prevent weight loss caused by the combustion of volatile compounds (Guo et al. 2020). The TGA data obtained were analyzed to determine the optimum drying temperature and drying kinetics of the coal.

2.2 Drying kinetics models

Mathematical models to describe the characteristics of moisture reduction in coal over time, such as the Lewis, Henderson and Pabis, Logarithmic, and Page models, have been widely used to characterize drying, particularly under isothermal conditions. However, when experimental data are obtained under nonisothermal conditions, these models must be modified to account for temperature variations over time, controlled by the heating rate β (°C/min) (Kian-Pour and Karatas 2019; Karmakar 2021).

Under isothermal conditions, kinetic parameters such as the drying rate constant k are commonly used to describe the coal drying process at a constant temperature, as shown in Table 1. This constant is linked to temperature through the Arrhenius equation in Eq. (1), which involves the pre-

TABLE 1. Drying models of coal for isothermal conditions.

Models	Model equations	Ref
Newton	$MR = exp(-kt)$	Lewis (1921)
Henderson and Pabis	$MR = a.exp(-kt)$	Henderson and Pabis (1961)
Logarithmic	$MR = a.exp(-kt) + c$	Doymaz (2006)
Page	$MR = exp(-kt^n)$	Page (1949)

Here, $MR = \frac{m_t - m_e}{m_i - m_e}$ is the moisture ratio; m_t is the moisture content at time t; m_e is the equilibrium moisture content; m_i is the initial moisture content; t is the time (min); a and n are drying constants specific to the model being used; and k is the drying rate constant (1/min).

exponential factor k_o (1/min), activation energy E_a (J/mol), temperature T (°C), and the ideal gas constant R. The isothermal model has proven effective for various materials, including coal, with k values calculated for each drying temperature.

$$k = k_0 \exp(-\frac{E_a}{R(T + 273.15)}) \tag{1}$$

On the other hand, under nonisothermal conditions, the drying kinetics model must be adjusted to account for temperature changes over time. In this scenario, the model must include the heating rate β (°C/min), which allows for the adjustment of kinetic parameters over the drying time t (min), as shown in Eq. (2). Consequently, the value of k will fluctuate according to temperature changes, enabling a more accurate modeling of the drying process under dynamic temperature variations, as presented in Table 2 (Rueda-Ordóñez and Tannous 2018).

The moisture ratio data fitting was conducted using four drying models under both isothermal and nonisothermal conditions, as shown in Tables 1 and 2. The statistical evaluation of the models was performed using chi-square (χ^2), coefficient of determination (R^2), and root mean square error (RMSE), as presented in Equations (3), (4), and (5), to assess the models' goodness-of-fit (Kucuk et al. 2014).

$$T = T_0 + \beta t \tag{2}$$

$$X^2 = \frac{\sum_{i=1}^{N} (MR_{pre,i} - MR_{exp,i})^2}{N - z} \tag{3}$$

$$R^2 = 1 - \left[\frac{\sum_{i=1}^{N} \left(MR_{pre,i} - MR_{exp,i}\right)^2}{\sum_{i=1}^{N} \left(\overline{MR}_{pre,i} - MR_{exp,i}\right)^2}\right] \tag{4}$$

TABLE 2. Drying models of coal for nonisothermal conditions.

Models	Model equations
Newton	$MR = \exp\left[-k_0 \exp\left(-\frac{E_a}{R(T+273.15)}\right)\left(\frac{T-T_0}{\beta}\right)\right]$
Henderson and Pabis	$MR = a \exp\left[-k_0 \exp\left(-\frac{E_a}{R(T+273.15)}\right)\left(\frac{T-T_0}{\beta}\right)\right]$
Logarithmic	$MR = a \exp\left[-k_0 \exp\left(-\frac{E_a}{R(T+273.15)}\right)\left(\frac{T-T_0}{\beta}\right)\right] + c$
Page	$MR = \exp\left[-k_0 \exp\left(-\frac{E_a}{R(T+273.15)}\right)\left(\frac{T-T_0}{\beta}\right)^n\right]$

Where, t is the time (min); a, c, n are drying constants specific to the model being applied; k_o is the drying rate constant (1/min); E_a is the activation energy (J/mol); β is the heating rate (°C/min); T is the drying temperature at time t (°C); T_o is the initial drying temperature (°C).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{exp,i}\right)^2}{N}} \quad (5)$$

Where, $MR_{pre,i}$ is the predicted moisture ratio for the i data point; $MR_{exp,i}$ is the experimental moisture ratio for the i data point; N is the number of observations; and z is the number of constants in the model. A model is considered to accurately represent the drying process if it yields a low χ^2 value, a high R^2 value, and a low RMSE. These criteria collectively assess the model's ability to fit the experimental data well.

3. RESULTS AND DISCUSSION

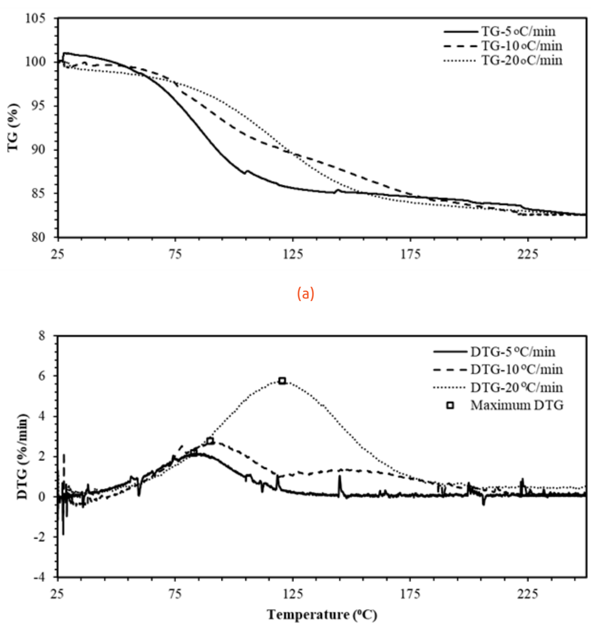
3.1 Temperature drying optimization under different heating rate conditions

Figures 1 and 2 display the Thermogravimetric (TG) and First Derivative Thermogravimetric (DTG) curves for two types of coal: lignite (Figure 1) and sub-bituminous (Figure 2). The horizontal axis (x) represents temperature (°C), while the vertical axis (y1) shows TG values (%) and (y2) DTG values (%/min), illustrating the rate of mass loss as the material heats. Each DTG curve highlights the temperature at which the mass reduction rate reaches its maximum, thereby indicating the optimal drying temperature for each type of coal at specific heating rates.

For lignite (Figure 1), the optimal drying temperature at a heating rate of 5°C/min is reached at 83.04°C, with a maximum DTG value of 2.17 %/min. At a heating rate of 10°C/min, the optimal temperature rises to 90.04°C, with a DTG maximum of 2.74 %/min. At the highest heating rate of 20°C/min, the optimal drying temperature reaches 120.51°C, with a maximum DTG value of 5.74 %/min. This increase in optimal temperature shows that as the heating rate intensifies, the energy received by the sample also increases, requiring a higher temperature to achieve the maximum mass reduction rate. Thus, lignite exhibits a trend where the optimal drying temperature rises with an increasing heating rate.

For sub-bituminous coal (Figure 2), a similar pattern emerges, with optimal drying temperatures increasing at higher heating rates. At a heating rate of 5°C/min, the optimal temperature is 77.12°C, with a DTG maximum of 3.82 %/min. For a heating rate of 10°C/min, the optimal drying temperature increases to 100.30°C, with a DTG maximum of 5.33 %/min. At a heating rate of 20°C/min, the optimal drying temperature reaches 109.65°C, with a DTG maximum of 8.77 %/min. Compared to lignite, sub-bituminous coal requires a higher optimal drying temperature, especially at faster heating rates, indicating that sub-bituminous coal has different thermal characteristics, needing higher temperatures for effective drying at elevated heating rates.

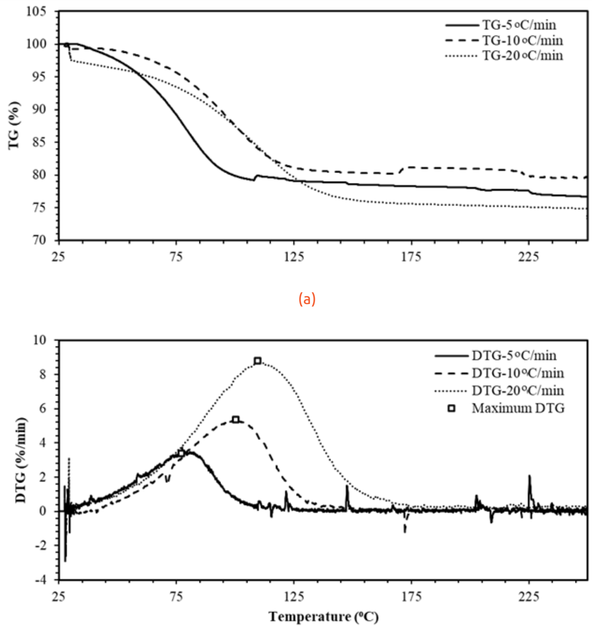
The results indicate that the drying temperature increases with the heating rate for both lignite and sub-bituminous coal, demonstrating a direct correlation between thermal energy input and the moisture removal rate. This aligns with findings in existing studies (e.g., Zhang et al. (2023); Paswan et al. (2023)) which also report that higher heating rates reduce the time needed to achieve maximum drying efficiency. The observed differences in optimal temperatures for lignite and sub-bituminous coal underline the role of intrinsic material properties, such as pore structure and moisture-binding characteristics, in influencing thermal behavior. Sub-bituminous coal, with higher optimal drying temperatures, suggests stronger moisture-binding energy, requiring more thermal energy to achieve similar weight loss rates as lignite. This information is essential in setting optimal drying conditions to enhance process efficiency. By understanding the drying characteristics of lignite and sub-bituminous coal, the drying process can be optimized for each type of coal and desired heating rate, thus supporting energy efficiency and time effectiveness in indus-



(a)

(b)

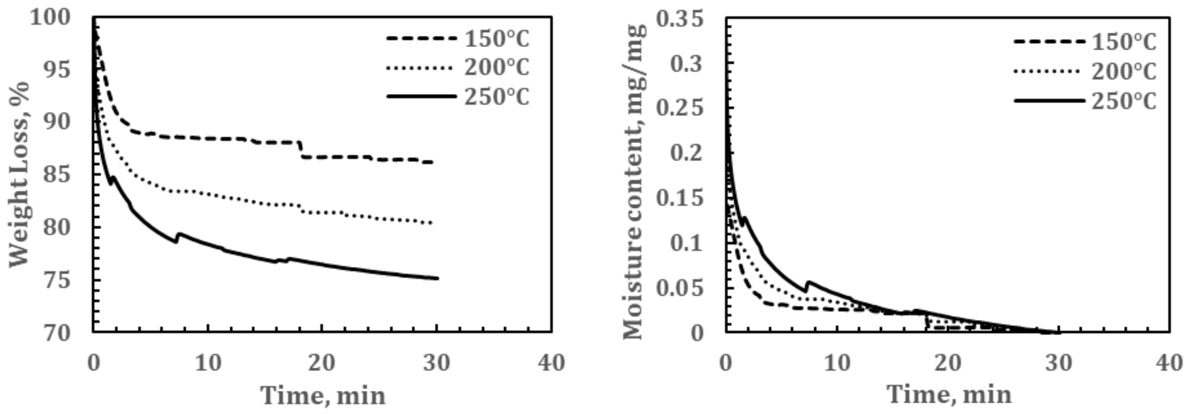
FIGURE 1. (a) Thermogravimetric (TG) and (b) first derivative thermogravimetric (DTG) analysis of lignite at different heat rates (5°C/min, 10°C/min, and 20°C/min).



(a)

(b)

FIGURE 2. (a) Thermogravimetric (TG) and (b) first derivative thermogravimetric (DTG) analysis of sub-bituminous at different heat rates (5°C/min, 10°C/min, and 20°C/min).



(a) (b)

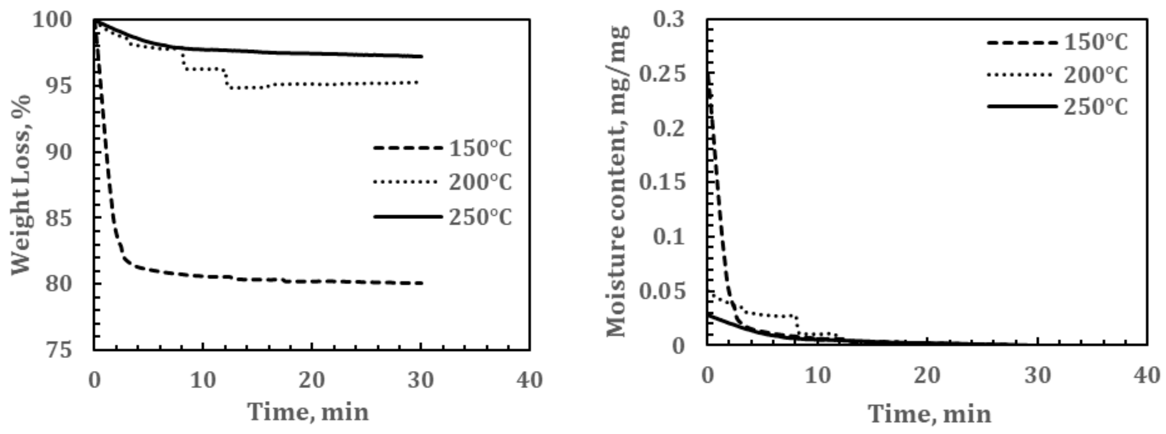
FIGURE 3. Drying curves of lignite coal under isothermal conditions: weigh loss curve (a) and moisture content curve (b).

tries using coal as an energy source. In practical applications, using higher heating rates can optimize the drying process by reducing energy consumption per unit moisture removed, especially when drying sub-bituminous coal. However, careful control is required to prevent thermal degradation at excessively high temperatures.

3.2 Drying characteristics under different temperature conditions

Figures 3 and Figure 4 display the drying curves for two types of coal, lignite (Figure 3) and sub-bituminous (Figure 4), dried at three different isothermal temperatures: 150°C, 200°C, and 250°C. Each figure consists of two parts: the weight loss curve (a) and the moisture content curve (b) over time at each temperature. In Figure 3, which shows the drying process of lignite coal, significant weight loss is observed early in the drying process, especially at the higher temperature of 250°C. The weight loss curve (3a) reveals that 250°C results in a faster weight reduction compared to 200°C and 150°C, indicating that at higher temperatures, surface and bound water in the coal evaporate more rapidly. At 150°C, the weight loss rate is slower and more stable, suggesting that at lower temperatures, the lignite drying process proceeds at a slower rate. The moisture content curve (3b) for lignite displays a similar pattern, where moisture reduction occurs sharply at the beginning of the drying process across all three temperatures, particularly at the higher temperature. After some time, the moisture reduction rate slows down and approaches a near-stable condition. Meanwhile, Figure 4 shows the drying curves for sub-bituminous coal under the same conditions. Similar to lignite, sub-bituminous coal experiences significant weight loss at the beginning of the drying process, with the highest rate at 250°C, as seen in the weight loss curve (4a). However, the difference in weight loss rates across the different temperatures is less pronounced for sub-bituminous coal compared to lignite, which may suggest that the water-binding characteristics of sub-bituminous coal are more stable or less responsive to temperature variations. The moisture content curve (4b) for sub-bituminous coal shows a sharp decrease in moisture content early in the drying process across all temperatures, but the rate of moisture reduction in sub-bituminous coal tends to stabilize more quickly, particularly at the lower temperature of 150°C. This indicates that although drying at higher temperatures is faster, drying at lower temperatures remains effective and provides a more stable rate of moisture reduction.

The drying curves reveal distinct weight loss behaviors for lignite and sub-bituminous coal, with lignite showing a higher sensitivity to temperature changes due to its higher



(a) (b)

FIGURE 4. Drying curves of sub-bituminous coal under isothermal conditions: weigh loss curve (a) and moisture content curve (b).

TABLE 3. Statistical results obtained from the isothermal models of lignite.

Model	Temperature (°C)	k (min^{-1})	X^2	R^2	RMSE
Newton	150	0.36	8.70x10^{-3}	6.22x10^{-1}	9.35x10^{-2}
	200	0.40	7.30x10^{-3}	5.90x10^{-1}	8.52x10^{-2}
	250	0.40	7.40x^{-3}	5.49x10^{-1}	8.62x10^{-2}
Henderson and Pabis	150	0.14	4.90x10^{-3}	7.85x10^{-1}	6.99x10^{-2}
	200	0.15	2.00x10^{-3}	8.78x10^{-1}	4.52x10^{-2}
	250	0.15	1.30x10^{-3}	9.14x10^{-1}	3.58x10^{-2}
Logarithmic	150	0.44	3.30x10^{-3}	8.56x10^{-1}	5.77x10^{-2}
	200	0.27	1.40x10^{-3}	9.14x10^{-1}	3.81x10^{-2}
	250	0.22	1.00x10^{-3}	9.35x10^{-1}	3.11x10^{-2}
Page	150	0.66	2.00x10^{-3}	9.14x10^{-1}	4.47x10^{-2}
	200	0.75	3.00x10^{-4}	9.81x10^{-1}	1.86x10^{-2}
	250	0.79	2.00x10^{-4}	9.86x10^{-1}	1.53x10^{-2}

inherent moisture content and less stable water-binding properties. In contrast, sub-bituminous coal demonstrates more uniform drying rates across different temperatures, potentially due to its denser structure or lower surface area exposed to thermal energy. At 250°C, the drying process is faster for both types of coal; however, lignite's greater sensitivity to temperature variations highlights its unique thermal properties, while sub-bituminous coal exhibits a more stable drying curve. These differences are crucial for optimizing the drying process, as they underscore the need for tailored drying strategies for each coal type to enhance efficiency and achieve the optimal balance between moisture reduction and energy input.

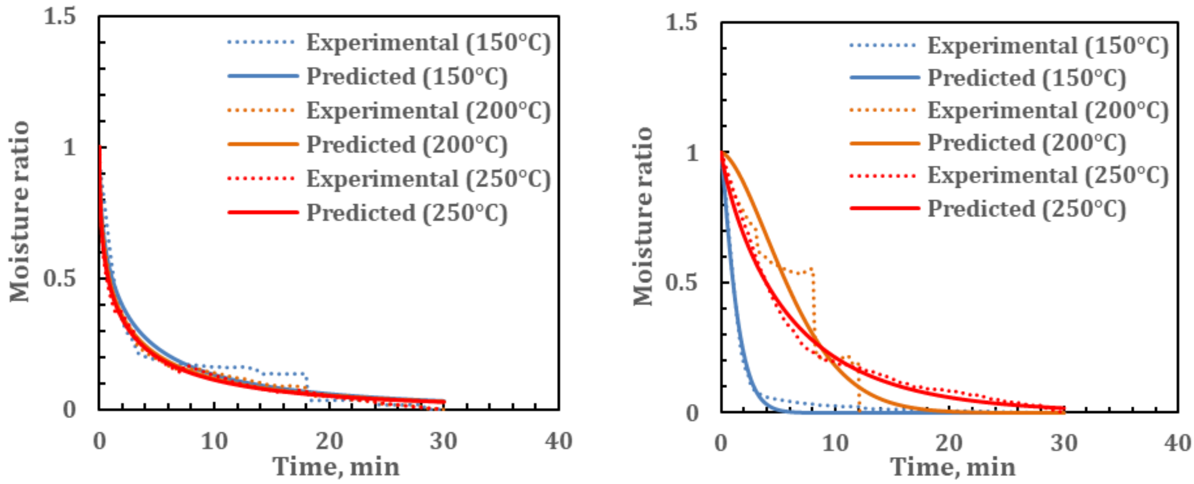
These findings resonate with earlier work by Kumar Mishra and Mohanty (2021), which noted that lower-rank coals generally exhibit steeper initial drying rates due to rapid surface moisture evaporation. However, the stabilization of moisture reduction in sub-bituminous coal at lower temperatures may reflect the influence of internal diffusion as the dominant moisture transport mechanism. The stabilization observed at lower temperatures suggests potential energy savings for sub-bituminous coal by operating at moderately high temperatures rather than extreme conditions. Industries focusing on lignite drying must prioritize higher temperature ranges for efficiency while balancing cost and energy consumption.

3.3 Isothermal drying kinetics

The four drying models in Tables 3 and 4 were used to fit TGA drying data under isothermal conditions. Table 3 presents the results for lignite samples, where the Page model demonstrated exceptional performance with R^2 values ranging from 0.9136 to 0.9858, significantly outperforming other models such as the Newton model, which showed lower R^2 values (0.5485–0.6221) and higher χ^2 and RMSE values. Similarly, Table 4 summarizes the results for sub-bituminous samples, where the Page model again emerged as the best fit, achieving the highest R^2 values of up to 0.9873 and the lowest χ^2 and RMSE values, confirming its robustness in describing the drying kinetics. In comparison, other models such as Henderson and Pabis and Logarithmic performed moderately well but were less consistent, particularly under varying temperature conditions. These results highlight the superior accuracy and reliability of the Page model for both lignite and sub-bituminous samples. The Page model fitting for the drying of low-rank coal (lignite and sub-bituminous) is shown in Figure 5. Additionally, the distinct activation energy values between the two coal types underline their differing thermal behaviors, with sub-bituminous coal requiring nearly six times the activation energy of lignite. This indicates stronger moisture-binding properties in sub-bituminous coal, making its drying process more energy-intensive compared to lignite.

TABLE 4. Statistical results obtained from the isothermal models of sub-bituminous.

Model	Temperature (°C)	k (min^{-1})	X^2	R^2	RMSE
Newton	150	0.16	5.00x10^{-4}	9.78x10^{-1}	2.23x10^{-2}
	200	0.16	1.12x10^{-2}	8.84x10^{-1}	1.05x10^{-1}
	250	0.71	1.10x10^{-3}	9.80x10^{-1}	3.34x10^{-2}
Henderson and Pabis	150	0.16	4.00x10^{-4}	9.82x10^{-1}	1.99x10^{-2}
	200	0.17	1.04x10^{-2}	8.92x10^{-1}	1.02x10^{-1}
	250	0.78	1.10x10^{-3}	9.80x10^{-1}	3.26x10^{-2}
Logarithmic	150	0.19	2.00x10^{-4}	9.89x10^{-1}	1.57x10^{-2}
	200	0.17	1.04x10^{-2}	8.92x10^{-1}	1.02x10^{-1}
	250	0.82	4.60x10^{-4}	9.92x10^{-1}	2.14x10^{-2}
Page	150	0.21	7.00x10^{-4}	9.87x10^{-1}	2.63x10^{-2}
	200	0.04	6.90x10^{-3}	9.29x10^{-1}	8.30x10^{-2}
	250	0.66	4.00x10^{-4}	9.82x10^{-1}	2.01x10^{-2}



(a) (b)

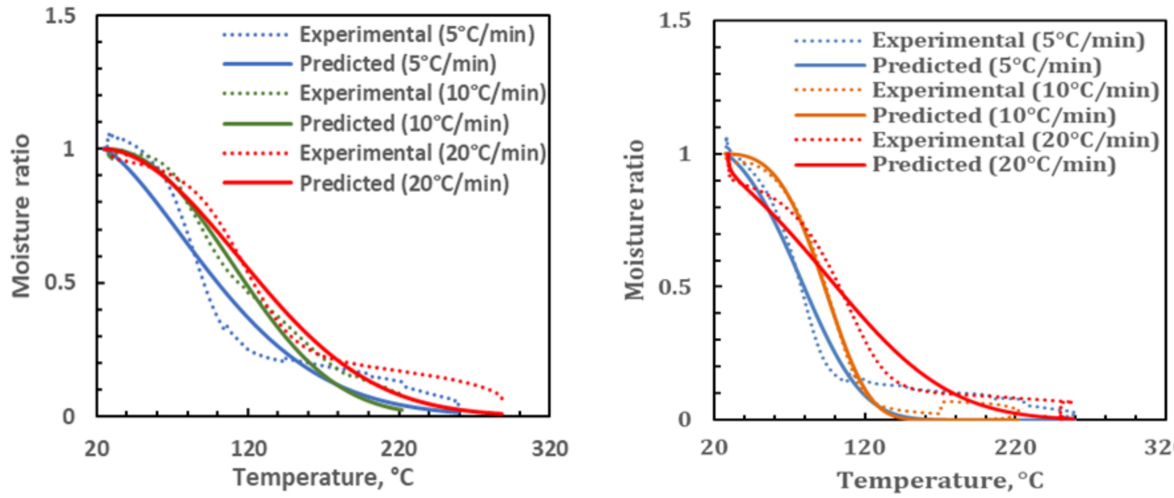
FIGURE 5. Comparison of experimental and predicted moisture ratios using the Page model for lignite (a) and sub-bituminous (b) coal under isothermal conditions.

3.4 Nonisothermal drying kinetics

As with isothermal conditions, the Page model also demonstrated exceptional performance in describing the drying characteristics of both lignite and sub-bituminous coal under non-isothermal conditions. Its accuracy across varying thermal conditions underscores its versatility and reliability in modeling drying processes. Statistical analyses presented in Tables 5 and 6 show that the non-isothermal Page model consistently achieved the highest R_2 values and the lowest χ_2 values compared to the other models, confirming its suitability for dynamic industrial processes. This highlights the model's ability to provide accurate predictions of drying behavior under different heating rates. Furthermore, Figure 6 illustrates a strong correlation between experimental data and predicted values using the non-isothermal Page model, further reinforcing its robustness and practical applicability for optimizing coal drying operations.

The results obtained in this study are consistent with previous research that has identified the Page model as the most accurate, particularly in relation to organic materials. For example, Cai and Chen (2008) found that the Page model best represented the drying kinetics of wheat straw and corn stalk, while Rueda-Ordóñez and Tannous (2018) concluded that the model accurately described the drying kinetics of sugarcane straw. However, Doymaz (2006) reported a different outcome, where the logarithmic model provided a better representation of the drying kinetics of mint leaves. This variation underscores the fact that the selection of the most appropriate model depends on the specific characteristics of the biomass being dried. Although these studies focused on organic materials rather than coal, they provide valuable insights into how different models perform under various conditions.

The activation energy for low-rank coal drying typically ranges from 11.62 to 37.24 kJ/mol (Li et al. 2009), which aligns with the values observed in this study. The activation energy for drying lignite (3.22 kJ/mol) is significantly lower than that for sub-bituminous coal (17.97 kJ/mol), which has direct implications for the drying process. These values represent



(a) (b)

FIGURE 6. Comparison of experimental and predicted moisture ratios using the Page model for lignite (a) and sub-bituminous (b) coal under nonisothermal conditions.

TABLE 5. Statistical results obtained from the nonisothermal models of lignite.

Model	Heat rate (°C/min)	ko (min^{-1})	E_a	X^2	R^2	RMSE
Newton	5	0.14	3224.04	$5.30x10^{-3}$	$9.62x10^{-1}$	$7.28x10^{-2}$
	10	0.29	3224.04	$5.10x10^{-3}$	$9.51x10^{-1}$	$7.14x10^{-2}$
	20	0.48	3224.04	$2.80x10^{-3}$	$9.71x10^{-1}$	$5.26x10^{-2}$
Henderson and Pabis	5	0.15	3224.04	$3.60x10^{-3}$	$9.75x10^{-1}$	$5.97x10^{-2}$
	10	0.30	3224.04	$4.70x10^{-3}$	$9.55x10^{-1}$	$6.85x10^{-2}$
	20	0.49	3224.04	$2.50x10^{-3}$	$9.74x10^{-1}$	$4.95x10^{-2}$
Logarithmic	5	0.15	3224.04	$3.60x10^{-3}$	$9.75x10^{-1}$	$5.97x10^{-2}$
	10	0.30	3224.04	$4.70x10^{-3}$	$9.55x10^{-1}$	$6.85x10^{-2}$
	20	0.50	3224.04	$2.50x10^{-3}$	$9.74x10^{-1}$	$4.95x10^{-2}$
Page	5	0.05	3224.04	$4.10x10^{-3}$	$9.71x10^{-1}$	$6.42x10^{-2}$
	10	0.03	3224.04	$1.20x10^{-3}$	$9.88x10^{-1}$	$3.52x10^{-2}$
	20	0.11	3224.04	$9.00x10^{-3}$	$9.90x10^{-1}$	$3.04x10^{-2}$

the energy barrier that must be overcome during drying and emphasize the critical role of activation energy in determining both the drying rate and the energy required for the process. A higher activation energy results in a lower drying rate constant, and as the constant decreases, the drying rate also decreases, in accordance with the Arrhenius equation (Eq.1). The findings suggest that the type of coal significantly influences both energy consumption and drying duration. Specifically, lignite, with its lower activation energy, requires less energy and a shorter drying time compared to sub-bituminous coal. Based on Eq. 1, the energy required to dry lignite in this study is approximately 2,365 kJ/kg H_2O, with a drying time of 225 minutes, whereas sub-bituminous coal requires 2,413 kJ/kg H_2O and takes 272 minutes to dry. These differences underscore the importance of tailoring drying conditions to the type of coal, which directly impacts energy consumption and operational costs. Understanding activation energy is crucial for designing efficient drying systems. By adjusting drying temperature, heating rates, and other operational parameters according to the activation energy values, more energy-efficient and cost-effective drying processes can be achieved. This approach also enables more accurate predictions of the minimum power requirements for drying equipment, supporting process optimization and ultimately enhancing both energy efficiency and cost-effectiveness in industrial coal drying operations.

3.5 Practical implications

Optimizing the drying process for LRC has significant practical implications, particularly in enhancing energy efficiency, reducing operational costs, and minimizing environmental impact. One of the key factors in this process is determining the optimal drying temperature, which directly influences energy consumption and fuel quality. By selecting the appropriate temperature, the energy required to remove moisture can be minimized, thereby increasing the coal's calorific value and reducing transportation costs due to mass reduction (Waghmare 2021; Rao et al. 2015). Furthermore, optimizing drying conditions contributes to environmental sustainability by lowering the energy demand for combustion, ultimately reducing CO_2 emissions (Ullah et al. 2018). On an industrial scale, achieving optimal drying conditions not only improves operational efficiency but also provides substantial economic benefits.

Developing accurate drying kinetic models is essential for optimizing the LRC drying process. These models serve as predictive tools to anticipate coal behavior under various drying conditions, ensuring consistent moisture removal while maintaining energy efficiency (Liu et al. 2021). By analyzing key variables such as drying time, temperature, and moisture diffusion, kinetic models enable operators to fine-tune operational parameters, preventing both overdrying and underdrying. This ensures coal quality, calorific value, and mechanical stability, thereby supporting efficient downstream utilization (Simanjuntak et al. 2024). Additionally, predictive

TABLE 6. Statistical results obtained from the nonisothermal models of sub bituminous coal.

Model	Heat rate (°C/min)	ko (min^{-1})	E_a	X^2	R^2	RMSE
Newton	5	30.75	17972.83	$3.50x10^{-3}$	$9.73x10^{-1}$	$5.91x10^{-2}$
	10	40.78	17972.83	$1.00x10^{-3}$	$9.91x10^{-1}$	$3.14x10^{-2}$
	20	61.22	17972.83	$1.00x10^{-3}$	$9.88x10^{-1}$	$3.10x10^{-2}$
Henderson and Pabis	5	33.02	17972.83	$3.20x10^{-3}$	$9.75x10^{-1}$	$5.69x10^{-2}$
	10	41.34	17972.83	$1.00x10^{-3}$	$9.91x10^{-1}$	$3.12x10^{-2}$
	20	54.10	17972.83	$5.00x10^{-3}$	$9.94x10^{-1}$	$2.25x10^{-2}$
Logarithmic	5	37.85	17972.83	$1.70x10^{-3}$	$9.87x10^{-1}$	$4.15x10^{-2}$
	10	41.99	17972.83	$9.00x10^{-3}$	$9.91x10^{-1}$	$3.08x10^{-2}$
	20	57.07	17972.83	$3.00x10^{-3}$	$9.96x10^{-1}$	$1.84x10^{-2}$
Page	5	27.73	17972.83	$3.50x10^{-3}$	$9.73x10^{-1}$	$5.91x10^{-2}$
	10	4.38	17972.83	$4.00x10^{-3}$	$9.96x10^{-1}$	$2.04x10^{-2}$
	20	155.31	17972.83	$6.00x10^{-3}$	$9.93x10^{-1}$	$2.43x10^{-2}$

modeling enhances adaptability to variations in feedstock and energy constraints, making industrial drying operations more resilient and cost-effective.

Another crucial aspect of LRC drying optimization is understanding activation energy, which defines the minimum thermal energy required to evaporate moisture from the coal. Lower activation energy enables effective drying at lower temperatures, reducing overall energy consumption and operational costs (Wen et al. 2017). Understanding activation energy also assists in selecting suitable drying technologies and fuel sources that align with the specific thermal properties of the coal. Moreover, it plays a vital role in ensuring operational safety by identifying critical conditions that may lead to coal reactivity or instability, helping to mitigate risks such as spontaneous combustion and overheating during the drying process (Rastogi 2020).

Despite the advancements presented in this study, several limitations must be addressed to improve its applicability as a reference for pilot-scale and industrial design. One significant limitation is the lack of a comprehensive analysis of particle size variation. The study primarily focuses on fine, uniform particles, whereas industrial applications involve a wide range of particle sizes that can significantly affect drying efficiency, moisture diffusion, and heat transfer. Further research is needed to assess the influence of particle size distribution on drying performance and energy efficiency. Additionally, the effects of fluidization and heat transfer distribution, particularly in rotary drying systems, remain a challenge. While this study acknowledges the presence of dynamic non-isothermal conditions, it does not explicitly analyze the impact of fluidization on drying efficiency. To enhance scalability and industrial relevance, more detailed experimental and computational studies are required to understand how heat distribution and fluidization mechanisms influence drying performance in large-scale systems.

Additionally, the environmental impact of coal drying has not been thoroughly explored. Issues such as emissions during the drying process, energy trade-offs, and potential environmental risks require further investigation. Future research should include life cycle assessments and environmental impact analyses to ensure that drying technologies align with sustainability objectives, particularly in reducing greenhouse gas emissions and optimizing energy use. By integrating key factors such as optimal drying temperature, kinetic modeling, activation energy analysis, and addressing existing research limitations, a more effective, safe, and sustainable approach to low-rank coal drying can be developed. These advancements will not only improve the economic feasibility of coal utilization but also contribute to cleaner energy practices and a reduced environmental footprint, supporting the shift towards more sustainable industrial operations.

4. CONCLUSIONS

This study successfully identifies the Page Model as the most suitable kinetic drying model for describing the drying behavior of Indonesian lignite and sub-bituminous coal under both isothermal and non-isothermal conditions. For Indonesian lignite coal, the optimal drying temperature was determined to be 83.04°C, with an activation energy of 3,224.04 J/mol. Meanwhile, Indonesian sub-bituminous coal exhibited an optimal drying temperature of 109.65°C, with a higher activation energy. These findings align with the study's objective of identifying the optimal drying temperature and the most appropriate kinetic model for Indonesian low-rank coal, demonstrating that the Page Model effectively captures the drying characteristics under both steady-state and dynamic temperature conditions.

By providing accurate kinetic parameters, this research contributes to optimizing drying processes for Indonesian low-rank coal. Specifically, it offers insights into improved temperature regulation and heating rate adjustments to significantly reduce coal moisture content while preserving energy quality and thermal stability. These findings are critical for enhancing the efficiency and sustainability of low-rank coal utilization in Indonesia, particularly as part of efforts to support the country's energy demand and down streaming policies.

Future research should explore advanced modeling techniques that incorporate a broader range of variables, including industrial-scale conditions and operational complexities, to further enhance model predictability and applicability across diverse coal processing scenarios in Indonesia. In addition, environmental considerations must be incorporated into future studies. Life cycle assessments and environmental impact analyses should be conducted to ensure that drying technologies align with sustainability objectives, particularly in reducing greenhouse gas emissions and optimizing energy use. By integrating key factors such as optimal drying temperature, kinetic modeling, activation energy analysis, and addressing existing research limitations, a more effective, safe, and sustainable approach to low-rank coal drying can be achieved. These advancements will not only improve the economic feasibility of coal utilization but also contribute to cleaner energy practices, reducing the environmental footprint and supporting the transition toward more sustainable industrial operations.

5. ACKNOWLEDGEMENTS

We would like to express our sincere gratitude to the Institute for Research and Community Service of Universitas Pembangunan Nasional (UPN) Veteran Yogyakarta for their funding and support for this research. Their commitment to advancing scientific research has been instrumental in facilitating our work and enabling us to pursue our objectives effectively. We appreciate their trust and encouragement throughout the research process.

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