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Pyrolysis Behaviour of Muara Enim Coals: The Influence of Temperature and Ranks

Raden Maria Ulfa[1], Takehiro Esaki[2], Theodora Noely Tambaria[2], and Yuichi Sugai[2]

[1]Geological Agency, Ministry of Energy and Mineral Resources of Indonesia, Bandung 40254, Indonesia
[2]Department of Earth Resources Engineering, Faculty of Engineering,
Kyushu University, Fukuoka 819-0395, Japan

Corresponding author: maria.ulfa@esdm.go.id
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Abstract - Underground coal gasification (UCG) is a clean coal technology that converts coal in-situ into synthetic gas (syngas) through thermal and chemical reactions. Coal pyrolysis, a key reaction in UCG, initiates the thermal decomposition of coal, and influences gas yield and composition. This study examines the influences of pyrolysis temperature and coal rank on gas production using coal samples from The Muara Enim Formation, South Sumatra Basin. Four coal samples, ranging from lignite to bituminous rank, were pyrolyzed at 300, 400, 500, and 600° C under inert conditions. The results indicate that gas yield increases with temperature due to enhanced thermal decomposition. At lower temperatures (300−400° C) CO_2 dominates, particularly in lower-rank coals due to their higher oxygen content. At higher temperatures (500−600° C) more CH_4 and H_2 productions become more prominent, particularly in higher-rank coals. CH_4 generation is driven by the breakdown of aliphatic structures, while H_2 production results from dehydrogenation and condensation of aromatic structures. Lower-rank coal produced higher gas at low temperatures, indicating greater suitability for UCG under such conditions. In contrast, higher-rank coals require elevated temperatures for effective decomposition due to their greater thermal stability. These findings provide valuable geochemical insights into the pyrolysis behaviour of Muara Enim coals and offer a scientific basis for optimizing UCG conditions to improve gas yield and quality.

Keywords: coal pyrolysis, thermal decomposition, gas yield, temperature, Muara Enim

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Introduction

Background

Underground coal gasification (UCG) is a clean coal technology that enables the in-situ conversion of unmineable coal seams into synthetic gas (syngas) - primarily composed of hydrogen (H_2), methane (CH_4), carbon monoxide (CO), and carbon dioxide (CO_2) (Shafirovich and Varma, 2009). This process utilizes injection and production wells to access deep or geologically complex coal deposits, minimizing surface environmental disruption compared to conventional mining (Bhutto *et al*., 2013).

Fundamentally, the UCG process establishes distinct reactions zones within the coal seams, including oxidation zone, reduction zone, and dry distillation zone, defined by temperature, chemical reaction, and gas compositions (Liu *et al*., 2012). In the oxidation zone, injected oxidant

combusts part of the coal, generating essential heat. This heat drives endothermic reactions in adjacent reduction zones, including Boudouard reaction ($C + CO_2 \rightarrow 2CO$) and water-gas reactions ($C + H_2O \rightarrow CO + H_2$). Simultaneously, in the dry distillation zones, pyrolysis occursthermal decomposition of coal in the absence of oxygen. This reaction yields volatile gases, water vapour, condensable tars, and forming char (Y. Chen *et al*., 2023; Yuan *et al*., 2024).

Pyrolysis critically influences UCG efficiency. The volatile gases contribute directly to syngas production, while the residual char undergoes further gasification (Doucet *et al*., 2016). Coal rank and pyrolysis temperature are key factors controlling pyrolysis behaviour. Lower-rank coal (*e.g.* lignite and subbituminous), characterized by higher volatile matter and oxygen content, generally yield more gas compared to higher-rank coal (*e.g*. bituminous). Furthermore, increasing pyrolysis temperature enhances gas yield and alters syngas composition *(Burton et al.* (2019); Wang *et al*. (2018)).

However, the combined effects of coal rank and pyrolysis temperature under UCG-relevant conditions remain underexplored. This study addresses this gap by evaluating the pyrolysis behaviour of coals from The Muara Enim Formation (South Sumatera Basin, Indonesia) — a region renowned for its abundance and geochemically diverse coal resources. Specifically, investigate the effects of temperature and coal rank on gas yield and composition.

The main objective is to produce insight for improving syngas quality and optimizing UCG system designs. The findings are expected to contribute to the advancement of clean coal technologies and sustainable coal utilization strategies.

Geological Settings

The South Sumatra Basin, situated in Sumatera Island, is one of Indonesia`s most prolific coal-bearing basins, and is classified as a back-arc basin. The geological evolution began during The Late Cretaceous to Early Tertiary period, primarily driven by the subduction of the Indo-Australian Oceanic Plate beneath The Eurasian Continental Crust (Darman and Sidi, 2000; Hall, 2002). This tectonic activity led to regional extensional regimes that formed a series of structurally controlled subbasins, including The Jambi, North Palembang, Central Palembang, and South Palembang Subbasins (Darman and Sidi, 2000).

These subbasins were delineated by paleohigh and uplifted fault blocks, which later provided substrates for Early Miocene carbonate reef development following marine transgression (Wilson *et al*., 2000). The basin has undergoes multiple tectonic events, including The Middle Mesozoic orogeny, Late Cretaceous-Eocene tectonism, and Plio-Pleistocene orogeny (Darman and Sidi, 2000), resulting in structurally complex setting with numerous normal and reverse faults and localized folding (Figure 1a). These tectonic events created compartmentalized depocentres, favouring the accumulation and prevention of thick successions, including coal-bearing units (Prijosoesilo *et al*., 1993).

Stratigraphically (Figure 1b), The South Sumatera Basin is dominated by Tertiary sedimentary sequences. The major coal-bearing formations include The Talang Akar (Oligocene-Early Miocene) and Muara Enim Formation (Late Miocene-Pliocene) containing extensive coal seams. The Muara Enim Formation is the principal coal-bearing unit in the basin, and consists of multiple thick coal seams interbedded with deltaic sandstones and lacustrine mudstones. Coal seams within this formation can reach the thicknesses of up to 12 m, making them economically viable deposits in the region.

Coals from The Muara Enim Formation varies in rank from lignite to bituminous. The lignite and subbituminous coals (lower rank coals) exhibit high volatile matter content, making them suitable for thermal decomposition processes such as pyrolysis and syngas production during UCG. Petrographic analysis indicates that vitrinite is dominant macerals, accompanied by minor amounts of inertinites and mineral matter such as clays and pyrite. These coal properties

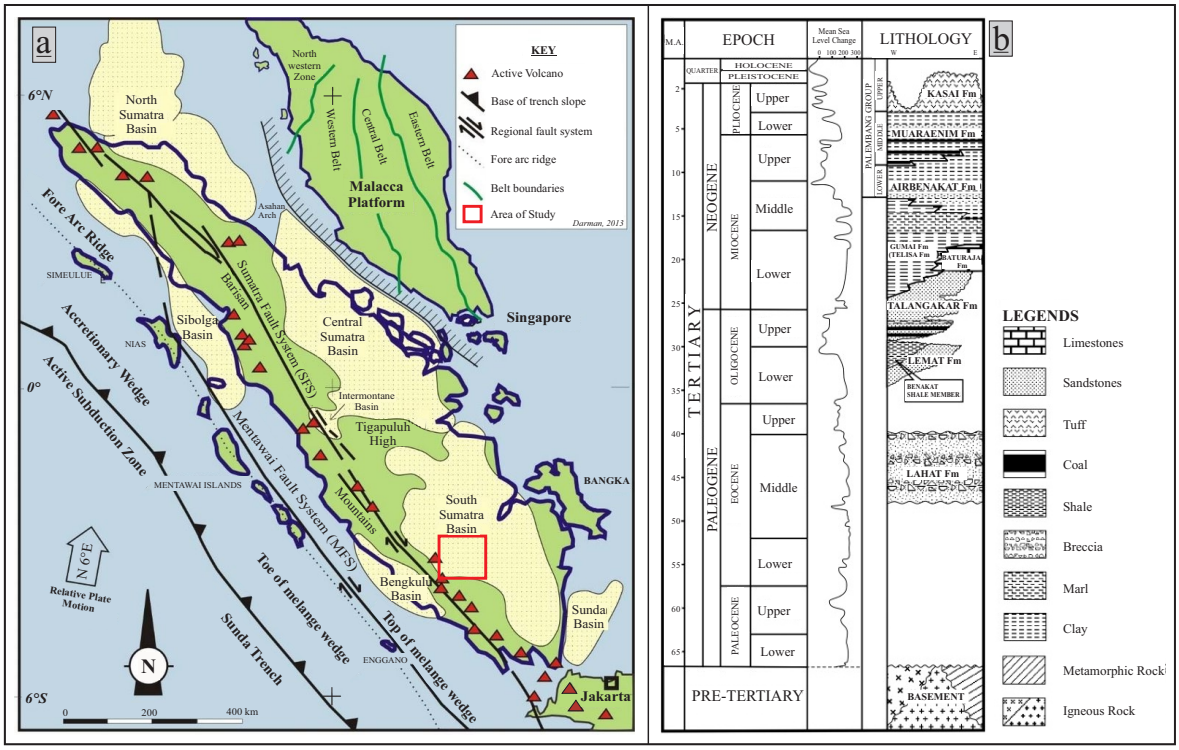

Figure 1. (a) Sumatera regional tectonic setting (Darman and Sidi, 2000); (b) Stratigraphy of The South Sumatra Basin (Sosrowidjojo and Saghafi, 2009).

make Muara Enim Formation an ideal material for studying decomposition kinetic and gasification potential under controlled pyrolysis conditions within UCG system. The combination of geological data and pyrolysis experiment contributes to a more comprehensive understanding of coal behaviour under gasification, supporting efforts to improve clean coal utilization in Indonesia.

Methods and Materials

Methods

Coal samples were characterized through proximate (ASTM D7582), ultimate (ASTM D5373), and petrographic analyses to determine their chemical, elemental, and maceral properties. Proximate analysis measured moisture content, volatile matter, fixed carbon, and ash content. Ultimate analysis determined the elemental composition (C, H, O, N, S by difference). Petrographic analysis assessed maceral composition to evaluate organic properties and thermal behaviour. All analyses were performed at The Centre of Mineral Coal and Geothermal Resources (CMCGR).

Pyrolysis experiments were conducted using a tubular electric furnace (TMF-700N, ASONE Corporation) under control conditions. For each experimental run, approximately 6 g of coal powder was evenly distributed between two alumina boat crucibles (3 g per crucible). Fresh samples were used for every target pyrolysis temperature (300° C, 400° C, 500° C, and 600° C), with independent runs conducted for each temperature-coal rank combination. The system was purged with high purity N_2 atmosphere with a flow rate of 15 ml/min. to maintain an inert environment. Coal samples were heated from ambient temperature to target temperatures at a heating rate of 10° C/min. Once the target temperature was reached, an isothermal hold for 30 minutes was maintained to ensure complete pyrolysis.

The gases generated during isothermal pyrolysis were continuously transferred into Tedlar® sampling bags. Gas composition of pyrolysis (CH_4, H_2, and CO_2) was qualified using a Gas Chromatograph (GC-3200S) equipped with

thermal conductivity detector (TCD), calibration with certified gas standards. Gas yield (in ml/g of coal) was calculated from integrated chromatographic peak areas and normalized to standard temperature and pressure (STP) condition. Due to analytical constraints, CO was not possible to be measured. This constraint is acknowledged as a limitation in the study, as CO is an important component in syngas composition. However, the available gases data still provide valuable insights into pyrolysis reactions and coal decomposition behaviour.

The influence of pyrolysis temperature and coal rank on gas yield was evaluated using linear regression analysis. Production trends for individual gases (CH_4, H_2, and CO_2) were evaluated to understand the pyrolysis mechanisms. This approach provided quantitative assessment of factors governing syngas precursor formation during coal pyrolysis.

Materials

Four coal samples were collected from The Muara Enim Formation (South Sumatera Basin), sampling targeted distinct lithological unit to capture variability in coal rank ranging from lignite (ME1), subbituminous (ME2) and bituminous coals (ME3 and ME4). Field tools such as geological hammers, sample bags, notebooks, and GPS were used to ensure accurate collection and documentation of sample collections. In the laboratory, coal samples were prepared by selecting the sample using the quartering method, followed by air-drying, crushing, and sieving to particle size <60 mesh (<250 µm) to ensure uniformity, which is critical for consistent pyrolysis experiment.

Result and Analysis

This study evaluates the pyrolysis behaviour of four Muara Enim coal samples - representing critical ranks for Underground Coal Gasification's (ME1: lignite B; ME2: sub-bituminous C; ME3: high volatile bituminous C; and ME4: low volatile bituminous) under temperature condition relevant to UCG reaction zones (dry distillation zones; <600° C. The quality parameters of these samples are summarized in Table 1 and Table 2. The results demonstrate how coal rank and pyrolysis temperature govern gas yield and composition, providing valuable insights into in-situ syngas generation efficiency during Underground Coal Gasification (UCG).

The coal samples were classified based on ASTM standards (ASTM, 2002), revealing distinct properties governing UCG reactivity. Lower-rank coals ME1 (lignite B) and ME2 (sub-bituminous C) exhibited high volatile matter (58.68 % dmmf for ME1), low fixed carbon (FC), and low calorific value. In contrast, higher-rank coals ME3 (high volatile bituminous C) and ME4 (low volatile bituminous) show inverse characteristics, with ME4 showing the lowest volatile matter content (17.5 % dmmf) and the highest fixed carbon content (83.35 % dmmf), aligning with its rank classification. These properties critically influence *in-situ* gasification behaviour, where high VM enhances volatile-driven syngas production in UCG cavities, while low VM necessitates greater thermal energy input for effective conversion.

The pyrolysis experiment (300-600° C) under a nitrogen (N_2) atmosphere demonstrated product yielded divided into three fractions that are relevant with UCG (Figure 2). Gas yield refers to the mea-

Table 1. The Coal Samples Parameter

Sample	Proximate (wt.%)					Ultimate (wt.%)				CV (kcal/kg)	TS (% adb)
	TM (% ar)	M (% adb)	Ash (% adb)	VM (% adb)	FC (% adb)	C (% daf)	H (% daf)	N (% daf)	O (% daf)		
ME1	57.47	11.54	9.72	45.66	33.09	66.16	5.95	1.01	26.53	4,707	0.28
ME2	30.85	9.64	0.78	46.33	43.26	72.88	6.39	0.98	20.54	6,174	0.18
ME3	12.86	3.69	3.5	41.29	51.52	79.43	6.98	1.22	12.10	7,208	0.25
ME4	7.04	1.4	2.49	16.68	79.44	89.48	4.84	1.70	2.84	8,230	1.09

Table 2. Petrographic Analysis of Coal Samples

Sample	Mean Vitrinite Reflectance (% Rv Random)	Maceral Composition			Mineral Matter	
		V	I	L	Clay	Py
ME1	0.3	70.2	3	1	24.8	1
ME2	0.41	81.8	9.4	5.4	3	0.4
ME3	0.54	83.6	8.2	5	3	0.2
ME4	1.42	85.4	-	-	13.8	0.8

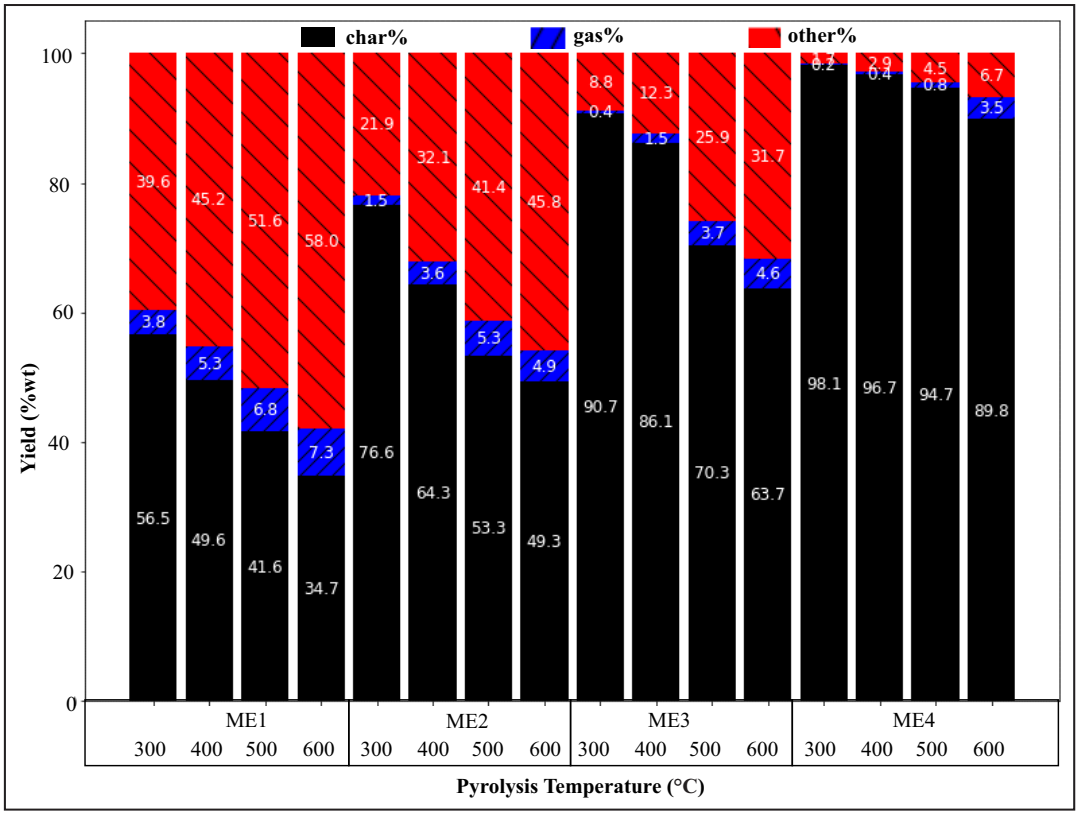

Figure 2. Pyrolysis product yield.

sured gaseous component, such as CO_2, CH_4, and H_2. Total gas yield (wt. %, daf) increased exponential with temperature for all ranks, consistent with enhanced devolatilization kinetics in UCG thermal regime. ME1 (lignite) achieved the highest gas yield (7.3 wt. % at 600° C), 105 % higher than ME4 (3.5 wt. %), attributable to its high volatile matter content. ME1 and ME2 generated significant yield at 300° C (ME1 3.8 wt. %; ME2 5.3 wt. %). In contrast, higher-rank coal (ME3 and ME4) produced lower gas yields due to their lower volatile matter content. ME4 demonstrated minimal gas production at lower temperatures (0.2 wt. % at 300° C), but experienced a notable increase (3.5 wt. % at 600° C), suggesting a threshold temperature for significant volatile release.

In addition to gas yield, the pyrolysis experiment also produced char and unmeasured volatile products, collectively as char % and other % in Figure 2. Char refers to the solid carbon-rich residue left after devolatilization, containing primarily of fixed carbon and ash. Its proportion decreases with increasing temperature, particularly in lower-rank coals (ME1 and ME2), reflecting greater volatile matter release and more extensive thermal decomposition, that will not explain in this paper.

The others % account, however, constitute a substantial portion of pyrolysis products yield,

particularly at intermediate temperatures (*e.g.* 400-500° C), reaching up to 58 % in some samples. This component represents pyrolysis products that were not directly quantified in this study due to instrumental constraints. These may include carbon monoxide (CO), a major syngas constituent, which was not measured due to gas absence of CO sensors: tar, and condensable hydrocarbons, which were not collected during experiment, as well as water vapour light organic volatiles, and gases released during the initial heating phase. The considerable size of this fraction highlights the complexity of pyrolysis reactions and underscores the need for more comprehensive characterization in future studies.

Gas compositions exhibited significant rank and temperature dependent variation (Figure 3). Carbon dioxide (CO_2) dominant at lower temperature (300-400° C), constituting 85-100 % across all ranks. This predominances reflect the decomposition of oxygen-containing functional group (carboxyl, carbonyls) in coal macromolecules. Above 400° C, CO_2 yields decreased by 24-97 % as thermal labile oxygen sources depleted. Methane (CH_4) generation initiated at 400° C through demethylation of aromatic clusters and cracking of aliphatic chains. ME3 (bituminous) produced the peak CH_4 content at 600° C (27.9 wt. %), whereas ME4 exhibits lower CH_4 production, emphasizing the role of coal rank in methane yield. Hydrogen (H_2) production emerged at 500° C, becoming more pronounced at 600° C via dehydrogenation of hydroaromatic structure and secondary cracking reaction – particularly pronounced in lower-rank coals (ME1/ME2) where aliphatic hydrogen content is elevated.

Discussion

This study showed that gas yield and composition during coal pyrolysis are influenced by the

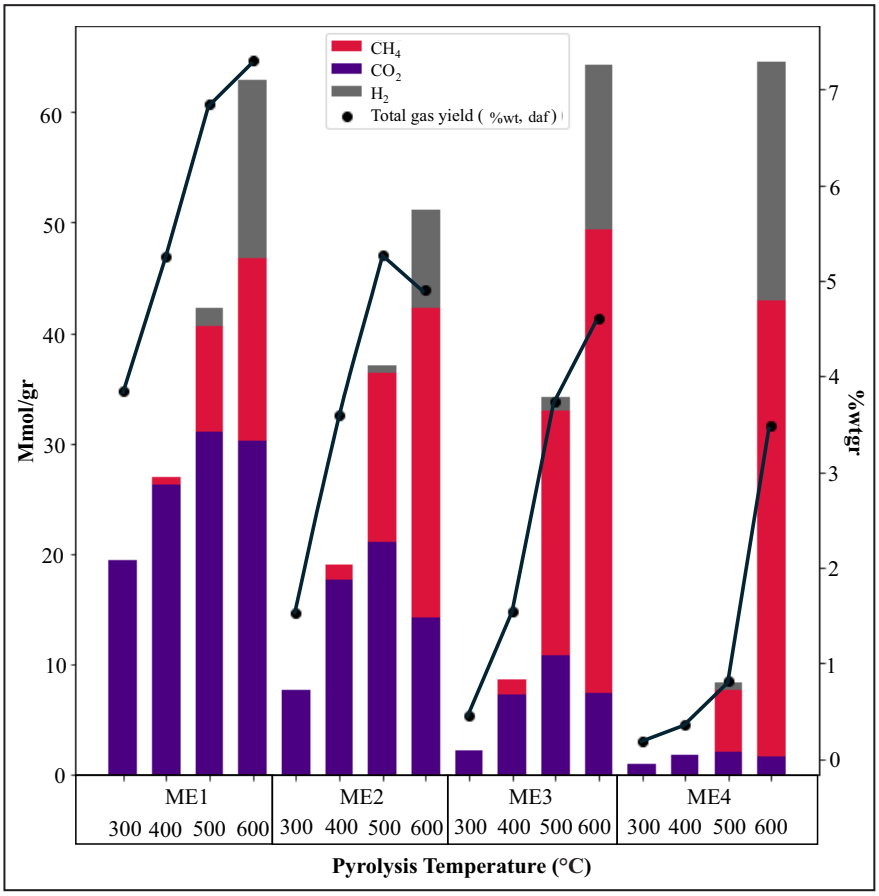

Figure 3. Gas composition and total gas yield.

interaction between coal rank and temperature regime, with profound implications for UCG efficiency. The results are aligned with the dynamics of the UCG reaction zone, where pyrolysis-mediated syngas modulation primary occurs in the dry distillation zone.

Temperature-Dependent Gas Production

This study confirms that pyrolysis gas yield and composition is temperature dependent with direct implication for in-situ syngas control in UCG. As illustrated in Figure 4a, the exponential increasing gas yield with temperature across all ranks align with enhanced devolatilization kinetics in UCG dry distillation zone. At lower temperatures (300-400° C), CO_2 was the dominant gas product (92-100 %), particularly in lower-rank coals (ME1 and ME2), due to the decomposition of oxygen-containing functional groups like carboxyl, which exhibit low thermal stability (R. Chen *et al.*, 2023). Conversely, higher-rank coals (ME3 and ME4) produced less CO_2 (85-100 %), reflecting their lower oxygen content and more condensed aromatic structures

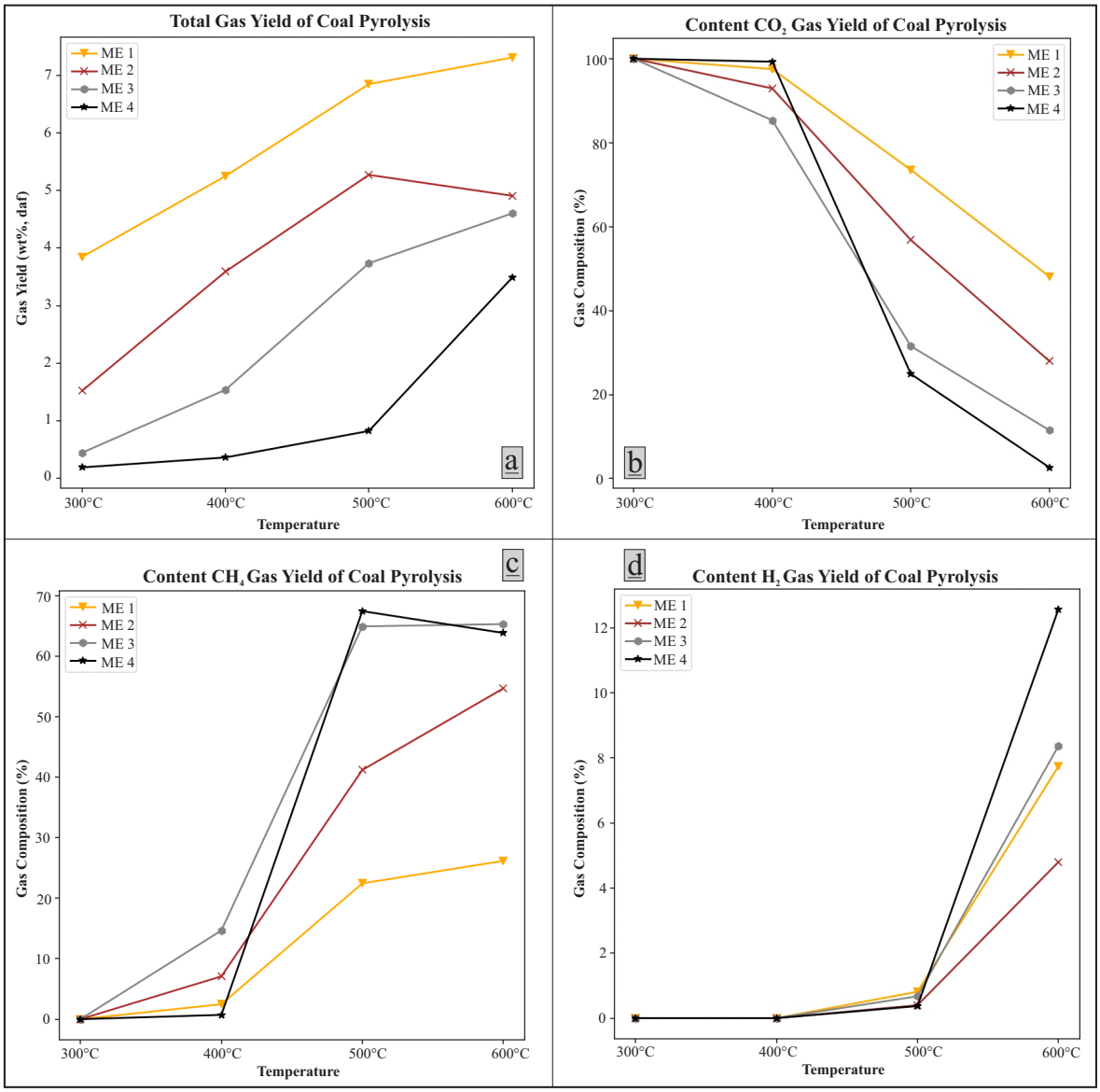

Figure 4. Cross-plot between: (a) Temperature and total gas yield, (b) Temperature and CO_2 production, (c) Temperature and CH_4 production, and (d) temperature and H_2.

resisting oxygen liberation (Guo *et al*., 2019; Meng e*t al*., 2021) (Figure 4b).

Methane (CH_4) production initiate at 400 °C across all coal ranks and continued to rise at higher temperatures (Figure 4c). Lower-rank coals, characterized by abundant aliphatic side chains, produced CH_4 more readily at this temperature due to primary cracking reactions that break weaker bonds, forming methyl (CH_3^-) radicals stabilized by donated hydrogen (Liu *et al*., 2014; Zhang *et al*., 2018). At 500-600° C, CH_4 generation increased substantially in higher-rank due to the secondary cracking reaction of aromatic structures (Liu *et al*., 2014; Xu *et al*., 2013). Hydrogen (H_2) production is negligible below 500° C become significant at 600° C (Figure 4d). This behaviour is associated with dehydrogenation, condensation and cyclization reaction (Wiktorsson and Wanzl, 2000).

Influence of Coal Rank on Gas Yields

Coal rank is a critical determinant of pyrolysis behaviour, primarily controlling the thermal decomposition rate, gas yield and composition during pyrolysis - the main reaction occurring in the dry distillation zone of UCG. Lower rank coal (ME1-ME2) possesses higher volatile matter and a greater abundance of oxygen containing functional group, making them more reactive under moderate pyrolysis temperatures (300-500° C). Their molecular structure–dominated by aliphatic chains and less-condensed aromatic rings– facilitate easier bond dissociation, leading to higher gas yield and earlier onset of gas evolution.

In contrast, higher rank coals (ME3-ME4) are characterized by lower volatile matter and a denser aromatic structure. These attributes confer greater thermal stability, leading to slower decomposition rate and requiring higher temperature to initiate significant gas release. As temperature increases, these coals tend to generate more CH_4 and H_2 through secondary cracking and dehydrogenation reactions, although their overall gas yield remains lower than that of lower rank coals.

These results are align with previous studies (Bao *et al*., 2016; Güney and Koyun, 2020; Widayat *et al*., 2025), which emphasize that higher rank coals generally exhibit lower thermal decomposition rates during pyrolysis due to reduced volatile matter content and stronger molecular structure. This supports the conclusion that increasing coal rank decreases the rate of volatile to gas conversion during pyrolysis.

A strong correlation was observed between volatile matter content and gas yield, particularly at 400-500° C range where CH_4 production is dominant. Furthermore, the observed trend of decreasing CO_2 content at higher temperatures indicates that targeting optimal pyrolysis temperature can help reduce CO_2 emission, aligning with clean coal and low-emission energy goals. Thus, adapting UCG conditions-particularly temperature profile to specific coal ranks is essential for optimizing gas yield and minimizing environmental impacts.

H_2/CH_4 Ratio and Syngas Optimization

The evolution of H_2/CH_4 ratio offers critical insight into pyrolysis reaction pathway and syngas composition within dry distillation zone of UCG system. Across all coal ranks, particularly at 600° C, this ratio reflects a strong tendency toward hydrogen-rich syngas production during pyrolysis.

Figure 5 present a comparative analysis of volatile matter (VM), vitrinite reflectance (Ro), and H_2/CH_4 ratio, highlighting the complex relationship between coal rank, molecular structure, and pyrolysis behaviour. ME1 (lignite B), with the highest VM (58.8 % dmmf) and lowest Ro (0.38 %), generated the highest H_2/CH_4 ratio (0.98). This outcome indicates extensive secondary cracking and dehydrogenation at high temperatures, facilitates by abundant aliphatic chains and weak molecular bonding.

Interestingly, ME2, despite having slightly higher VM than ME3, yielded the lowest H_2/CH_4 ratio (0.317). This implies that hydrogen production is not solely governed by volatile content, but also influenced by macromolecular ordering and the availability of donating hydrogen structures.

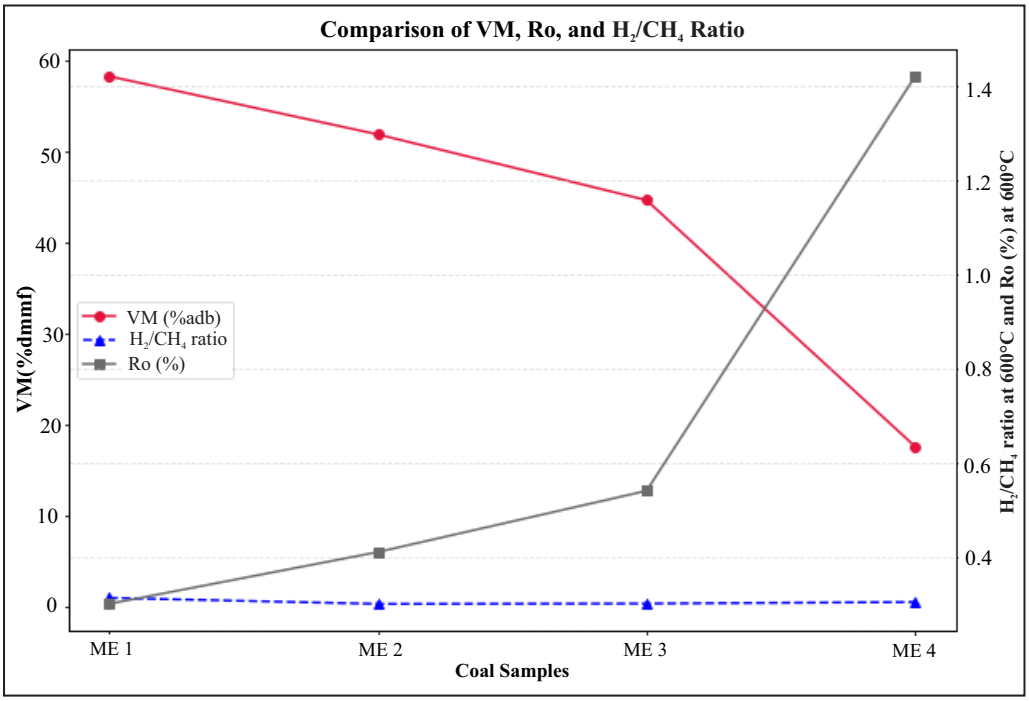

Figure 5. Comparison of Volatile Matter (VM), Vitrinite Reflectance (Ro), and H_2/CH_4 ratio.

ME4 (Ro= 1.42 %) exhibited a higher H_2/CH_4 ratio (0.524) than ME3 (Ro= 0.54 %), despite its lower VM. This finding indicates that higher-rank coals with more condensed and ordered aromatic structure may still favour hydrogen generation under sufficiently high temperatures through dehydrogenation, condensation, and aromatization.

These trends suggest that while gas yield generally correlated with volatile matter, the H2/CH4 ratio is more strongly controlled by coal rank and macromolecular structure. Therefore, using both VM and Ro as indicator provides a more comprehensive understanding of hydrogen yielding potential, which is crucial for tailoring UCG operation to achieve the desired syngas composition.

Lower-rank coals (ME1 - ME2) demonstrated strong potential for producing hydrogen-rich syngas due to high volatile content and favourable thermal decomposition characteristics at moderate to high temperatures. In contrast, higher-rank coals generated lower overall gas yield, but produced proportionally more methane, making them potentially advantageous for methane-rich syngas applications.

Implication and Study Limitations

These findings confirm that coal rank and pyrolysis temperature as key parameters for optimizing UCG efficiency. Lower-rank coals (ME1, ME2) showed higher gas yields and higher H_2/CH_4 ratios at moderate to high temperatures, making them suitable for hydrogen-rich syngas application. In contrast, higher-rank coals (ME3, ME4) favoured methane generation at elevated temperatures, supporting CH_4-rich gas target. These results can guide syngas composition control in UCG design.

Notably, the observed decline in CO_2 concentrations at higher temperatures suggests potential for reducing emissions through thermal optimization, supporting the role of UCG in clean coal technology development.

However, several limitations should be acknowledged. Carbon monoxide (CO) concentrations could not be measured due to equipment constraints, limiting the analysis of redox reactions during pyrolysis. Tar yield was not quantified, preventing a complete mass balance and full evaluation of pyrolysis product distribution. Additionally, the laboratories-scale pyrolysis

conditions may not fully represent field-scale UCG behaviour.

Future studies should include CO detection, tar quantification, and char reactivity analysis to provide more complete understanding of pyrolysis behaviour and syngas optimization in UCG system.

Conclusions

This study investigated the pyrolysis behaviour of South Sumatera Coal, focusing on the influence of pyrolysis temperature and coal rank on gas yield and composition under UCG conditions, particularly within the dry distillation zone. The result demonstrates that both pyrolysis temperature and coal rank significantly govern pyrolysis behaviour, with direct implications for syngas quality, gas yield optimization, and emission reduction.

Lower-rank coals (ME1 and ME2), characterized by higher volatile matter and lower aromaticity, exhibited higher reactivity, producing greater total gas yields and elevated H_2/CH_4 ratios-especially at moderate to high temperatures (500-600° C). These coals are more favourable for hydrogen-rich syngas production and low temperature pyrolysis on UCG system. In contrast, higher-rank coal (ME3 and ME4), with denser aromatic structure and greater thermal stability, produced lower total gas yield, but favoured methane generation at elevated temperatures making them more appropriate for CH_4-rich syngas targeting.

Gas composition trends revealed that CO_2 dominated at lower temperatures (300-400° C), while CH_4 generation commenced around 400° C and increased with temperature due to primary cracking reactions of aliphatic structure. Hydrogen (H_2) generation became significant above 500° C and peaked at 600° C due to dehydrogenation, condensation, and aromatization reactions.

The evolution of the H_2/CH_4 ratio across pyrolysis temperatures and coal ranks provides insight into underlying reaction mechanisms, such as secondary cracking, dehydrogenation, and demethylation, which are governed by the macromolecular structure. Notably, ME1 achieved the highest H_2/CH_4 ratio (0.98), while ME2 exhibited the lowest (0.371), illustrating the complex interplay between volatile matter, vitrinite reflectance, and hydrogen-forming potential.

Overall, this study confirms that coal rank and pyrolysis temperature are keys levers in tailoring UCG processes. Providing a better understanding of their influence on gas yield and composition enhances the potential for cleaner, more efficient coal utilization technologies.

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