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Experimental Study on Evaluation of Underground Coal Gasification with a Horizontal Hole using Two Different Coals

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Abstract:

Underground coal gasification (UCG) is a technique to extract coal energy with heat energy and combustible gases through chemical reactions in the underground gasifier. In this study, an application of a coaxial UCG system with a horizontal hole is discussed by means of the model UCG experiments with a large-scale simulated coal seam having dimensions of 550 × 600 × 2740 mm. The two types of coal having 30.18 MJ/kg of calorific value with 7.9% of ash (type 1) and 22.66 MJ/kg of calorific value with 28.3% of ash (type 2) were used for the experiments to evaluate the effect of coal quality on temperature distribution of the gasification area and product gas quality. The oxygen-enriched air was used. The injection rate of the gasification agents was elevated during the experiments to analyze the effect on the product gas. The results show that the gasification area is expanded along the wall of a coaxial hole, not upwards for the type 2 coal with high ash content. The average calorific value of product gas for types 1 and 2 is 8.05 MJ/m^3 and 6.91 MJ/m^3 respectively, while an increase of injection flow rate produces an improvement of the calorific value for both types of coal. Additionally, it is suggested that the reacted carbon and the product gas volume can be estimated with the volume of oxygen injected regardless of the coal quality if the gasification efficiency and the reaction temperature are similar. These results help to estimate several important parameters, e.g. reacted coal amount, recovered gas volume, and recovered energy from the coal when the actual field implementation is designed.

Keywords:

Acoustic emission; Balance computation; Coaxial hole; Gasification efficiency; Underground coal gasification

1. Introduction

Underground coal gasification (UCG) is an unconventional coal mining technique to recover coal energy through the chemical reactions in the underground gasifier. UCG is a gasification process using injection and production holes drilled from the surface, which collects heat energy and product gas mainly composed of nitrogen, carbon monoxide, carbon dioxide, hydrogen, and methane. Although some successful examples of industrial-scale/pilot scale are reported in the literature [1], the difficulties to control the gasification process remain even now. The gasification process can be divided mainly into three zones: oxidization zone, reduction zone, and drying and pyrolysis zone [2]. The oxidation zone has the highest temperature area which is usually above 900 ℃ [3, 4], and this is the source of heat to promote the gasification process. The main chemical reaction to generate the

combustible gas in UCG process occurs in the reduction and pyrolysis zone. The quality of the product gas is influenced by several parameters such as heat and mass transport within the coal seam, which are determined by temperature, coal properties, water influx, the thickness of coal seams, and operational pressure [1]. Due to dilution by added nitrogen, the calorific value of the product gas recovered by UCG is 4-12 MJ/m^3, which is lower than that of natural gas (38-40 MJ/m^3). UCG gas can be used to supply electricity through a combined cycle power generation [5-7] and to produce raw materials such as hydrogen, ammonia, and methanol [8-10]. This technique has the potential to utilize coal resources that remain unrecoverable in the underground due to either technological or economic reasons. Although Japan still has abundant coal resources more than 20 billion tones, almost all the coal mines closed by the early 21 centuries due to the expensive operation costs, expensive labor costs, and complicated geological structures to excavate. Japan's energy self-sufficiency rate was 11.8% in 2018 based on the report prepared by the Ministry of Economy, Trade and Industry in Japan, meaning that most of the energy sources rely on imports from overseas. Therefore, the utilization of the untouched energy source contributes not only to satisfy the increasing demand in the future but also to the diversification of the sources to secure a stable supply. Additionally, UCG has advantages in terms of simplification of surface facilities, no disposal of coal ash on the surface, and the possibility of CO_2 storage [11-13]. On the other hand, the environmental impact on the surrounding is significant if the operation is failed due to the lack of knowledge. Especially, the groundwater pollution due to tar contamination must be considered carefully because the remediation of the pollution needs much effort and a long time.

UCG is a technology that uses a borehole to gasify underground coal seams in situ and recover coal energy as combustible gas at the surface; however, it requires a high level of skill and knowledge to control the reaction because the UCG is a multidisciplinary phenomenon including heat transfer, oxidants flow, chemical reactions, and hydrogeology [14-16]. Therefore, the ex-situ UCG model experiments are required to collect the data and knowledge to control UCG process before the actual field implementation. Various parameters have to be controlled and monitored to assess the evolution of gasification area and gasification efficiency during the experiment: including gasification agents, injection/production rate, pressure, the temperature in multiple points, product gas component [17]. Low-grade, non-coking coals with high reactivity and high volatile content are preferred to expand the gasification area and achieve an efficient gasification process for UCG. However, the gasification agents have to be selected carefully considering the coal quality [18]. For instance, the temperature of lignite is hard to raise due to its high moisture compared to bituminous coal if the same gasification agent is used. Therefore, UCG for lignite needs oxygen-enriched air as the gasification agent [19-21]. Oxygen is a key

parameter to decide the temperature in the reaction zone, growth of the gasified area, and product gas quality. The optimum ratio of oxygen/air can increase the efficiency of UCG because it brings high temperature in an oxidizing zone required for UCG reaction (above 1000 °C) [22]. Increasing the supply rate of oxygen also improves the energy recovery rate due to the increase of the reaction temperature and the expansion of the gasification area [23]. The evolution of the gasification area and the quality of product gas are affected by the quality of coal and the injection conditions, e.g., the flow rate and oxygen concentration when the air and oxygen are used as a gasification agent [22, 24]. The results of some laboratory experiments showed that the ash in the coal reduces the product gas quality and inhibits the gasification process [25, 26]. Additionally, sufficient oxygen has to be injected to sustain the UCG process in coal contained high ash [27]. The gasification technique is also a parameter to affect the gasification phenomena. The blinding-hole UCG with a closed hole is suggested to be applied to the "three unders" (i.e., under buildings, water bodies, and roads) [28]. This technique injects the gasification agents from the injection pipe and recovers the product gas via the annular space between the hole and pipe. A forward and reverse gasification system of lignite and bituminous coal was carried out in this work [29]. It was found that in order to extend the gasification period and produce high-quality product gas, reverse gasification is effective for both types of coals, while the volume of the product gas is related to supply. Another research focuses on the reverse gasification process with lignite under the different oxygen concentrations and injection rates [30]. It is reported that the supply of enriched oxygen contributed to a rapid growth rate of the flame face and a higher calorific value of product gas. Additionally, the movable injection with the removable injection devices is discussed. The total efficiency of gasification could be improved with moving the injection points compared to fixed gas injection [4, 31].

We are developing a novel/improved coaxial UCG system with a horizontal hole (Fig. 1). In this method, the injection of oxidant to promote gasification and the recovery of product gas generated underground are carried out using a single borehole (coaxial hole), meaning that the digging cost of the hole can be saved compared to the conventional one. The coaxial UCG system has several disadvantages compared to the conventional UCG system: difficulty to expand the gasification area, a shorter gasification duration, less product gas volume, and lower calorific value [32, 33]. In order to improve the total efficiency of the gasification process, previous research has focused on the application of a coaxial UCG system with a horizontal hole [34], resulting in improved gasification similar to conventional UCG. However, it is still uncertain how the coal quality and injection conditions affect the combustible gas components produced and the extent of the gasification reaction zone in the coaxial UCG system with a horizontal hole. This study investigates these effects by means of the experiments.

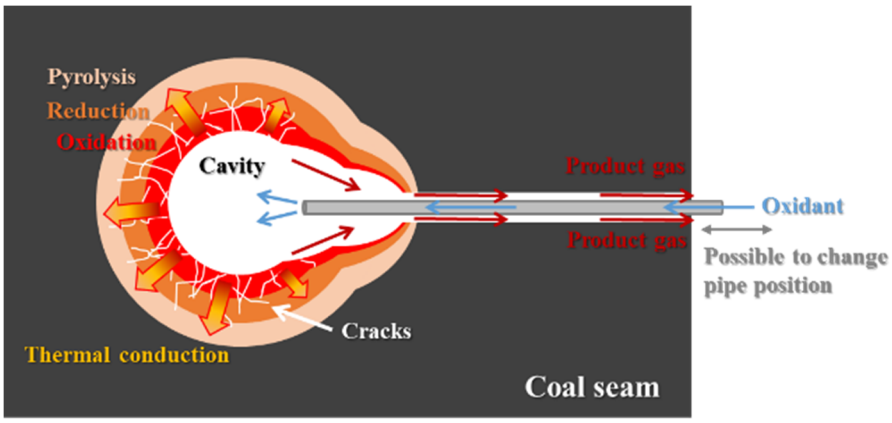


Fig. 1. Concept of coaxial UCG system.

2. Materials and Methods

The experiment was conducted at the site of the Potential Coal Energy Research Laboratory which is located at Mikasa-city, Hokkaido prefecture, Japan. The UCG model experiments were carried out in a steel container using coal blocks. Some coal blocks of more than 500 mm length/width were used to construct a simulated coal seam. A linear assembly of coal blocks was used to construct the simulated coal seam whose size was 550 × 600 × 2740 mm. The mixture of cement and fine coal was filled between coal blocks to establish continuous conditions. The ratio of cement to coal is 1:10. External walls of the simulated coal seam were covered with refractory cement to prevent heat release and gas leakage. The two different types of coal which had different calorific values, ash, and carbon content were used as shown in Table 1. The results show the properties of raw coal samples because the coal samples were sent directly from the mine site for analysis. Fig. 2 shows the diagram of UCG model experiments.

A hole housing coaxial ignition, injection, and production facilities were prepared in the lower part of the simulated coal seam, 125 mm from the bottom of the seam with 2600 mm length. The diameter of the hole and pipe is 45 mm and 21.7 mm, respectively. Oxidants were injected from the inner pipe and the product gas was recovered from the space between the pipe and the hole wall. In this study, the gas burner was used to ignite the coal. After the ignition stage, a mixture of air and oxygen was injected continuously to sustain the UCG process. The experiments were implemented under atmospheric conditions. More oxidant is needed to sustain the gasification reaction in the later stage because the reaction surface area is increased due to the expansion of the cavity. Therefore, the injection rate was increased as time elapsed to sustain the stable gasification process: 10~61 L/min for type 1 and 20~45 L/min for type 2 (see Fig. 3 for conditions) while the oxygen concentration was

constant about 50%. Meanwhile, temperature and acoustic emission (AE) were monitored to visualize the inner part of the coal seam by using type K thermocouples (Chino Corp.) and piezoelectric acceleration transducers (620HT; Teac Corp.), respectively. The distribution of each sensor is shown in Fig. 4. All AE waveforms from sensors were first recorded using a multi recorder (GR-7000; Keyence Corp.) with a sampling time of 2 μs. The compositions of product gas (O_2, N_2, CO_2, H_2, CO, CH_4, C_2H_4, C_2H_6, C_3H_6, and C_3H_8) were monitored using a gas chromatograph (Micro GC 3000A; Inficon Co. Ltd.). The tar content and vapor generated during the experiment were removed by tar removal equipment and the heat exchanger equipment respectively. Additionally, the position of an injection pipe was moved periodically every 100 mm toward the inlet of the oxidant in around 5 hours intervals to move the gasification area. The gasification period was 95 hours for type 1 and 27 hours for type 2.

Table 1. The proximate and ultimate analyses are on an as-fired basis.

	Calorific value (MJ/kg)	Proximate analysis (wt%)				Ultimate analysis (wt%)				
		Moisture	Ash	Volatiles	Fixed carbon	C	H	N	S	O
Type 1	30.18	2.9	7.9	42.2	47.0	73.2	5.46	1.64	0.95	10.64
Type 2	22.66	2.2	28.8	34.0	35.0	55.3	4.20	1.28	0.76	9.31

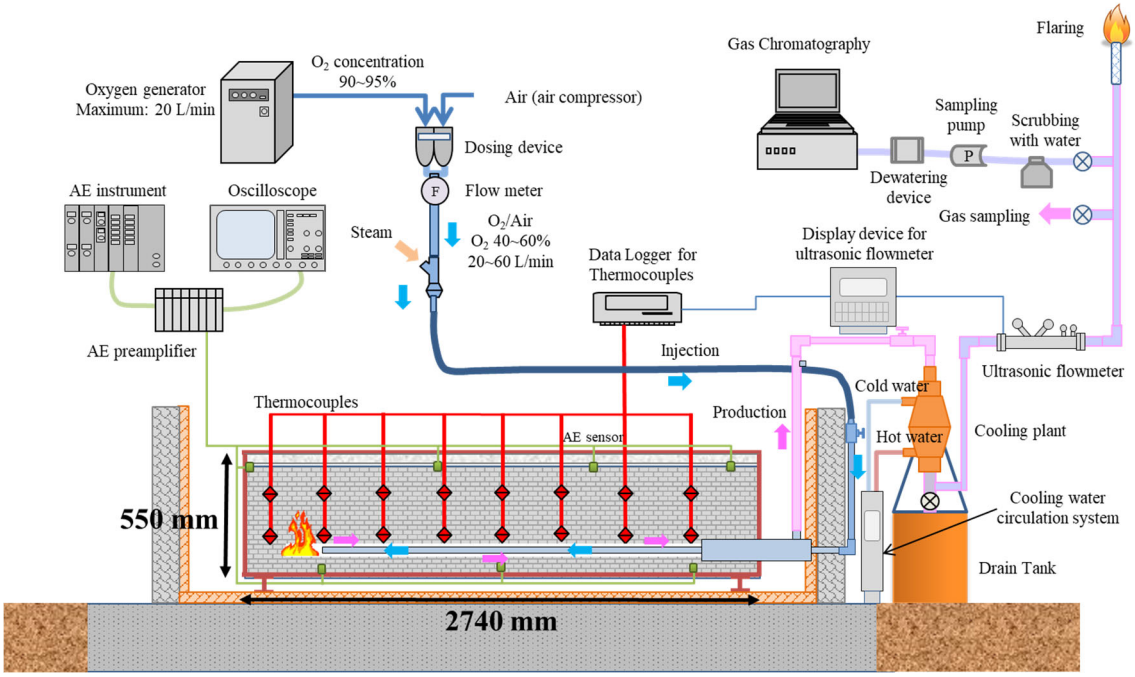
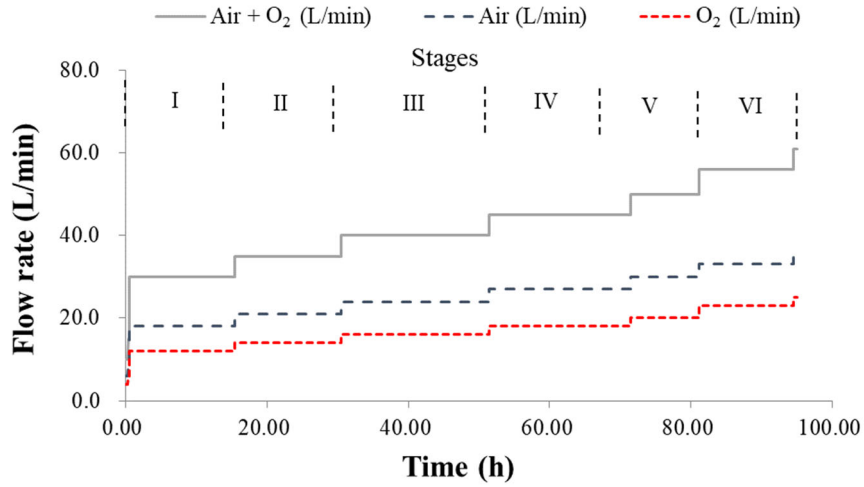


Fig. 2. Diagram of UCG model experiments.



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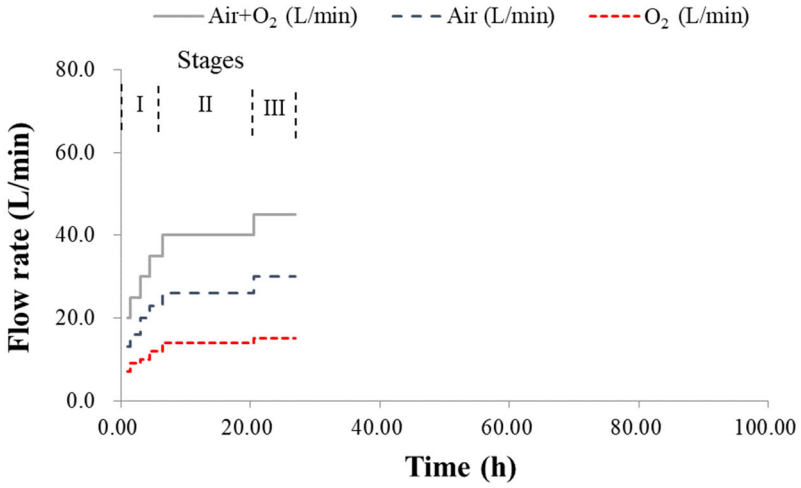
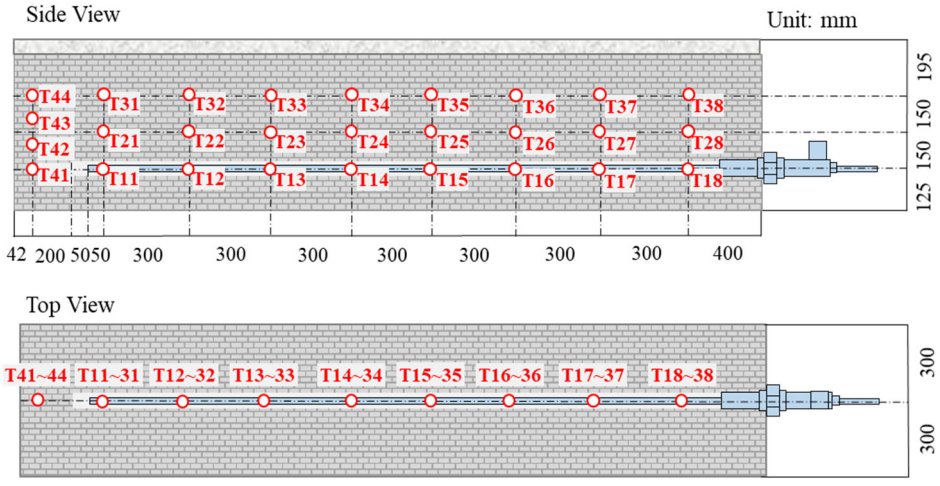


144 b)

145 **Fig. 3.** Gasification agents during experiments: a) Type 1; b) Type 2.



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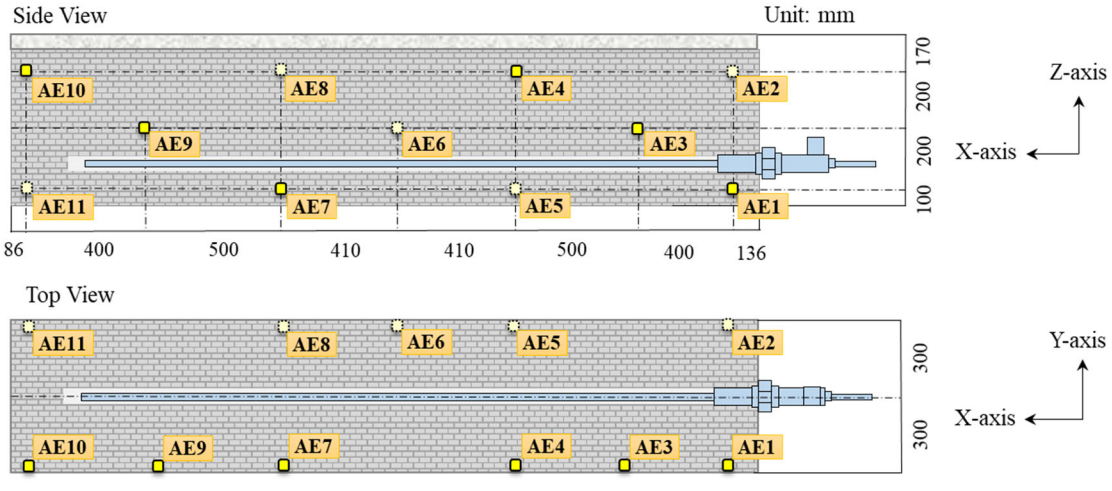


b)

Fig. 4. Thermocouples and acceleration transducers arrangement: a) Thermocouples; b) Acceleration transducers.

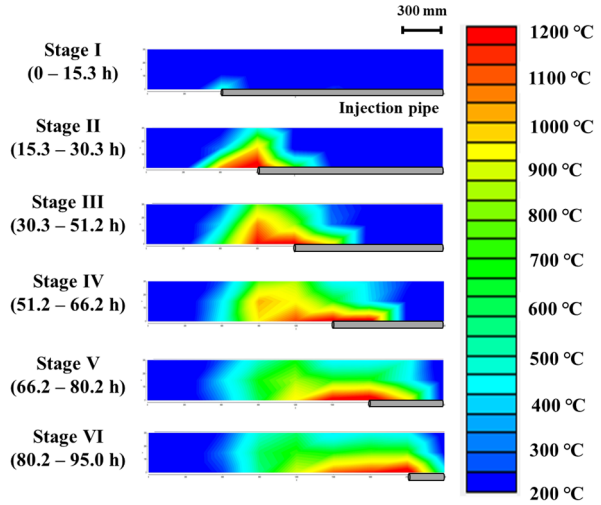
3. Results and Discussion

3.1 Temperature profile and AE monitoring

The two-dimensional temperature profiles are plotted for each experimental period based on injection rate (Stage I ~ VI) in Fig. 5, representing the temperature distribution in a cross-section of a horizontal hole. The position of the injection pipe is also illustrated below the contour results for each stage. The contour range is divided in 100 ℃ intervals from 200 ℃ to 1200 ℃ and the UCG reaction occurs in the high-temperature area in these figures. The maximum temperature for the gasification area is more than 1000 ℃ for both types of coal. The figures clearly show that the movement of the high-temperature area corresponds with moving an injection pipe and the gasification occurs around the tip of the injection pipe. Considering the temperature rise due to the oxidation reaction in UCG process, the coal temperature rises as a result of the rapid oxygen consumption around the injection pipe. These results indicate the possibility to control the gasification area by moving the injection position of the gasification agents. In type 2, the temperature increment is limited near the coaxial hole while the temperature rises widely in type 1, implying that the gasification area expands along the face of a coaxial hole in type 2. Considering both experiments were carried out under the atmospheric condition and the oxygen concentration was almost the same, the difference in temperature profile is due to the difference in coal quality. The coal of type 2 contained much ash compared to that of type 1, i.e. the gasification area is expanded along the face of a coaxial hole because of less reactivity of coal in type 2. High ash contents also cause the molten slag formation to prevent the promotion of gasification reaction. The other parameters, such as porosity, permeability,

and cleat network, may also affect the temperature profile during the gasification.

Figs. S1 and S2 show the monitoring results of temperature in the gasification channel (Please kindly see the Supplementary section). It shows that the temperature in the gasification channel rises with elapsed time and decline gradually after it shows maximum temperature. The maximum temperature monitored during UCG experiment is almost the same for both types of coal, 1300 ℃ for type 1 and 1250 ℃ for type 2 while the high-temperature area does not expand upward in type 2. The maximum temperature in type 1 shows that 15.5 h, 43.2 h, and 68.8 h elapsed from the beginning of the experiment for T12, T14, and T16, respectively. On the other hand, it shows that 10.0 h, 17.3 h, and 27.0 h elapsed for T12, T14, and T16, respectively in type 2. Based on the temperature results, the velocity to move the gasification area in a horizontal direction is calculated from the elapsed time indicated by the maximum temperature in each thermocouple as shown in Table 2. It can be understood that the velocity in type 2 is three times faster than that of type 1. This result also supports the expansion of the gasification area not toward the coal blocks but along the face of the hole. Therefore, it is necessary to consider injection conditions/pressure to expand the gasification area toward the coal seam when UCG is performed for coal with high ash content.



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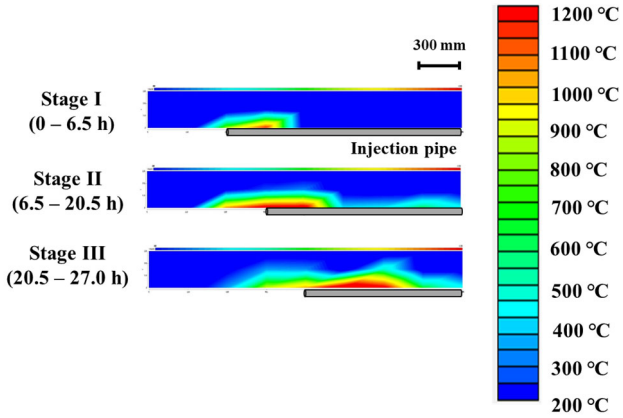


b)

Fig. 5. Temperature profiles: a) Type 1; b) Type 2.

Table 2. Velocity to move the gasification area in a horizontal direction.

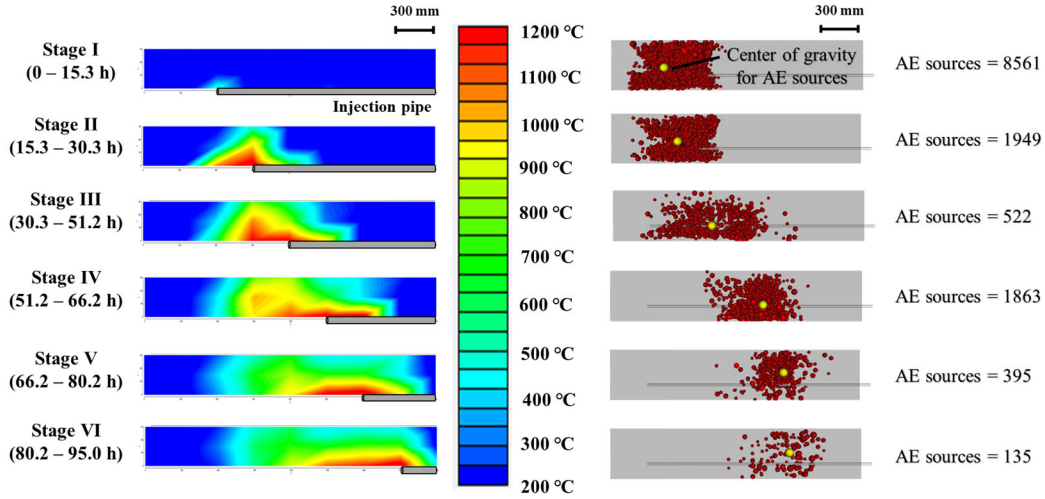
	Velocity to move gasification area (mm/h)		
	T12 ~ T14	T14 ~ T16	Average
Type 1	21.69	23.38	22.53
Type 2	81.82	62.07	71.94

Gasification reaction in UCG process is promoted by enlargement of the oxidation surface around the gasification channel with crack initiation and development inside the coal seam. Fracturing activities inside the coal seam are accelerated with an increase of thermal stress caused by exothermic reactions and heat transfer, as a result, gasification reaction and cavity growth are promoted. According to previous researches, acoustic emission (AE) monitoring can be used for the evaluation of fracturing activity around the gasification zone [35-38]. The AE technique can visualize fracture extension around the reactor by adopting the source location analysis. The elastic velocity has to be decided when the source location is conducted by using the travel-time-difference method. We used the different elastic velocity during gasification experiment; V_x = 690 (m/s), V_y = 390 (m/s), and V_z = 395 (m/s) for Stage I~III and V_x = 640 (m/s), V_y = 540 (m/s), V_z = 600 (m/s) for Stage IV~VI in type 1, and V_x = 900 (m/s), V_y = 540 (m/s), V_z = 500 (m/s) in type 2. These elastic velocities were obtained from the measurements with an impact damage test by a hammer. The difference in elastic velocity in different stages comes from the discontinuity and heterogeneous properties of coal blocks. The direction of each axis is shown in Fig. 4. The number of processable AE events are 90732 (type 1) and 17222 (type 2), respectively. Many of the recorded

waveforms cannot be used for the analysis due to high noise, excessive attenuation, or other unknown factors.

Fig. 6 shows the comparison between the temperature profile and AE source location for each stage. The red sphere shows the results of AE source location and the yellow sphere shows the center of gravity of AE source clouds for each stage. The AE source clouds are moved with elapsed time as well as the movement of the high-temperature area. This fact indicates the possibility to monitor the gasification area by using the AE technique instead of temperature monitoring. Additionally, the AE clouds locate upward in type 1 while they concentrate around the hole in type 2. These results correspond to the temperature profiles. The velocity to move the center of gravity of the AE source clouds was calculated as shown in Table 3. In comparison with the results of the velocity obtained from the temperature profile, the velocity to move AE source clouds in type 2 is also shown to be about three times faster than that of type 1 as well as the previous results although the average velocity is slightly different. This fact supports that the gasification toward the horizontal way along the face of the hole is faster in type 2.

These AE events are considered to be generated simultaneously with crack initiation due to thermal stress inside the coal seam and internal structural changes such as softening and melting of coal under high-temperature conditions, meaning that AE sources can be obtained in real-time during UCG process. Monitoring of fracture activity during the UCG process is crucial/significant in terms of two aspects: control of the risk of environmental impacts and the coal gasification efficiency. The groundwater contamination in UCG and gas leaks are associated with an appropriate pressure regime in the reactor in relation to the hydrostatic pressure of the UCG field. On the other hand, the fracturing into the coal seam creates a new oxidation surface and expands the gasification area widely. Therefore, the establishment of an AE monitoring system with real-time monitoring and control contributes not only to a safe and less environmental impact but also to enhancing the gasification efficiency. Additionally, the coal of type 2 should be more cohesive and have less reactivity because fewer AE sources are detected under heating. The higher elastic velocity in x-direction also supports that the coal is dense and cohesive. The fewer fracturing events during the heating causes to inhibit the oxygen penetration into the coal, suggesting that the gasification area is difficult to expand. Besides, the molten slag generated by the ash content in coal disturbs the promotion of gasification reaction and the occurrence of fracturing events due to less reactivity. Therefore, the mechanism to expand the gasification area will be explained by clarifying the fusibility of the ash.



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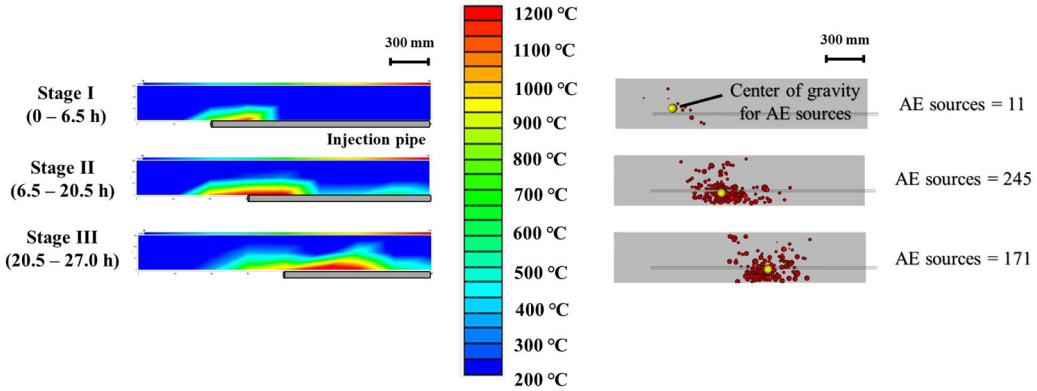


b)

Fig. 6. Comparison of temperature profiles and AE sources location: a) Type 1; b) Type 2.

Table 3. Velocity to move the center of gravity for AE sources in a horizontal direction.

	Velocity to move the center of gravity for AE sources (mm/h)					
	Stage I ~ II	Stage II ~ III	Stage III ~ IV	Stage IV ~ V	Stage V ~ VI	Average
Type 1	10.00	19.52	32.23	16.44	4.59	16.55
Type 2	55.49	47.14	-	-	-	51.31

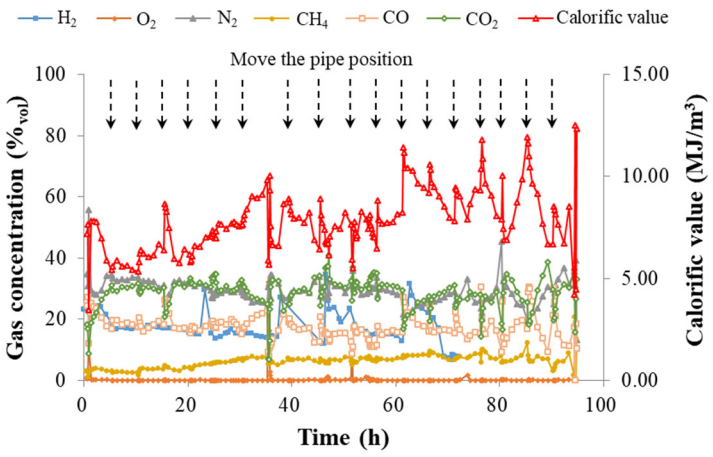
3.2 Product gas

Monitoring results of the main compositions and the calorific value of a product gas are presented in Fig. 7. The oxygen concentration was almost zero throughout both types of coal, indicating that all of the oxygen injected as an oxidant was consumed in the gasification reactions. The main components of the gases produced by the UCG

process were H_2, CO, CH_4, and CO_2. The time to move the position of the injection pipe is also pointed in the figure. The composition of product gas changed immediately after the position of the injection pipe was moved in both type 1 and type 2, meaning that the concentrations of main combustible gases such as H_2, CO, and CH_4 tend to increase at the beginning of the experiment and after the injection pipe is moved. On the other hand, the concentration of CO_2 is related to the change in the combustible gases which tends to decrease when the injection pipe is moved and increase gradually when the combustible gas components decrease. Although there is a certain amount of fluctuation in the product gas components in both experiments, a stable product gas contained in the combustible contents is recovered by moving the injection pipe periodically. This is because the gasification area could be moved to the unreacted part of the coal seam, indicating that it is possible to control the quality of the produced gas by moving the injection pipe. The calorific value of the product gas can be calculated with the concentration of the combustible gas contents [39]. The variation of the calorific value during the experiment shows the same trend as that of the concentration change of H_2, CO, and CH_4, which are the main components of the combustible gas. Furthermore, it shows a gradual increase toward the latter stage of the experiment. According to Table 4, the average concentration of H_2, CO, and CH_4 is 17.1%, 17.2%, and 6.59% for type 1 and 17.6%, 19.9%, and 3.75% for type 2. The average calorific value of product gas is 8.05 MJ/m^3 and 6.91 MJ/m^3 respectively. Considering the gasification period in type 2 is much shorter than in type 1, it should be noted that the product gas compositions are largely influenced by the pyrolysis in type 2. The hydrogen shows higher concentrations although the inherent moisture contents of coal are quite small of coal blocks, which are 2.9% and 2.2 % for types 1 and 2, respectively. This experiment used the cement between coal blocks and the refractory cement as the external wall, indicating that the moisture contents of these materials joined the gasification to produce the hydrogen. The product gas rate shows the increasing trend for both types 1 and 2 as shown in Fig. 8. This result is consistent with the increasing the gasification agents as shown in Fig. 3. Additionally, the product gas rate also increased immediately after the position of the injection pipe was moved. This is due to the rapid increment of the combustible gas with the promotion of gasification reactions. Table 5 shows the average calorific value of product gas for each injection rate. The calorific value is slightly increased with increasing the injection rate in both types of coal. This is due to the expansion of the gasification area of high temperature with an increase of oxidant volume injected. Therefore, it is possible to roughly control the quality of product gas by arranging the injection rate.

The calorific value of product gas in type 2 is lower than that of type 1. This is due to the lower inherent calorific value of coal in type 2. However, it is questionable that the efficiency of the gasification reaction is different or

not. This experiment was conducted under atmospheric conditions, the injection conditions were almost the same, and the maximum temperature during gasification was similar. Therefore, the recovered energy, the amount of reacted coal and product gas, and the gasification efficiency were evaluated by normalization using various parameters. Balance computation of C element is adopted to calculate the amount of reacted coal/carbon [40]. The amount of carbon contents contained in tar is ignored in this study. According to the calculation results shown in Table 6, the recovered energy per the mass of reacted coal for types 1 and 2 is 19.66 MJ/kg and 14.01 MJ/kg, and the product gas volume for types 1 and 2 shows 1.74 m^3/kg and 1.37 m^3/kg, respectively. In both results, the type 1 coal shows higher values. However, both values turn out to be almost the same if they are normalized with reacted carbon: types 1 and 2 shows 26.86 MJ/kg and 25.34 MJ/kg for recovered energy and 2.38 m^3/kg and 2.47 m^3/kg for product gas volume. This means that the several parameters on the outputs from UCG can be estimated by normalizing with reacted carbon regardless of the coal quality if the gasification conditions are the same. The reacted carbon and product gas volume are plotted as a function of oxygen injection rate in Fig. 9. These plots are prepared based on the average value when the position of the injection pipe is constant. According to the results, both the reacted carbon and product gas volume are strongly correlated with the oxygen injected flow rate. This fact indicates the possibility to estimate these parameters with the volume of oxygen injected while it should be noted that this correlation may be established when the gasification temperature is comparable. This relationship is also helpful to design the equipment that treated the injection/production gas for the pilot-scale trial/field implementation. Although the reacted coal and product gas volume are estimated with the volume of oxygen injected, another indicator related to the energy recovery from the coal is required to evaluate the recovered energy by UCG process. The gasification efficiency, which means the energy recovery ratio from coal, is calculable with the amount of recovered energy per unit mass of the gasified coal and the inherent calorific value of coal. The gasification efficiency is 65.15% and 61.84% respectively for types 1 and 2 as shown in Table 6. The gasification efficiency in type 2 is slightly lower than in type 1. This may be due to the difference in the size of the gasification area, meaning that the gasification area is limited along the hole while it expands upwards as well in type 1. In the UCG process, some of the heat energy generated by the oxidation reaction is lost due to the gas leakage and heat transfer to the surrounding rock mass. This heat loss seems to be one of the factors leading to the decrease in gasification efficiency. The ratio of heat loss will be decreased as the amount of heat energy generated increases (i.e., the more coal reacted and the more gas produced). In other words, it is also expected to decrease the ratio of heat loss and improve the gasification efficiency in the UCG field implementation since the larger scale of gasification area will be created compared to the current scale of the ex-situ UCG model experiment.



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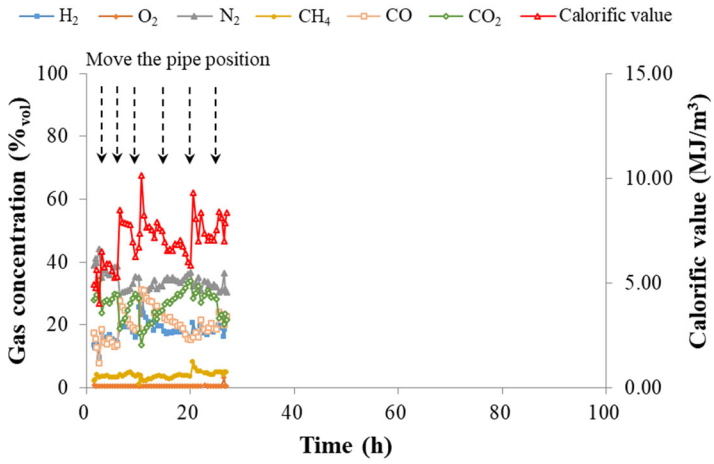
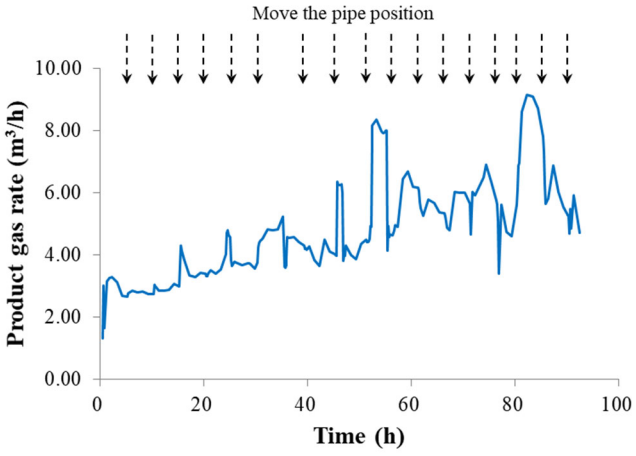


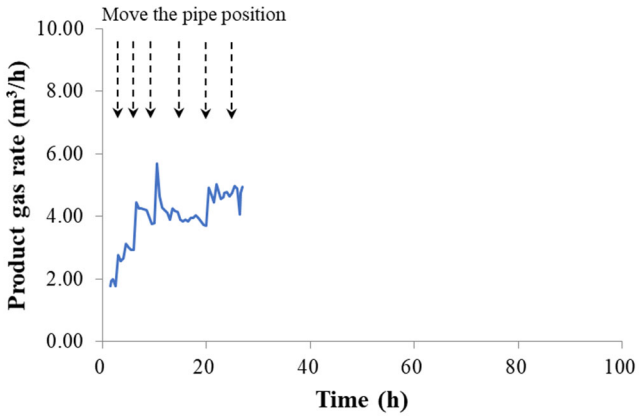
299 b)

300 **Fig. 7.** Product gas composition: a) Type 1; b) Type 2.

301

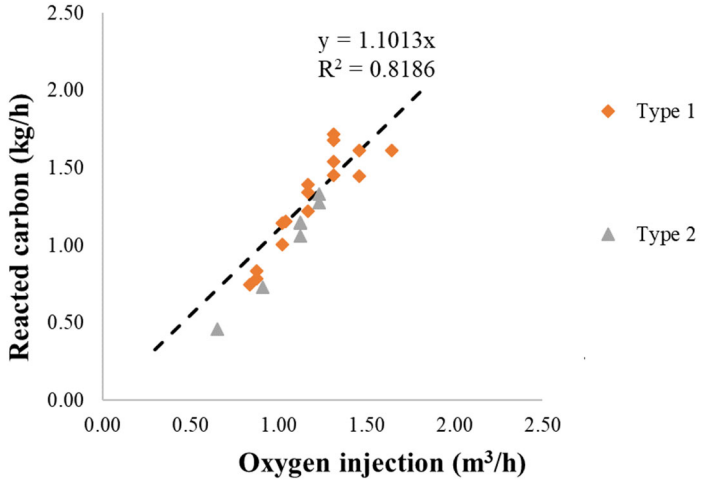


302 a)

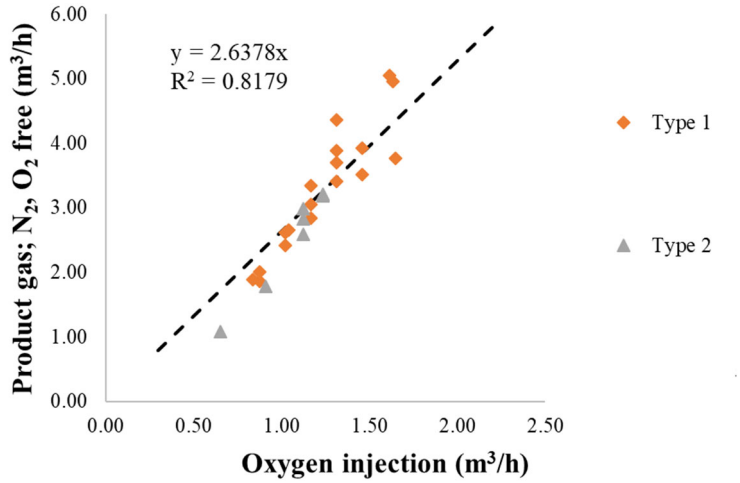


b)

Fig. 8. Product gas rate: a) Type 1; b) Type 2.



a)



b)

Fig. 9. Correlation of the reacted carbon and product gas volume with oxygen injection rate: a) reacted carbon; b) product gas volume (N_2, O_2 free).

309 **Table 4.** Average calorific value and product gas composition.

	Calorific value (MJ/m^3)	H_2 (%)	O_2 (%)	N_2 (%)	CO (%)	CH_4 (%)	CO_2 (%)	C_2H_4 (%)	C_2H_6 (%)	C_3H_6 (%)	C_3H_8 (%)
Type 1	8.05	17.1	0.16	28.6	17.2	6.59	28.9	0.47	0.61	0.20	0.17
Type 2	6.91	17.6	0.52	32.1	19.9	3.75	25.2	0.36	0.32	0.12	0.09

310

311 **Table 5.** Calorific value and product gas composition for each injection rate.

	Injection rate (L/min)	Calorific value (MJ/m^3)	H_2 (%)	O_2 (%)	N_2 (%)	CO (%)	CH_4 (%)	CO_2 (%)	C_2H_4 (%)	C_2H_6 (%)	C_3H_6 (%)	C_3H_8 (%)
Type 1	10~30	6.21	16.4	0.19	32.1	19.2	3.17	28.3	0.25	0.21	0.07	0.06
	35	7.00	15.1	0.03	30.0	18.2	5.07	30.6	0.27	0.47	0.14	0.14
	40	8.08	16.3	0.19	28.6	17.3	6.87	29.3	0.37	0.67	0.20	0.19
	45	8.54	18.1	0.16	27.6	16.4	7.40	28.7	0.47	0.71	0.22	0.20
	50	8.90	18.7	0.33	29.2	16.2	7.81	26.0	0.60	0.76	0.25	0.21
	56~61	8.52	17.2	0.11	27.1	17.2	7.24	29.4	0.71	0.61	0.23	0.17
Type 2	20~35	5.46	14.7	0.49	38.1	14.73	3.10	28.2	0.33	0.20	0.09	0.06
	40	7.00	18.4	0.45	31.2	21.90	3.32	24.0	0.33	0.27	0.10	0.07
	45	7.39	17.4	0.66	31.2	18.76	4.79	26.0	0.44	0.46	0.16	0.13

312

313 **Table 6.** Calculation of recovered energy, product gas volume per unit mass and gasification efficiency.

	Recovered energy (MJ/kg)		Product gas volume N_2, O_2 free (m^3/kg)		Gasification efficiency (%)
	/coal	/carbon	/coal	/carbon	
Type 1	19.66	26.86	1.74	2.38	65.15
Type 2	14.01	25.34	1.37	2.47	61.84

314

315 **4. Conclusions**

316 An experimental study of UCG using a coaxial horizontal hole in two different coals gasified with oxygen-
317 enriched air found the following:

318 ● The expansion of gasification area is different depending on the coal quality: expanded along the wall of a

coaxial hole, not upwards when the coal of type 2 with low calorific value and high ash is gasified in this study. The other parameters, such as porosity, permeability, and cleat network, may also affect the temperature profile during the gasification.

- The velocity to move the gasification area in a horizontal direction for type 2 is faster than type 1. The results of AE source location also agree with the rapid movement. The establishment of an AE monitoring system contributes to identify and control the gasification area.

- The coal of type 2 is cohesive and has less reactivity compared to type 1 according to the elastic velocity and detected number of the fracturing events. The fewer fracturing events during the heating and the molten slag generated by the ash content inhibit expanding the gasification area.

- The quality of product gas can be improved by moving an injection pipe in the coaxial UCG system with a horizontal hole because the gasification area can be moved to the unreacted coal. To control the position of the gasification area is significant to produce the product gas with high quality.

- The calorific value of the product gas improves with an increase in oxygen supply for both types of coal due to the expansion of the gasification area of high temperature. It is possible to roughly control the quality of product gas by arranging the injection rate.

- The reacted carbon is an effective parameter to estimate several parameters on the outputs from UCG. Additionally, the amount of the reacted carbon and the product gas volume are related to the volume of oxygen injected.

- The recovered energy of the field implementation can be evaluated by assuming that the reacted coal amount and gasification efficiency is constant while it is expected to improve the gasification efficiency in the UCG field implementation.

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