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

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19 **Abstract:**

20 *Underground coal gasification (UCG) is a technique to extract coal energy with heat energy and combustible*
21 *gases through chemical reactions in the underground gasifier. In this study, an application of a coaxial UCG*
22 *system with a horizontal hole is discussed by means of the model UCG experiments with a large-scale simulated*
23 *coal seam having dimensions of 550 × 600 × 2740 mm. The two types of coal having 30.18 MJ/kg of calorific*
24 *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*
25 *experiments to evaluate the effect of coal quality on temperature distribution of the gasification area and product*
26 *gas quality. The oxygen-enriched air was used. The injection rate of the gasification agents was elevated during*
27 *the experiments to analyze the effect on the product gas. The results show that the gasification area is expanded*
28 *along the wall of a coaxial hole, not upwards for the type 2 coal with high ash content. The average calorific*
29 *value of product gas for types 1 and 2 is 8.05 MJ/m³ and 6.91 MJ/m³ respectively, while an increase of injection*
30 *flow rate produces an improvement of the calorific value for both types of coal. Additionally, it is suggested that*
31 *the reacted carbon and the product gas volume can be estimated with the volume of oxygen injected regardless of*
32 *the coal quality if the gasification efficiency and the reaction temperature are similar. These results help to*
33 *estimate several important parameters, e.g. reacted coal amount, recovered gas volume, and recovered energy*
34 *from the coal when the actual field implementation is designed.*

35 **Keywords:**

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

37

38 **1. Introduction**

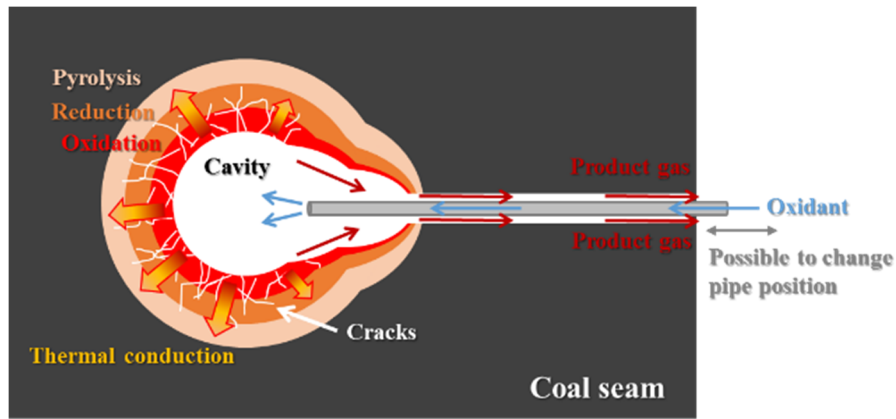
39 Underground coal gasification (UCG) is an unconventional coal mining technique to recover coal energy through
40 the chemical reactions in the underground gasifier. UCG is a gasification process using injection and production
41 holes drilled from the surface, which collects heat energy and product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

47 combustible gas in UCG process occurs in the reduction and pyrolysis zone. The quality of the product gas is
48 influenced by several parameters such as heat and mass transport within the coal seam, which are determined by
49 temperature, coal properties, water influx, the thickness of coal seams, and operational pressure [1]. Due to
50 dilution by added nitrogen, the calorific value of the product gas recovered by UCG is 4-12 MJ/m³, which is lower
51 than that of natural gas (38-40 MJ/m³). UCG gas can be used to supply electricity through a combined cycle power
52 generation [5-7] and to produce raw materials such as hydrogen, ammonia, and methanol [8-10]. This technique
53 has the potential to utilize coal resources that remain unrecoverable in the underground due to either technological
54 or economic reasons. Although Japan still has abundant coal resources more than 20 billion tones, almost all the
55 coal mines closed by the early 21 centuries due to the expensive operation costs, expensive labor costs, and
56 complicated geological structures to excavate. Japan's energy self-sufficiency rate was 11.8% in 2018 based on
57 the report prepared by the Ministry of Economy, Trade and Industry in Japan, meaning that most of the energy
58 sources rely on imports from overseas. Therefore, the utilization of the untouched energy source contributes not
59 only to satisfy the increasing demand in the future but also to the diversification of the sources to secure a stable
60 supply. Additionally, UCG has advantages in terms of simplification of surface facilities, no disposal of coal ash
61 on the surface, and the possibility of CO₂ storage [11-13]. On the other hand, the environmental impact on the
62 surrounding is significant if the operation is failed due to the lack of knowledge. Especially, the groundwater
63 pollution due to tar contamination must be considered carefully because the remediation of the pollution needs
64 much effort and a long time.

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

77 parameter to decide the temperature in the reaction zone, growth of the gasified area, and product gas quality. The
78 optimum ratio of oxygen/air can increase the efficiency of UCG because it brings high temperature in an oxidizing
79 zone required for UCG reaction (above 1000 °C) [22]. Increasing the supply rate of oxygen also improves the
80 energy recovery rate due to the increase of the reaction temperature and the expansion of the gasification area
81 [23]. The evolution of the gasification area and the quality of product gas are affected by the quality of coal and
82 the injection conditions, e.g., the flow rate and oxygen concentration when the air and oxygen are used as a
83 gasification agent [22, 24]. The results of some laboratory experiments showed that the ash in the coal reduces
84 the product gas quality and inhibits the gasification process [25, 26]. Additionally, sufficient oxygen has to be
85 injected to sustain the UCG process in coal contained high ash [27]. The gasification technique is also a parameter
86 to affect the gasification phenomena. The blinding-hole UCG with a closed hole is suggested to be applied to the
87 “three unders” (i.e., under buildings, water bodies, and roads) [28]. This technique injects the gasification agents
88 from the injection pipe and recovers the product gas via the annular space between the hole and pipe. A forward
89 and reverse gasification system of lignite and bituminous coal was carried out in this work [29]. It was found that
90 in order to extend the gasification period and produce high-quality product gas, reverse gasification is effective
91 for both types of coals, while the volume of the product gas is related to supply. Another research focuses on the
92 reverse gasification process with lignite under the different oxygen concentrations and injection rates [30]. It is
93 reported that the supply of enriched oxygen contributed to a rapid growth rate of the flame face and a higher
94 calorific value of product gas. Additionally, the movable injection with the removable injection devices is
95 discussed. The total efficiency of gasification could be improved with moving the injection points compared to
96 fixed gas injection [4, 31].

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



107

108 **Fig. 1.** Concept of coaxial UCG system.

109 **2. Materials and Methods**

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

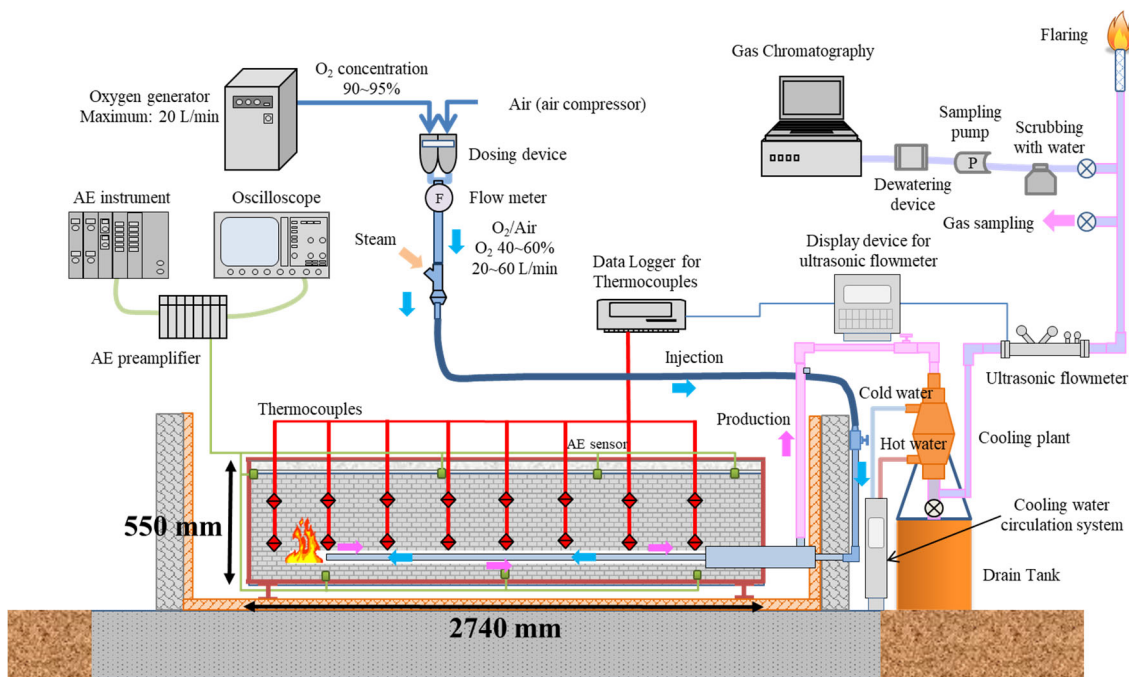
120 A hole housing coaxial ignition, injection, and production facilities were prepared in the lower part of the
 121 simulated coal seam, 125 mm from the bottom of the seam with 2600 mm length. The diameter of the hole and
 122 pipe is 45 mm and 21.7 mm, respectively. Oxidants were injected from the inner pipe and the product gas was
 123 recovered from the space between the pipe and the hole wall. In this study, the gas burner was used to ignite the
 124 coal. After the ignition stage, a mixture of air and oxygen was injected continuously to sustain the UCG process.
 125 The experiments were implemented under atmospheric conditions. More oxidant is needed to sustain the
 126 gasification reaction in the later stage because the reaction surface area is increased due to the expansion of the
 127 cavity. Therefore, the injection rate was increased as time elapsed to sustain the stable gasification process:
 128 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

129 constant about 50%. Meanwhile, temperature and acoustic emission (AE) were monitored to visualize the inner
 130 part of the coal seam by using type K thermocouples (Chino Corp.) and piezoelectric acceleration transducers
 131 (620HT; Teac Corp.), respectively. The distribution of each sensor is shown in Fig. 4. All AE waveforms from
 132 sensors were first recorded using a multi recorder (GR-7000; Keyence Corp.) with a sampling time of 2 μ s. The
 133 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
 134 gas chromatograph (Micro GC 3000A; Inficon Co. Ltd.). The tar content and vapor generated during the
 135 experiment were removed by tar removal equipment and the heat exchanger equipment respectively. Additionally,
 136 the position of an injection pipe was moved periodically every 100 mm toward the inlet of the oxidant in around
 137 5 hours intervals to move the gasification area. The gasification period was 95 hours for type 1 and 27 hours for
 138 type 2.

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

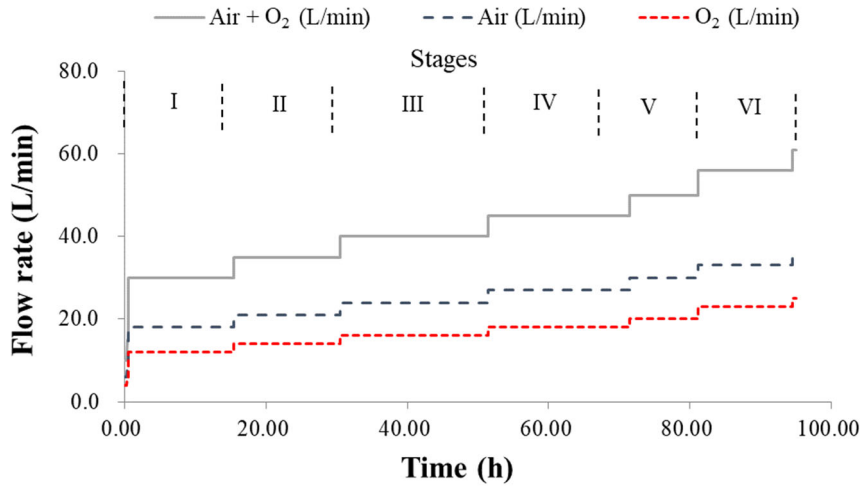
	Calorific value (MJ/kg)	Proximate analysis (wt%)				Ultimate analysis (wt%)				
		Moisture	Ash	Volatiles	Fixed carbon	C	H	N	S	O
Type 1	30.18	2.9	7.9	42.2	47.0	73.2	5.46	1.64	0.95	10.64
Type 2	22.66	2.2	28.8	34.0	35.0	55.3	4.20	1.28	0.76	9.31

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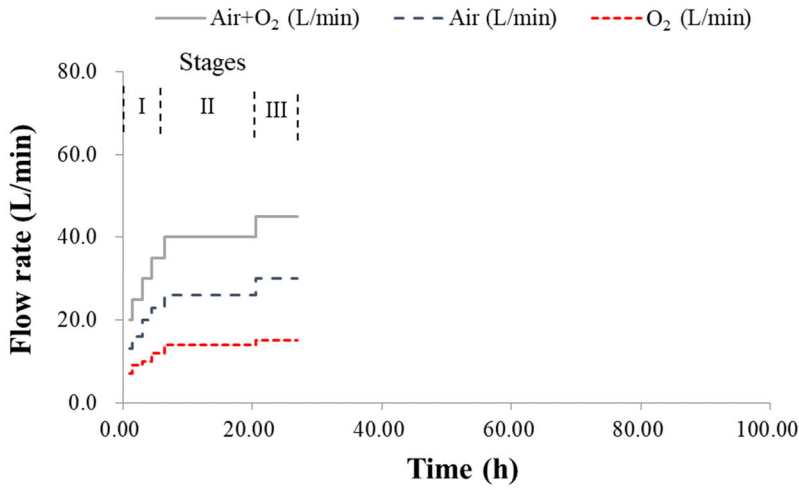


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142 **Fig. 2.** Diagram of UCG model experiments.

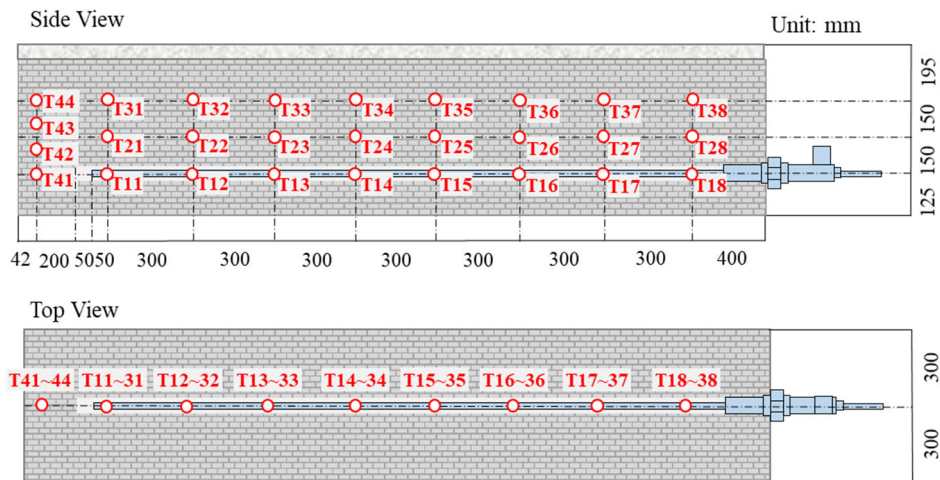


143 a)

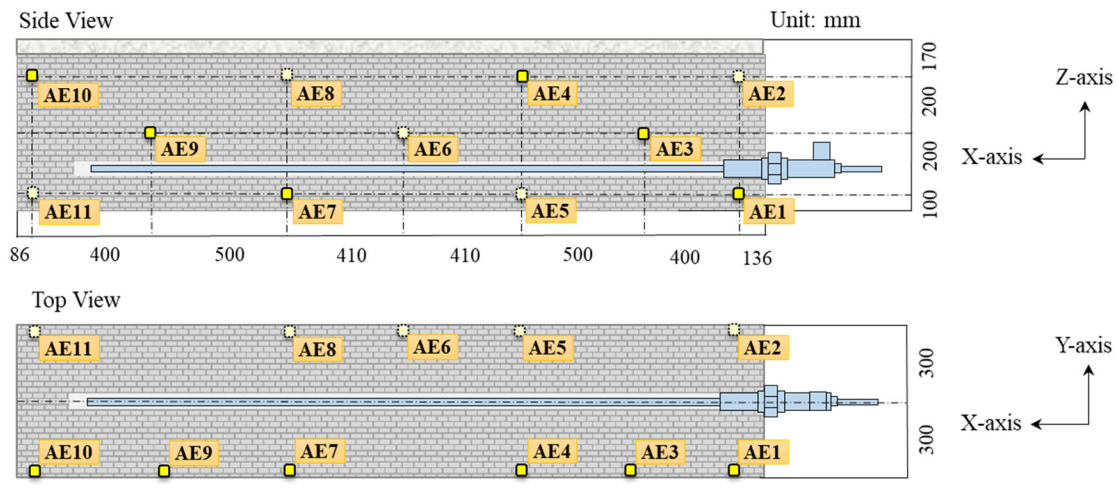


144 b)

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



146 a)



147 b)

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

149

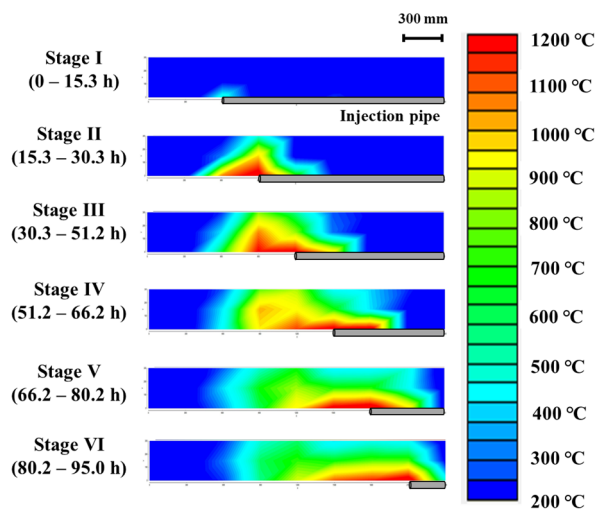
150 3. Results and Discussion

151 3.1 Temperature profile and AE monitoring

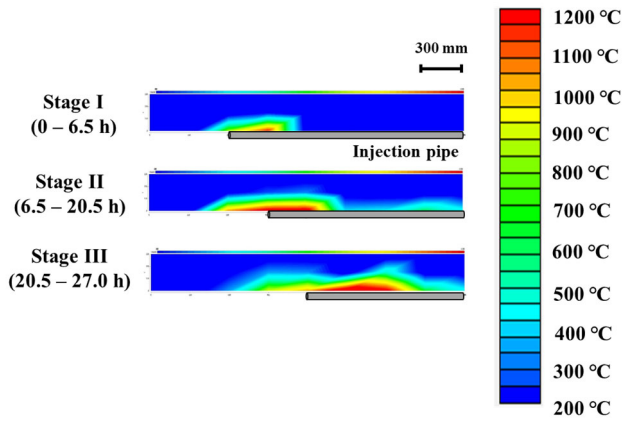
152 The two-dimensional temperature profiles are plotted for each experimental period based on injection rate (Stage
 153 I ~ VI) in Fig. 5, representing the temperature distribution in a cross-section of a horizontal hole. The position of
 154 the injection pipe is also illustrated below the contour results for each stage. The contour range is divided in
 155 100 °C intervals from 200 °C to 1200 °C and the UCG reaction occurs in the high-temperature area in these figures.
 156 The maximum temperature for the gasification area is more than 1000 °C for both types of coal. The figures
 157 clearly show that the movement of the high-temperature area corresponds with moving an injection pipe and the
 158 gasification occurs around the tip of the injection pipe. Considering the temperature rise due to the oxidation
 159 reaction in UCG process, the coal temperature rises as a result of the rapid oxygen consumption around the
 160 injection pipe. These results indicate the possibility to control the gasification area by moving the injection
 161 position of the gasification agents. In type 2, the temperature increment is limited near the coaxial hole while the
 162 temperature rises widely in type 1, implying that the gasification area expands along the face of a coaxial hole in
 163 type 2. Considering both experiments were carried out under the atmospheric condition and the oxygen
 164 concentration was almost the same, the difference in temperature profile is due to the difference in coal quality.
 165 The coal of type 2 contained much ash compared to that of type 1, i.e. the gasification area is expanded along the
 166 face of a coaxial hole because of less reactivity of coal in type 2. High ash contents also cause the molten slag
 167 formation to prevent the promotion of gasification reaction. The other parameters, such as porosity, permeability,

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

169 Figs. S1 and S2 show the monitoring results of temperature in the gasification channel (Please kindly see the
170 Supplementary section). It shows that the temperature in the gasification channel rises with elapsed time and
171 decline gradually after it shows maximum temperature. The maximum temperature monitored during UCG
172 experiment is almost the same for both types of coal, 1300 °C for type 1 and 1250 °C for type 2 while the high-
173 temperature area does not expand upward in type 2. The maximum temperature in type 1 shows that 15.5 h, 43.2
174 h, and 68.8 h elapsed from the beginning of the experiment for T12, T14, and T16, respectively. On the other
175 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
176 temperature results, the velocity to move the gasification area in a horizontal direction is calculated from the
177 elapsed time indicated by the maximum temperature in each thermocouple as shown in Table 2. It can be
178 understood that the velocity in type 2 is three times faster than that of type 1. This result also supports the
179 expansion of the gasification area not toward the coal blocks but along the face of the hole. Therefore, it is
180 necessary to consider injection conditions/pressure to expand the gasification area toward the coal seam when
181 UCG is performed for coal with high ash content.



182 a)



183 b)

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

185

186 **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

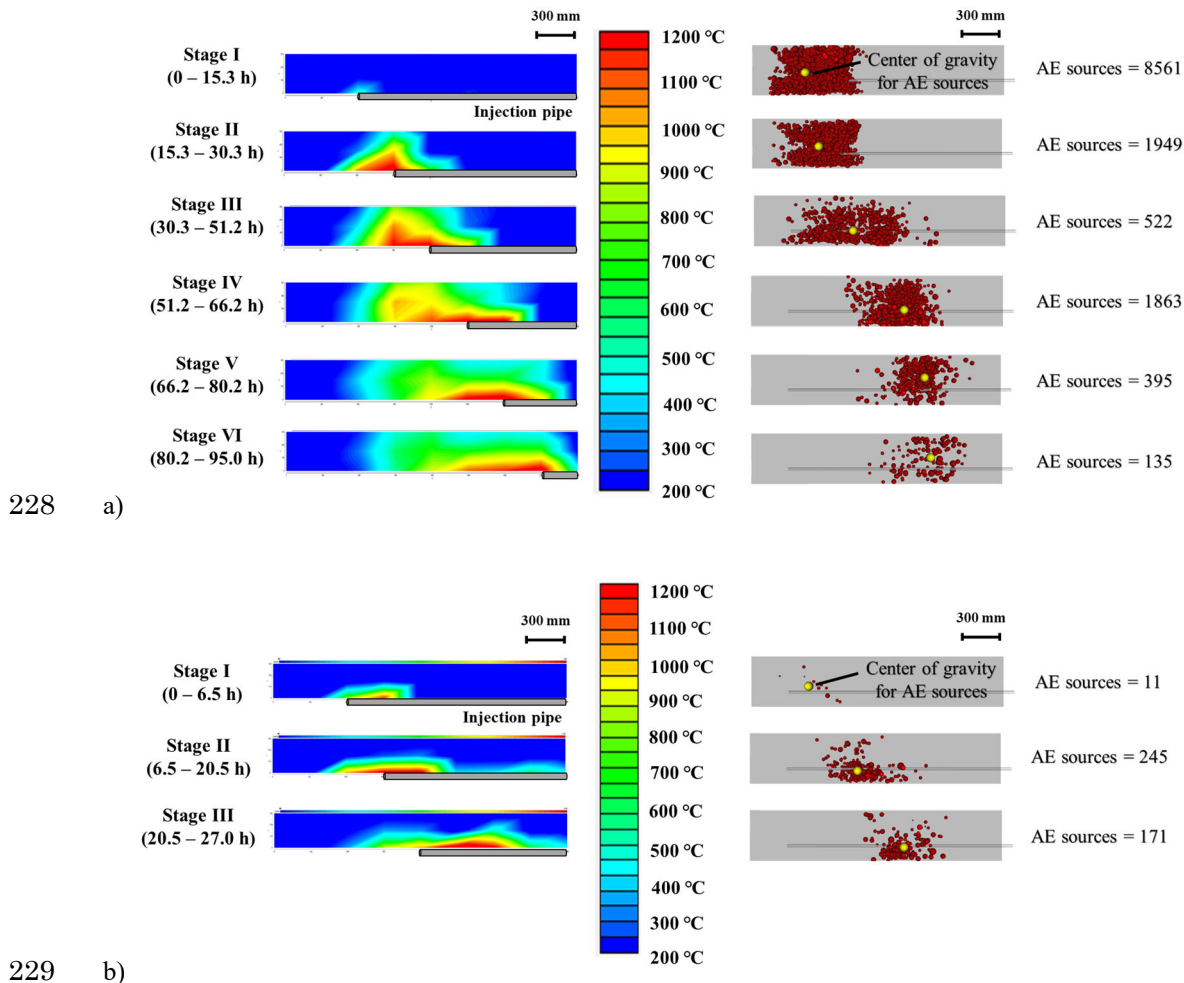
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188 Gasification reaction in UCG process is promoted by enlargement of the oxidation surface around the gasification
 189 channel with crack initiation and development inside the coal seam. Fracturing activities inside the coal seam are
 190 accelerated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

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

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

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



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

231

232 **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)					Average
	Stage I ~ II	Stage II ~ III	Stage III ~ IV	Stage IV ~ V	Stage V ~ VI	
Type 1	10.00	19.52	32.23	16.44	4.59	16.55
Type 2	55.49	47.14	-	-	-	51.31

233

234 3.2 Product gas

235 Monitoring results of the main compositions and the calorific value of a product gas are presented in Fig. 7. The

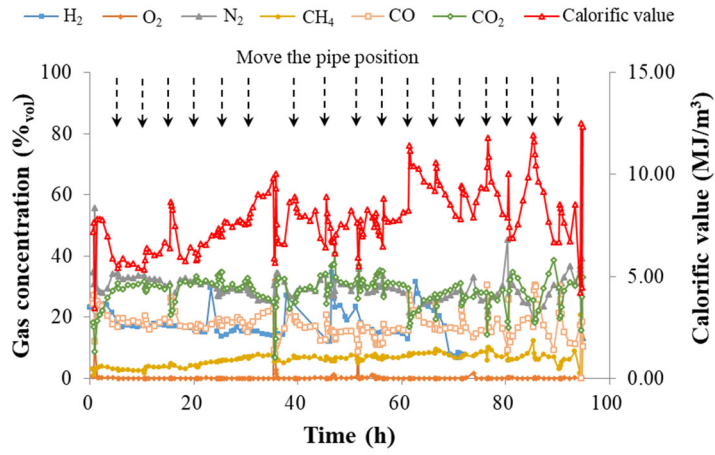
236 oxygen concentration was almost zero throughout both types of coal, indicating that all of the oxygen injected as

237 an oxidant was consumed in the gasification reactions. The main components of the gases produced by the UCG

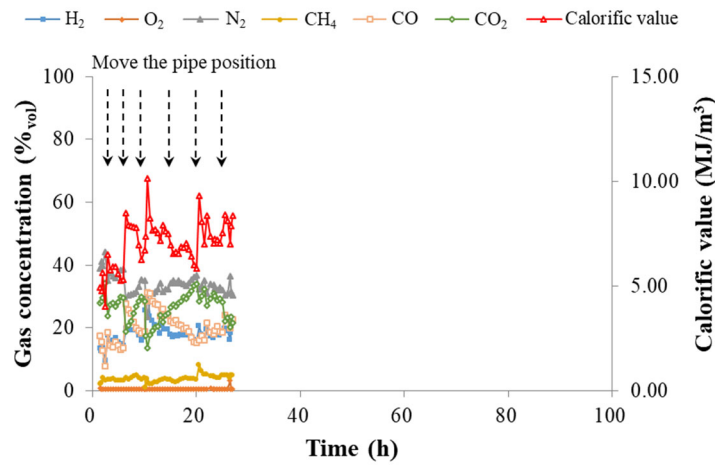
238 process were H₂, CO, CH₄, and CO₂. The time to move the position of the injection pipe is also pointed in the
239 figure. The composition of product gas changed immediately after the position of the injection pipe was moved
240 in both type 1 and type 2, meaning that the concentrations of main combustible gases such as H₂, CO, and CH₄
241 tend to increase at the beginning of the experiment and after the injection pipe is moved. On the other hand, the
242 concentration of CO₂ is related to the change in the combustible gases which tends to decrease when the injection
243 pipe is moved and increase gradually when the combustible gas components decrease. Although there is a certain
244 amount of fluctuation in the product gas components in both experiments, a stable product gas contained in the
245 combustible contents is recovered by moving the injection pipe periodically. This is because the gasification area
246 could be moved to the unreacted part of the coal seam, indicating that it is possible to control the quality of the
247 produced gas by moving the injection pipe. The calorific value of the product gas can be calculated with the
248 concentration of the combustible gas contents [39]. The variation of the calorific value during the experiment
249 shows the same trend as that of the concentration change of H₂, CO, and CH₄, which are the main components of
250 the combustible gas. Furthermore, it shows a gradual increase toward the latter stage of the experiment. According
251 to Table 4, the average concentration of H₂, CO, and CH₄ is 17.1%, 17.2%, and 6.59% for type 1 and 17.6%,
252 19.9%, and 3.75% for type 2. The average calorific value of product gas is 8.05 MJ/m³ and 6.91 MJ/m³
253 respectively. Considering the gasification period in type 2 is much shorter than in type 1, it should be noted that
254 the product gas compositions are largely influenced by the pyrolysis in type 2. The hydrogen shows higher
255 concentrations although the inherent moisture contents of coal are quite small of coal blocks, which are 2.9% and
256 2.2 % for types 1 and 2, respectively. This experiment used the cement between coal blocks and the refractory
257 cement as the external wall, indicating that the moisture contents of these materials joined the gasification to
258 produce the hydrogen. The product gas rate shows the increasing trend for both types 1 and 2 as shown in Fig. 8.
259 This result is consistent with the increasing the gasification agents as shown in Fig. 3. Additionally, the product
260 gas rate also increased immediately after the position of the injection pipe was moved. This is due to the rapid
261 increment of the combustible gas with the promotion of gasification reactions. Table 5 shows the average calorific
262 value of product gas for each injection rate. The calorific value is slightly increased with increasing the injection
263 rate in both types of coal. This is due to the expansion of the gasification area of high temperature with an increase
264 of oxidant volume injected. Therefore, it is possible to roughly control the quality of product gas by arranging the
265 injection rate.

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

268 not. This experiment was conducted under atmospheric conditions, the injection conditions were almost the same,
269 and the maximum temperature during gasification was similar. Therefore, the recovered energy, the amount of
270 reacted coal and product gas, and the gasification efficiency were evaluated by normalization using various
271 parameters. Balance computation of C element is adopted to calculate the amount of reacted coal/carbon [40].
272 The amount of carbon contents contained in tar is ignored in this study. According to the calculation results shown
273 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,
274 and the product gas volume for types 1 and 2 shows 1.74 m³/kg and 1.37 m³/kg, respectively. In both results, the
275 type 1 coal shows higher values. However, both values turn out to be almost the same if they are normalized with
276 reacted carbon: types 1 and 2 shows 26.86 MJ/kg and 25.34 MJ/kg for recovered energy and 2.38 m³/kg and 2.47
277 m³/kg for product gas volume. This means that the several parameters on the outputs from UCG can be estimated
278 by normalizing with reacted carbon regardless of the coal quality if the gasification conditions are the same. The
279 reacted carbon and product gas volume are plotted as a function of oxygen injection rate in Fig. 9. These plots are
280 prepared based on the average value when the position of the injection pipe is constant. According to the results,
281 both the reacted carbon and product gas volume are strongly correlated with the oxygen injected flow rate. This
282 fact indicates the possibility to estimate these parameters with the volume of oxygen injected while it should be
283 noted that this correlation may be established when the gasification temperature is comparable. This relationship
284 is also helpful to design the equipment that treated the injection/production gas for the pilot-scale trial/field
285 implementation. Although the reacted coal and product gas volume are estimated with the volume of oxygen
286 injected, another indicator related to the energy recovery from the coal is required to evaluate the recovered energy
287 by UCG process. The gasification efficiency, which means the energy recovery ratio from coal, is calculable with
288 the amount of recovered energy per unit mass of the gasified coal and the inherent calorific value of coal. The
289 gasification efficiency is 65.15% and 61.84% respectively for types 1 and 2 as shown in Table 6. The gasification
290 efficiency in type 2 is slightly lower than in type 1. This may be due to the difference in the size of the gasification
291 area, meaning that the gasification area is limited along the hole while it expands upwards as well in type 1. In the
292 UCG process, some of the heat energy generated by the oxidation reaction is lost due to the gas leakage and heat
293 transfer to the surrounding rock mass. This heat loss seems to be one of the factors leading to the decrease in
294 gasification efficiency. The ratio of heat loss will be decreased as the amount of heat energy generated increases
295 (i.e., the more coal reacted and the more gas produced). In other words, it is also expected to decrease the ratio of
296 heat loss and improve the gasification efficiency in the UCG field implementation since the larger scale of
297 gasification area will be created compared to the current scale of the ex-situ UCG model experiment.



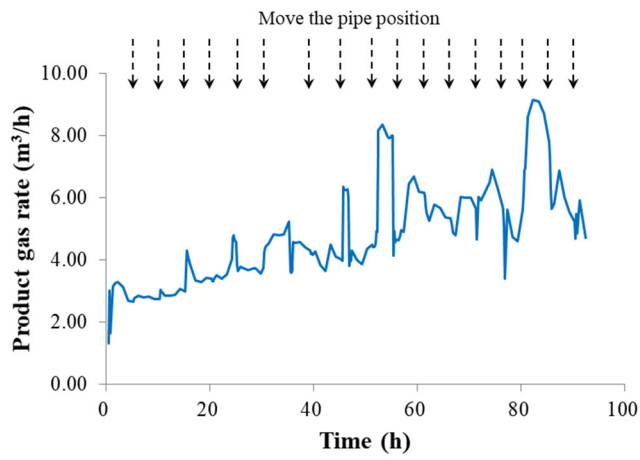
298 a)



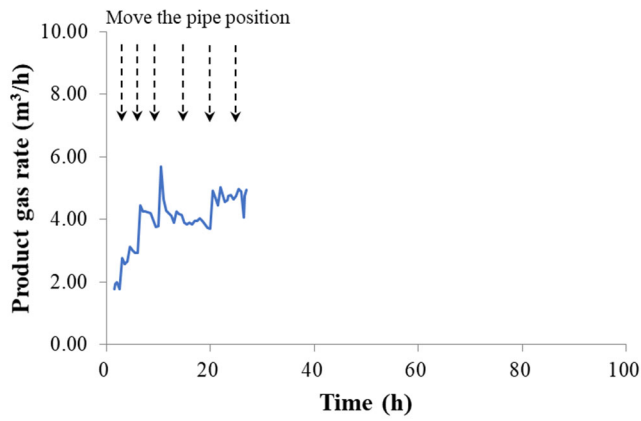
299 b)

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

301

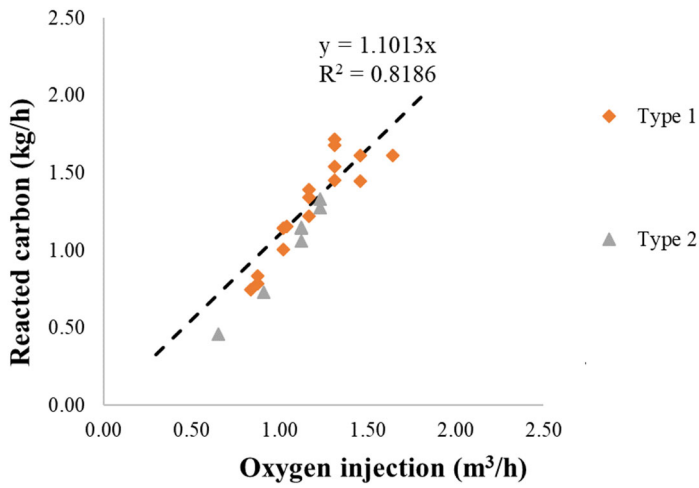


302 a)

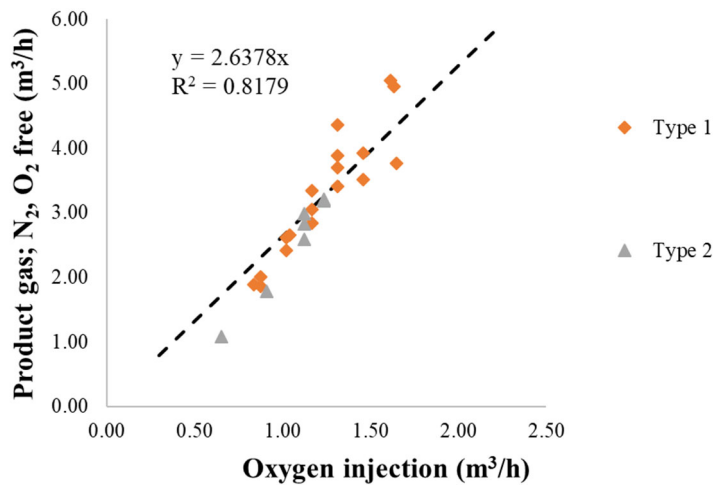


303 b)

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



305 a)



306 b)

307 Fig. 9. Correlation of the reacted carbon and product gas volume with oxygen injection rate: a) reacted carbon; b)
308 product gas volume (N₂, O₂ 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 ₂ H ₄ (%)	C ₂ H ₆ (%)	C ₃ H ₆ (%)	C ₃ H 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 ₂ H ₄ (%)	C ₂ H ₆ (%)	C ₃ H ₆ (%)	C ₃ H 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

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

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

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

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

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

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

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

340

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347

348 References

- 349 1. Perkins, G., *Underground coal gasification - Part I: Field demonstrations and process*
350 *performance*. Progress in Energy and Combustion Science, 2018. **67**: p. 158-187.
- 351 2. Wang, Z.Q., et al., *Expansion of three reaction zones during underground coal gasification*
352 *with free and percolation channels*. Fuel, 2017. **190**: p. 435-443.
- 353 3. Laciak, M., et al., *Application of geostatistical methods in spatio-temporal modelling of*
354 *temperature changes of UCG experimental trial*. Measurement, 2021. **171**: p. 13.
- 355 4. Wang, Z.Q., X.Y. Xu, and Y. Cui, *Effect of Fixed and Removable Gas-Injection Patterns on*
356 *the Expansion of Reaction Zones during Underground Coal Gasification*. Energy & Fuels,
357 2019. **33**(6): p. 4740-4747.
- 358 5. Pei, P., K. Barse, and J. Nasah, *Competitiveness and Cost Sensitivity Study of*
359 *Underground Coal Gasification Combined Cycle Using Lignite*. Energy & Fuels, 2016.
360 **30**(3): p. 2111-2118.
- 361 6. Mao, F., *Underground coal gasification (UCG): A new trend of supply-side economics of*
362 *fossil fuels*. Natural Gas Industry B, 2016. **3**(4): p. 312-322.
- 363 7. Prabu, V. and K. Geeta, *CO₂ enhanced in-situ oxy-coal gasification based carbon-neutral*
364 *conventional power generating systems*. Energy, 2015. **84**: p. 672-683.
- 365 8. Kanta, D. and V. Prabu, *Experimental studies on humidified/water influx O₂ gasification*
366 *for enhanced hydrogen production in the context of underground coal gasification*.
367 International Journal of Hydrogen Energy, 2017. **42**(20): p. 14089-14102.
- 368 9. Yang, L.H., et al., *Field test of large-scale hydrogen manufacturing from underground*
369 *coal gasification (UCG)*. International Journal of Hydrogen Energy, 2008. **33**(4): p. 1275-
370 1285.
- 371 10. Nakaten, N. and T. Kempka, *Techno-Economic Comparison of Onshore and Offshore*
372 *Underground Coal Gasification End-Product Competitiveness*. Energies, 2019. **12**(17): p.
373 28.
- 374 11. Burchart-Korol, D., et al., *Eco-efficiency of underground coal gasification (UCG) for*
375 *electricity production*. Fuel, 2016. **173**: p. 239-246.
- 376 12. Yang, D.M., et al., *Recent development on underground coal gasification and subsequent*
377 *CO₂ storage*. Journal of the Energy Institute, 2016. **89**(4): p. 469-484.
- 378 13. Khadse, A., et al., *Underground coal gasification: A new clean coal utilization technique*
379 *for India*. Energy, 2007. **32**(11): p. 2061-2071.
- 380 14. Yang, L., *Study on the model experiment and numerical simulation for underground coal*

- 381 *gasification*. Fuel, 2004. **83**(4-5): p. 573-584.
- 382 15. Perkins, G., *Underground coal gasification - Part II: Fundamental phenomena and*
383 *modeling*. Progress in Energy and Combustion Science, 2018. **67**: p. 234-274.
- 384 16. Khan, M.M., et al., *Modelling Underground Coal Gasification-A Review*. Energies, 2015.
385 **8**(11): p. 12603-12668.
- 386 17. Laciak, M., et al., *The analysis of the underground coal gasification in experimental*
387 *equipment*. Energy, 2016. **114**: p. 332-343.
- 388 18. Shafirovich, E. and A. Varma, *Underground Coal Gasification: A Brief Review of Current*
389 *Status*. Industrial & Engineering Chemistry Research, 2009. **48**(17): p. 7865-7875.
- 390 19. Stanczyk, K., et al., *Gasification of lignite and hard coal with air and oxygen enriched air*
391 *in a pilot scale ex situ reactor for underground gasification*. Fuel, 2011. **90**(5): p. 1953-
392 1962.
- 393 20. Kapusta, K., M. Wiatowski, and K. Stanczyk, *An experimental ex-situ study of the*
394 *suitability of a high moisture ortho-lignite for underground coal gasification (UCG)*
395 *process*. Fuel, 2016. **179**: p. 150-155.
- 396 21. Gur, M., et al., *Experimental results of underground coal gasification of Turkish lignite in*
397 *an ex-situ reactor*. Fuel, 2017. **203**: p. 997-1006.
- 398 22. Kacur, J., et al., *Impact analysis of the oxidant in the process of underground coal*
399 *gasification*. Measurement, 2014. **51**: p. 147-155.
- 400 23. Hamanaka, A., et al., *Effect of Injection Flow Rate on Product Gas Quality in*
401 *Underground Coal Gasification (UCG) Based on Laboratory Scale Experiment:*
402 *Development of Co-Axial UCG System*. Energies, 2017. **10**(2): p. 11.
- 403 24. Bhutto, A.W., A.A. Bazmi, and G. Zahedi, *Underground coal gasification: From*
404 *fundamentals to applications*. Progress in Energy and Combustion Science, 2013. **39**(1): p.
405 189-214.
- 406 25. Kumari, G. and P. Vairakannu, *CO₂-air based two stage gasification of low ash and high*
407 *ash Indian coals in the context of underground coal gasification*. Energy, 2018. **143**: p.
408 822-832.
- 409 26. Prabu, V. and S. Jayanti, *Simulation of cavity formation in underground coal gasification*
410 *using bore hole combustion experiments*. Energy, 2011. **36**(10): p. 5854-5864.
- 411 27. Prabu, V. and S. Jayanti, *Laboratory scale studies on simulated underground coal*
412 *gasification of high ash coals for carbon-neutral power generation*. Energy, 2012. **46**(1): p.
413 351-358.
- 414 28. Yang, L.H., *Study of the model experiment of blinding-hole UCG*. Fuel Processing
415 Technology, 2003. **82**(1): p. 11-25.
- 416 29. Cui, Y., et al., *Forward and reverse combustion gasification of coal with production of*
417 *high-quality syngas in a simulated pilot system for in situ gasification*. Applied Energy,
418 2014. **131**: p. 9-19.

- 419 30. Liu, H.T., et al., *Experimental Study of Reverse Underground Coal Gasification*.
420 Energies, 2018. **11**(11): p. 13.
- 421 31. Kashyap, S. and P. Vairakannu, *Movable injection point-based syngas production in the*
422 *context of underground coal gasification*. International Journal of Energy Research, 2020.
423 **44**(5): p. 3574-3586.
- 424 32. Su, F.Q., et al., *Monitoring and evaluation of simulated underground coal gasification in*
425 *an ex-situ experimental artificial coal seam system*. Applied Energy, 2018. **223**: p. 82-92.
- 426 33. Su, F.Q., et al., *Evaluation of Coal Combustion Zone and Gas Energy Recovery for*
427 *Underground Coal Gasification (UCG) Process*. Energy & Fuels, 2017. **31**(1): p. 154-169.
- 428 34. Su, F.Q., et al., *Evaluation of a Compact Coaxial Underground Coal Gasification System*
429 *Inside an Artificial Coal Seam*. Energies, 2018. **11**(4): p. 11.
- 430 35. Su, F.Q., et al., *Monitoring of coal fracturing in underground coal gasification by acoustic*
431 *emission techniques*. Applied Energy, 2017. **189**: p. 142-156.
- 432 36. Su, F.Q., et al., *Evaluation of Structural Changes in the Coal Specimen Heating Process*
433 *and UCG Model Experiments for Developing Efficient UCG Systems*. Energies, 2013.
434 **6**(5): p. 2386-2406.
- 435 37. Xie, J., et al., *Technical application of safety and cleaner production technology by*
436 *underground coal gasification in China*. Journal of Cleaner Production, 2020. **250**: p. 14.
- 437 38. Xin, L., et al., *Technological aspects for underground coal gasification in steeply inclined*
438 *thin coal seams at Zhongliangshan coal mine in China*. Fuel, 2017. **191**: p. 486-494.
- 439 39. Su, F.Q., et al., *Evaluation of Energy Recovery from Laboratory Experiments and Small-*
440 *scale Field Tests of Underground Coal Gasification (UCG)*. Journal of MMIJ, 2015.
441 **131**(5): p. 203-218.
- 442 40. Wiatowski, M., et al., *Technological aspects of underground coal gasification in the*
443 *Experimental "Barbara" Mine*. Fuel, 2015. **159**: p. 454-462.