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H_2 production enhancement in underground coal gasification with steam addition: Effect of injection conditions

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ABSTRACT

Hydrogen is a clean energy source, and its use helps to mitigate climate change. Underground coal gasification for hydrogen production is a promising method for countries with abundant coal resources and high hydrogen demand. However, the existing coal-to-hydrogen process underground exhibit low production efficiency. This work proposes the use of swirl flow injection to improve hydrogen production efficiency, and also explores the influence of other injection conditions (oxygen flow rate, steam mass flow and steam temperature) on hydrogen production. For straight flow injection, the effect of steam addition on gasification performance depends on the oxygen flow rate, and the highest H_2 production is 14.6 L under 1 L/min oxygen and 1 g/L steam. With a swirl flow injection, H_2 production increases with steam addition for both 1 L/min and 2 L/min oxygen, which shows a larger H_2 production than straight flow injection. The highest H_2 production for swirl flow injection is 19 L under 2 L/min oxygen and 1 g/L steam. An increase in steam temperature barely affects the composition of products but apparently increases the amount of products. The fracture effect of high temperature steam might cause a sudden increase of H_2 and CH_4 at the late stage.

1. Introduction

Globally, fossil fuels (oil, natural gas, and coal) still dominate the global energy consumption, while the proportion of renewable energy is steadily increasing [1,2]. Hydrogen is a representative fuel of renewable energy, with high mass energy density and zero emission. The use of hydrogen is expected to mitigate the climate change caused by CO_2 emissions from fossil fuels [3]. In China, hydrogen production was 37.81 million tons in 2022, and will exceed 50 million tons in 2030 according to the prediction based on the Carbon Peak goal [4]. The existing hydrogen production methods are divided into four categories, namely coal based hydrogen production [5], natural gas based hydrogen production [6], industrial by-products based hydrogen production [7], and electrolytic water based hydrogen production [8]. In China, coal resource is far more than oil and gas, thus the coal-to-hydrogen technology is the best choice, which also featured with mature process and low cost. In recent years, underground coal gasification (UCG) has received wide attention, which can convert in-situ coal resources into high calorific value synthetic gas, as a solution to the difficulty of mining operations in deep ground [9,10]. Study on the hydrogen production from UCG is essential especially for countries with abundant coal resources and high hydrogen demand.

At first, researchers used air or pure oxygen as the injection gas to the underground gasifier, thus the product at outlet mainly contains CO and CH_4, while H_2 content in product is limited. Gur et al. [11] used a laboratory scale model experiment to study the UCG characteristic of lignite, and found the maximum H_2 content in product is 22 % under different inlet O_2 concentrations. Kumari et al. [12] add CO_2 to O_2 as injection of UCG, and found when CO_2/O_2 molar ratio is 0.2 the H_2 content is highest (25.7 %). Wiatowski et al. [13] increased the pressure to 0.5 MPa in ex-situ UCG experiment, resulting in an average H_2 content of 32.1 % and a total production rate of 5.4 Nm^3/h. Mocek et al. [14] carried out field test in "Wieczorek" mine, and concluded that highest H_2 content is 20 % at different inlet O_2 concentrations and supply rates. In summary, when the injection gas is air, O_2 or CO_2/O_2, H_2 production is not satisfactory since the H element in coal is the only source for H_2 yield.

To further increase the H_2 content in product, H_2O is added in the injection gas either as liquid (spray) or gas (steam). As for liquid H_2O, De

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Nomenclature

C_{CH4}	Volume fraction of CH_4 [%]
C_{CO}	Volume fraction of CO [%]
C_{CO2}	Volume fraction of CO_2 [%]
C_{H2}	Volume fraction of H_2 [%]
H	Maximum hydrogen content [%]
Q	Cumulative gas production [L]
t	Time [h]
T	Temperature [°C]
X	Axial distance [mm]
Y	Vertical distance [mm]

Table 1
Coal analysis results.

Proximate Analysis (air dry base, wt %)		Ultimate Analysis (dry and ash free base, wt %)	
Fixed carbon	58.52	C	79.56
Volatile	33.70	O	14.56
Ash	5.12	H	4.55
Moisture	2.66	N	1.16
		S_d	0.15

et al. [15] conducted laboratory scale UCG experiments of sub-bituminous coal with humidified oxygen as the gasifying medium, and found the maximum concentration of H_2 in product is 31 %. Kashyap et al. [16] also studied the effect of water addition on the UCG products, and found that the average hydrogen content is 26.9 % for low ash coal while 18.1 % for high ash coal. As for steam, Zagorscak et al. [17] added gaseous H_2O to pure O_2 as the injection of the ex-situ gasification system with a high rank coal under different pressure, resulting in an average H_2 content of 25.27 % at 1 bar and 14.64 % at 30 bar. Ramakrishnan et al. [18] established a numerical model of UCG, and found that when the mass ratio of oxygen to steam increases the hydrogen yield increases first and then decreases. In summary, when liquid H_2O is used in UCG, its cooling effect might weaken the reaction or cause shut down, thus steam is a better choice for H_2O addition in UCG to improve H_2 production.

When steam is added in the injection, its amount and temperature greatly affects the performance of coal gasification behaviors. Xie et al. [19] carried out in-situ UCG experiments at Zhongliangshan coal mine and Huating Ankou coal mine, and found that when the H_2O/O_2 ratio increased from 0.75 kg/kg to 1.2 kg/kg, both H_2 and CO in the products increased, and H_2 is more sensitive to steam addition. Konstantinou et al. [20] used a lab scale reactor to study the UCG behavior of a bituminous coal under high pressure and high temperature, and found that when the steam injection increased 3 times, H_2 production increased first while then decreased. Zhang et al. [21] established a coupled numerical model for underground gasification, and found that the H_2 content in products increased from 28 % to 37 % as the H_2O/O_2 ratio changed from 1:2 to 2:1. Daggupati et al. [22] and Stanczyk et al. [23] added steam with a temperature <150 °C to the injection of a lab scale UCG reactor, causing the extinction of combustion front and poor gasification efficiency. Pei et al. [24] found that the ultra-superheated steam is helpful for higher H_2 content in gasification products. Komatsu et al. [25] found that when the steam temperature increased from 110 °C to 170 °C, the drying rate of lignite coal was enhanced. Li et al. [26] studied the pore structure and moisture content of coal under steam processing, and found that when steam temperature is 100 °C, the original pores in lignite expanded and new cracks were generated, while when the steam temperature was >200 °C, over 96 % of the moisture in coal was lost. In summary, the choice of a proper steam temperature is essential to improve the UCG performance.

The mentioned studies above are meaningful and inspiring which have insights into the effect of steam addition on UCG performance. However, there are still some limitations and more work remains to be done. Firstly, to study the effect of H_2O/O_2 ratio, researchers usually only changes the feeding rate of steam while other parameters are constant. However, the best H_2O/O_2 ratio might change at different O_2 feeding rate and temperature, indicating that a matching relationship remains to be found between steam feeding rate and other parameters for improving H_2 production in UCG. Secondly, straight jet is the only type used in the experiments so far, while in such cases the diffusion of steam from jet core to coal surface is poor, which limits the gasification reaction between coal and steam. Swirl jet is a potential solution to this problem, while few studies are reported on this. Finally, the comprehensive study on effect of steam temperature on H_2 production is rarely reported.

To fulfill these gaps, a lab scale reactor was used in this work to study the effect of steam addition on H_2 production in UCG. The feeding rate of

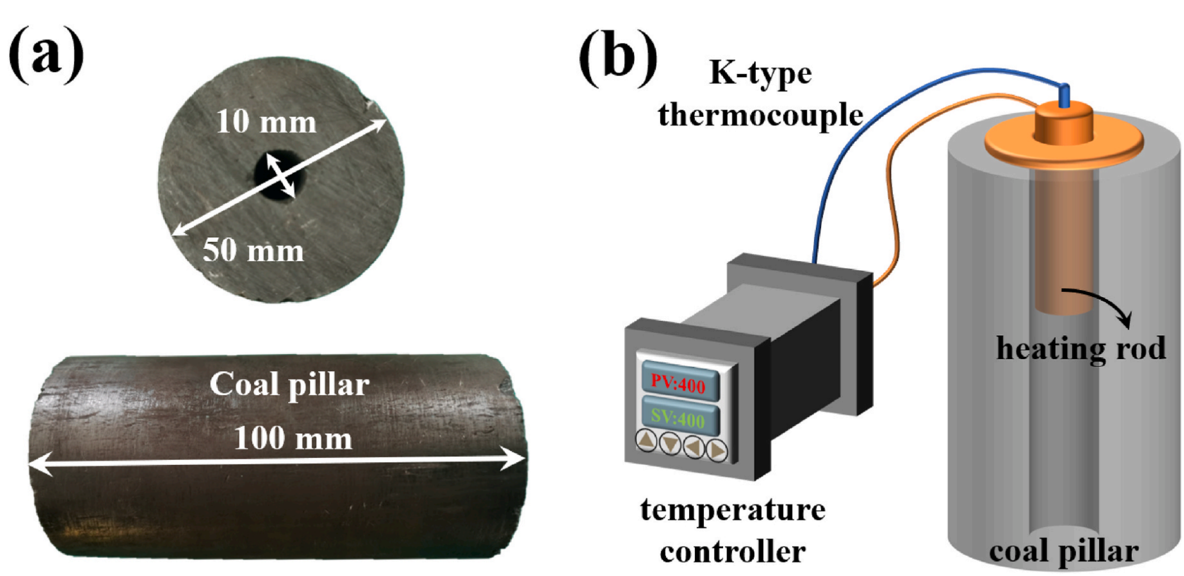

Fig. 1. (A) Structure of the coal sample, (b) ignition by electrical heating.

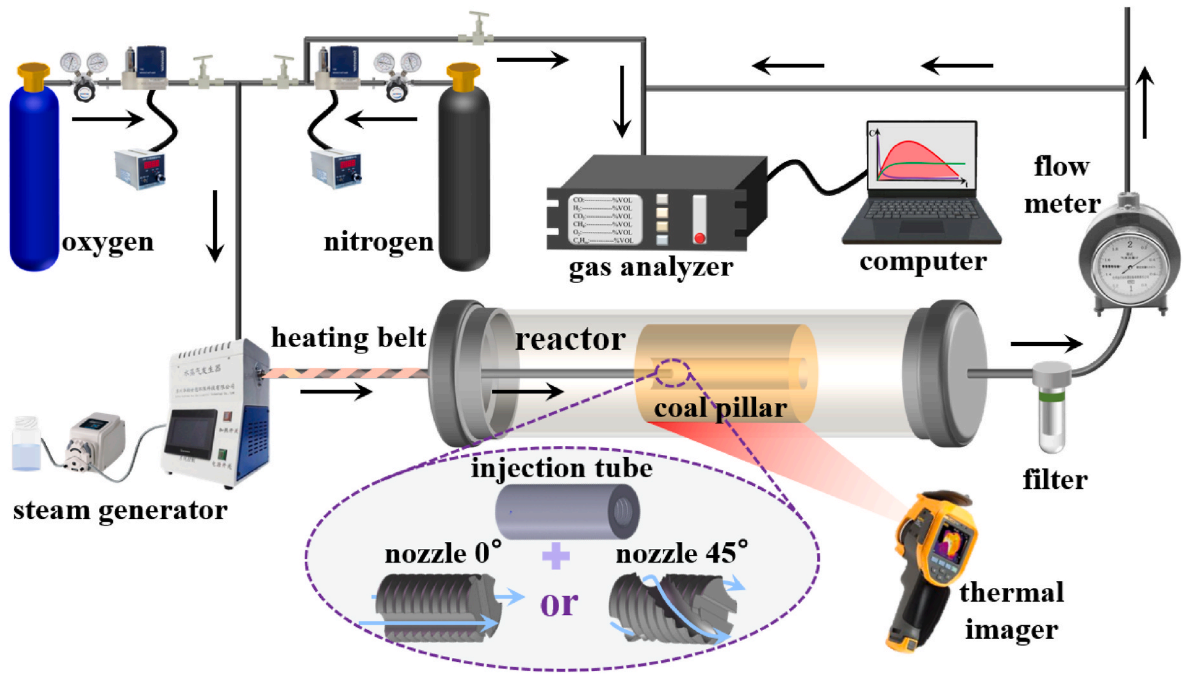

Fig. 2. Schematics of experimental system.

Table 2
Parameters of experimental conditions.

Case	Steam temperature (°C)	Injection angle (°)	Oxygen flow rate (L/min)	Steam addition per oxygen volume (g/L)
1	120	0	1	0.5
2	120	0	1	1
3	120	0	2	0.5
4	120	0	2	1
5	120	45	1	0.5
6	120	45	1	1
7	120	45	2	0.5
8	120	45	2	1
9	150	45	1	1
10	180	45	1	1
11	150	45	2	1
12	180	45	2	1

steam and O_2 are changed to investigate the effect of H_2O/O_2. A novel swirl nozzle is compared to the straight jet nozzle as the inlet to improve UCG performance. The transient temperature field and gas products at different steam temperature are studied in detail. This work is essential for modifying the steam addition method in UCG to improve the H_2 production.

2. Methodology

2.1. Coal sample

The coal sample used in experiments was bituminous coal from Hongyan coal mine in Shaanxi, China. On the one hand, this coal type has a harder texture, facilitating the processing into the wanted shape. On the other hand, this coal type exhibits notable advantages of high volatile content, low ash content and low sulfur content, as listed in Table 1. In the gasification experiments, a cylindrical coal pillar was used with a diameter of 50 mm and a height of 100 mm. In addition, a hole is drilled in the middle of the coal pillar with a diameter of 10 mm, which is the initial gasification channel, as shown in Fig. 1(a).

2.2. Ignition method

In this work, an electric heating device is used for ignition of coal pillars, as shown in Fig. 1(b). The heating rod (220 V, 200 W) is connected to the temperature controller through wires, with a constant temperature of 400 °C. The diameter of the heating rod is 9.5 mm, so it can be smoothly inserted into the gasification channel of the coal pillar. According to the preliminary experiments, the ignition of coal pillar required 3 h when the heating temperature is 400 °C. Therefore, 400 °C and 3 h are determined as the ignition parameters in this work for all conditions.

2.3. Experimental system

Once the coal pillar is successfully ignited, it is immediately sent into a reactor and the gasification test is initiated with the injection of the gasification agent, as show in Fig. 2. For the gas injection system, oxygen and steam are introduced during the gasification experiment, while nitrogen is used after the experiment for cooling and fire extinguishing. The flow rate of gas and steam are adjusted by a mass flow controller (D07-7 B, Sevenstar) and a peristaltic pump attached to the steam generator (HSG02, HuaXiangStar), respectively. A heating belt is wrapped around the pipeline in order to prevent the condensation of steam, with an adjustable temperature. The gasification reactor is made of quartz with a size of 72 mm in diameter and 950 mm in length. In order to study the effect of injection angles, different nozzles are designed and used. When the nozzle angle is 0°, it is straight flow; while when the nozzle angle is 45°, it is swirl flow. The temperature of the coal pillar is monitored using a thermal imaging camera. A wet gas flow meter (LMF-2) is applied to monitor syngas flow and a gas analyzer (YF–V01) is used for online analysis of the syngas composition. A filter is set before the analysis unit to remove impurities such as tar, moisture and particulate matter.

2.4. Operation conditions

As listed in Table 2, a series of experiments were conducted to investigate the H_2 production performance during gasification. The effect of swirl flow, steam temperature, oxygen and steam flow rate are

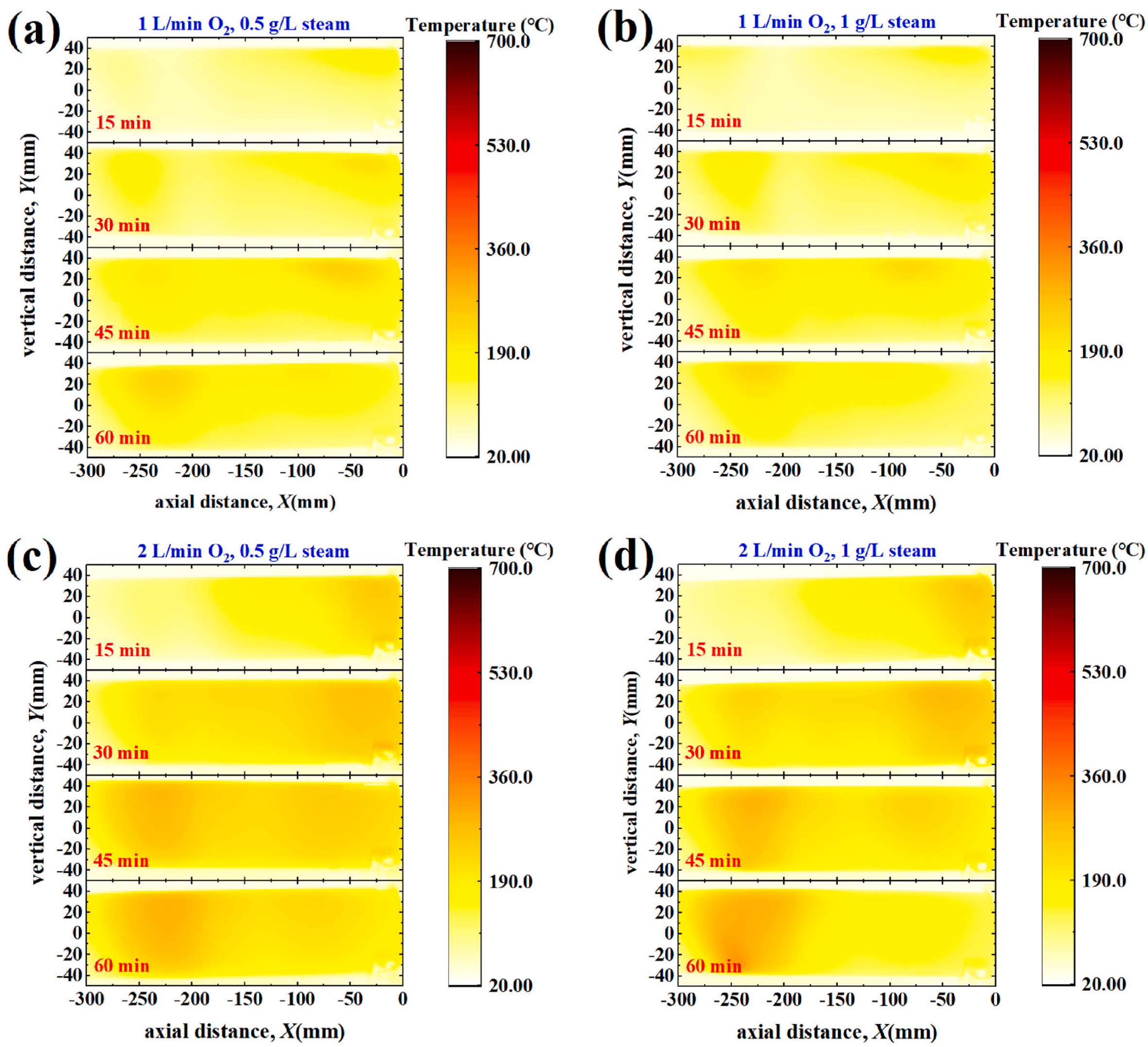

Fig. 3. Temperature distribution. (a) case 1, (b) case 2, (c) case 3, (d) case 4.

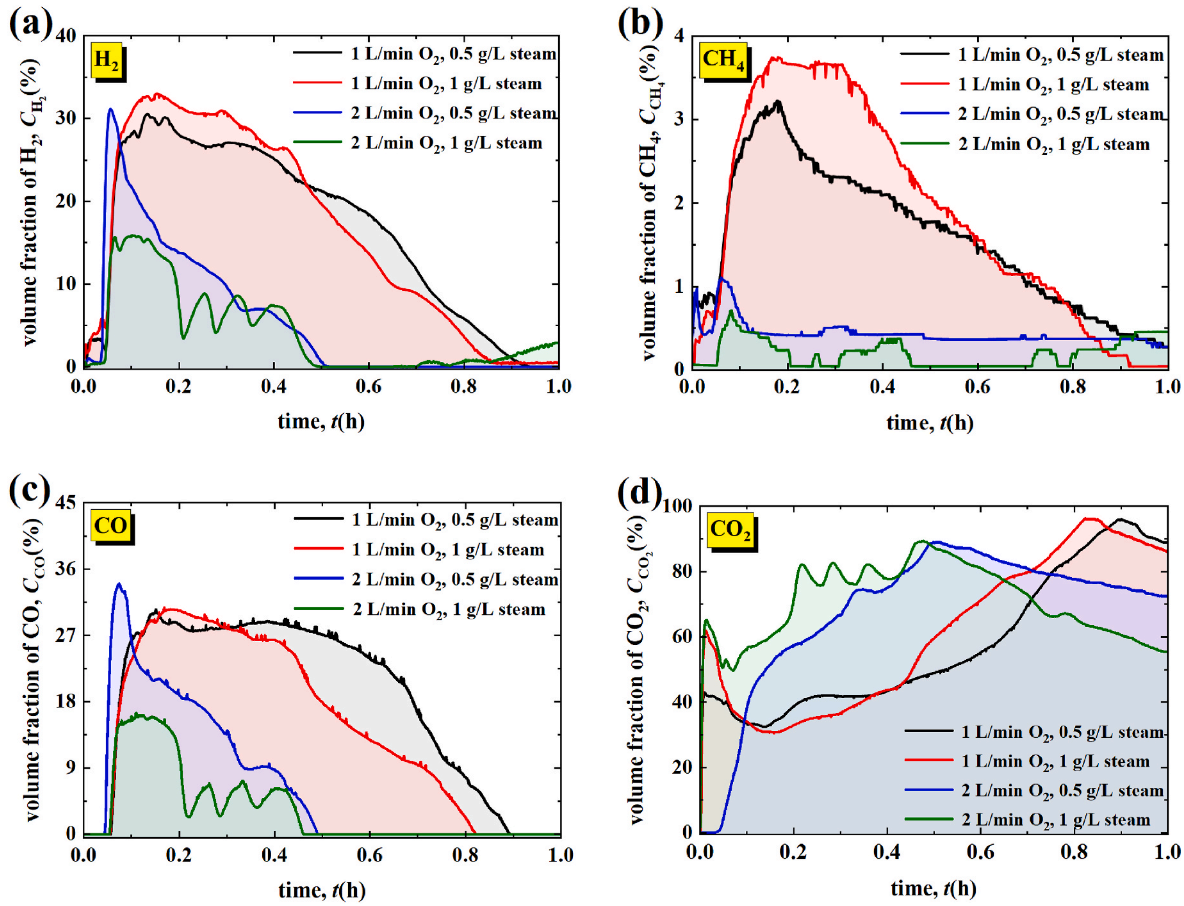

Fig. 4. Gas content in products for case 1–4. (a) H_2, (b) CH_4, (c) CO, (d) CO_2.

studied.

3. Results and discussion

3.1. Effect of steam and oxygen flow rate with 0° nozzle

For case 1–4 in Tables 2 and 0° nozzle was used to form a straight flow at inlet. Fig. 3 shows the temperature distribution at coal surface for case 1–4 with different steam and oxygen flow rates. The inlet is at the left side and the outlet in at the right side. For the case with 1 L/min oxygen and 0.5 g/L steam shown in Fig. 3(a), the maximum temperature increases with time and the high temperature region moves slowly from the outlet to the inlet. Compared to that, when the steam addition increases to 1 g/L as shown in Fig. 3(b), the maximum temperature is slightly lower while the movement of high temperature region is faster. Further, when the oxygen flow rate increases to 2 L/min as shown in Fig. 3(d), the maximum temperature is apparently higher and the movement of high temperature region is faster. Finally, when the steam addition decreases to 0.5 g/L as shown in Fig. 3(c), the maximum temperature decreases a little and the high temperature region moves slower. In summary, the effect of steam addition on the temperature evolution is related to the oxygen flow rate, thus it is essential to find a matching relationship between steam and oxygen flow rate to optimize the reaction intensity and expansion of reaction zone.

The composition of gas products for case 1–4 are compared in Fig. 4. According to Fig. 4(a), for the case with 1 L/min oxygen and 0.5 g/L steam, H_2 content in products increases fast from 0 to 30 % at 0.12 h after the gasification begins, and then gradually decreases to 0 at 0.92 h. When the steam addition increases to 1 g/L, the maximum H_2 content is larger while it decreases faster with time. That is because that more steam promotes the gasification reaction, but the faster expansion of high temperature region as shown in Fig. 3 leads to a shorter reaction time. When the oxygen increases to 2 L/min with 1 g/L steam (green line), the maximum H_2 content decreases a lot to 15 % since excess oxygen promotes the oxidization reaction rather than gasification. When the steam addition decreases to 0.5 g/L (blue line), the maximum H_2 content increases a lot, since the temperature decreases shown in Fig. 3 and H_2 formation reactions are mostly endothermic reactions. These reactions include steam gasification reaction ($C + H_2O \rightarrow CO + H_2$, $\Delta H = +131$ kJ/mol) and methane-steam reforming reaction ($CH_4 + H_2O \rightarrow CO + 3H_2$, $\Delta H = +206$ kJ/mol). However, the H_2 content decreases dramatically with time, indication that oxidization is dominating and too much oxygen is not good for H_2 production. According to Fig. 4(b) and (c), the effect of steam and oxygen flow rate on CH_4 and CO production with 0° nozzle is similar to that on H_2 production. According to Fig. 4(d), the change of CO_2 production in different cases is opposite to that of H_2, CH_4 and CO. When the oxygen flow rate is 2 L/min, the main content in the products is CO_2.

Based on the gas product flow rate and composition, the cumulative gas production of H_2, CH_4, CO, CO_2 at different time is calculated, as shown in Fig. 5. The final yields of H_2 volume for case 1–4 are 10.2 L, 14.6 L, 6.2 L and 4.7 L, respectively. For 1 L/min oxygen, H_2 yields increases with steam addition; while for 2 L/min oxygen, H_2 yields decreases with steam addition. Based on the temperature distribution in Fig. 3, it is evident that, under 1 L/min oxygen, the increase of steam reduces the high temperature area and the maximum temperature. This indicates that the dominant reaction is the hydrogen-producing gasification reaction, leading to an increase in H_2 yield. In contrast, under 2 L/

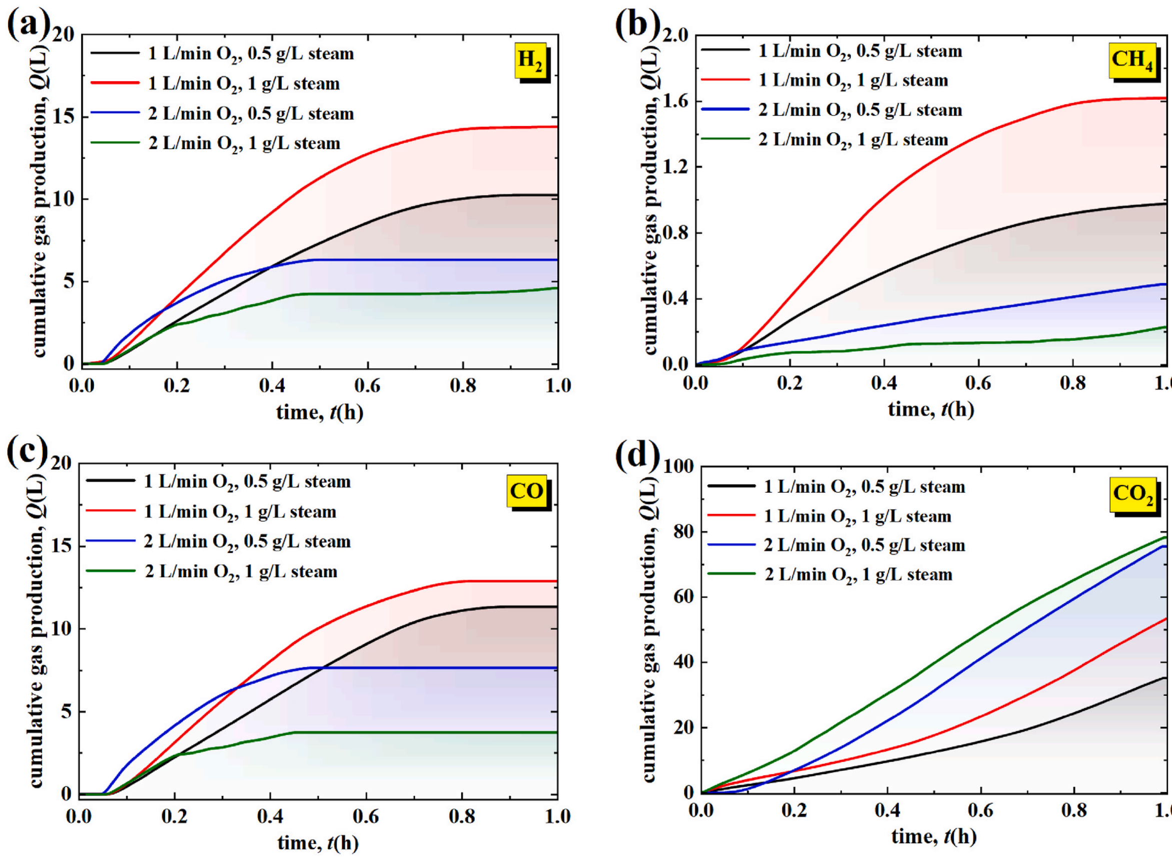

Fig. 5. Cumulative gas production for case 1–4. (a) H_2, (b) CH_4, (c) CO, (d) CO_2.

min oxygen, the increase of steam slightly reduces the high temperature area, while increases the maximum temperature. Simultaneously, the influence of high flow rate oxygen and high concentration steam may cause uneven gas mixing, making the combustion reaction of oxygen to generate CO_2 the dominant reaction, thereby reducing the H_2 yield. According to Fig. 5 (b) ~ (d), influence of steam and oxygen on CH_4 and CO production is similar to that on H_2 production, and excess oxygen leads to more CO_2 production than the combustible gases.

In summary, when the injection is straight flow (0° nozzle), the effect of steam addition on gasification performance depends on the oxygen flow rate. The good match between steam and oxygen is essential for H_2 yields. The best parameters with 0° nozzle are 1 L/min oxygen and 1 g/L steam, with a cumulative H_2 production of 14.6 L.

3.2. Effect of steam and oxygen flow rate with 45° nozzle

For case 5–8 in Table 2, 45° nozzle was used to form a swirl flow at inlet. Fig. 6 shows the temperature distribution at coal surface for case 5–8 with different steam and oxygen flow rates. For the case with 1 L/min oxygen and 0.5 g/L steam shown in Fig. 6(a), the maximum temperature increases with time at first and then decreases, while the high temperature region is close to the inlet and expand gradually. Compared to that, when the steam addition increases to 1 g/L as shown in Fig. 6(b), the maximum temperature decreases faster with time, and the high temperature region is closer to the inlet. Further, when the oxygen flow rate increases to 2 L/min as shown in Fig. 6(d), the maximum temperature is much higher and the high temperature region is larger. Finally, when the steam addition decreases to 0.5 g/L as shown in Fig. 6(c), the maximum temperature increases and the high temperature region is farther from the inlet. In summary, compared to the injection with straight flow, when swirl flow is used, the maximum temperature is apparently higher and the reaction region is closer to the inlet.

The composition of gas products for case 5–8 are compared in Fig. 7. According to Fig. 7(a), for the case with 1 L/min oxygen and 0.5 g/L steam, H_2 content in products increases fast from 0 to 35 % at 0.16 h, and then gradually decreases. When the steam addition increases to 1 g/L, the maximum H_2 content barely changes while it decreases slower with time. That is because that more steam promotes the gasification reaction. When the oxygen increases to 2 L/min with 1 g/L steam (green line), the maximum H_2 content barely changes while it decreases faster with time, because coal is consumed faster by more oxygen. When the steam addition decreases to 0.5 g/L (blue line), the maximum H_2 content increases a lot even though the temperature increases, which is different from that in Fig. 4. That is because when swirl flow injection is used, oxygen consumption is better than that with straight flow, leading to a better gasification performance. According to Fig. 7(b) and (c), the effect of steam and oxygen flow rate on CH_4 and CO production with 45° nozzle is similar to that on H_2 production. According to Fig. 7(d), the increase of steam addition leads to more CO_2 at early stage and less CO_2 at late stage for both 1 L/min and 2/min oxygen.

Based on the gas product flow rate and composition, the cumulative gas production of H_2, CH_4, CO, CO_2 at different time is calculated, as shown in Fig. 8. When swirl flow injection is used, for either 1 L/min or 2 L/min oxygen, H_2 yields increases with steam addition, which is different from that with straight flow injection. In addition, under the same parameters of oxygen and steam, the H_2 yield generated by swirl flow injection is higher than that of straight flow injection. This is because swirl flow injection can achieve gas velocity splitting based on the total gas velocity constant, which can reduce the axial velocity of gas and increase the longitudinal velocity of gas. The reduction in axial gas velocity is beneficial for increasing gas residence time, while the increase in longitudinal gas velocity helps to expand the reaction zone

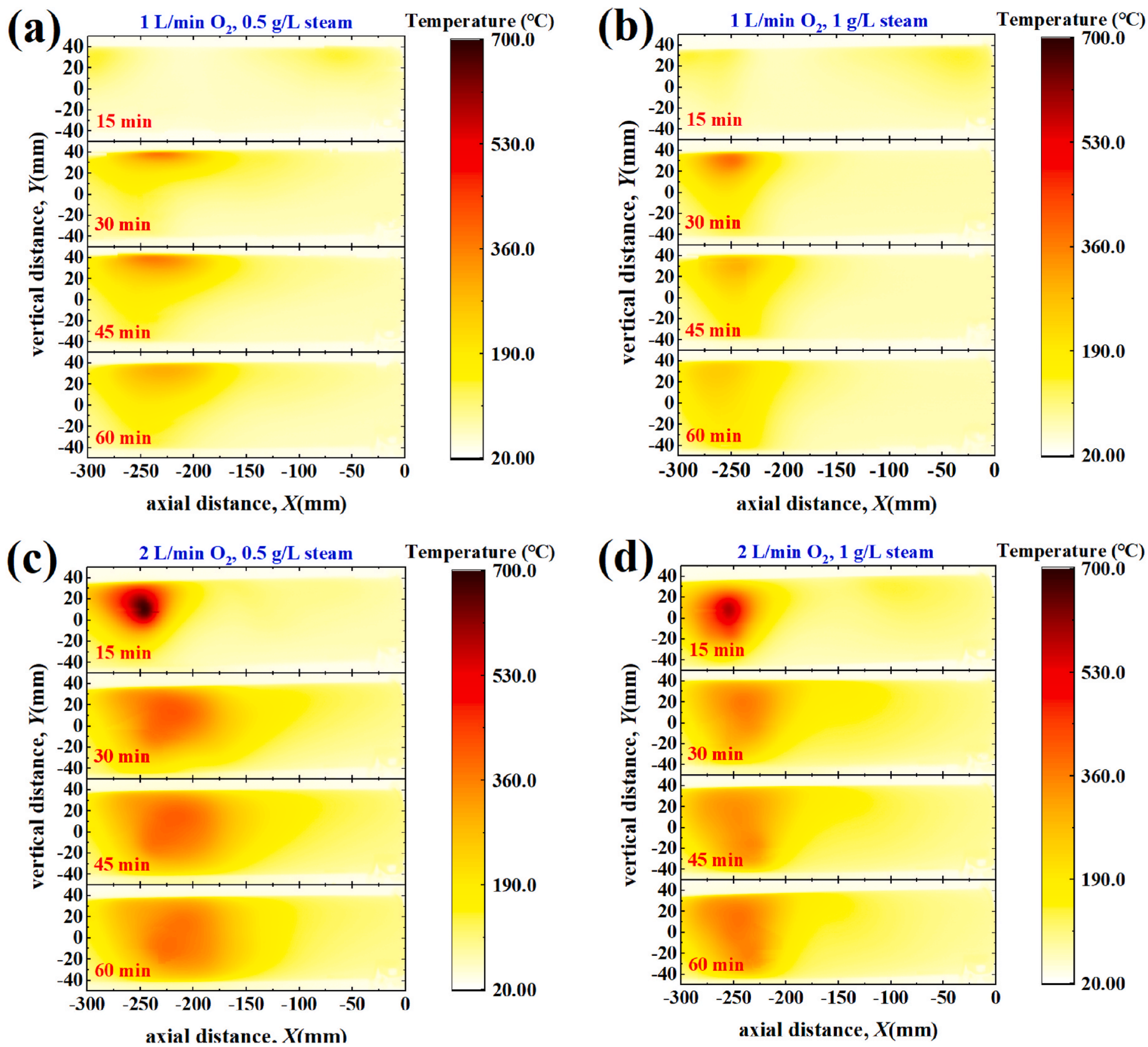

Fig. 6. Temperature distribution. (a) case 5, (b) case 6, (c) case 7, (d) case 8.

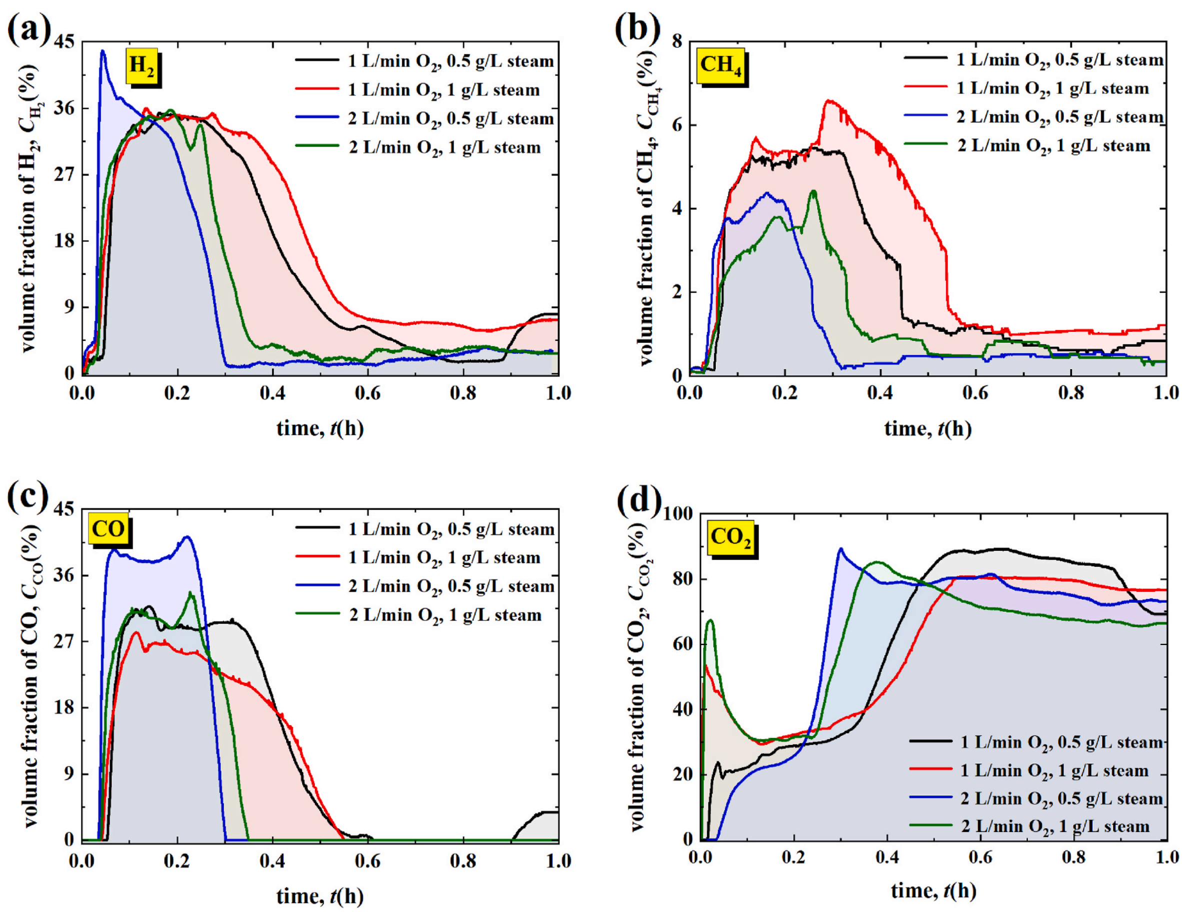

Fig. 7. Gas content in products for case 5–8. (a) H_2, (b) CH_4, (c) CO, (d) CO_2.

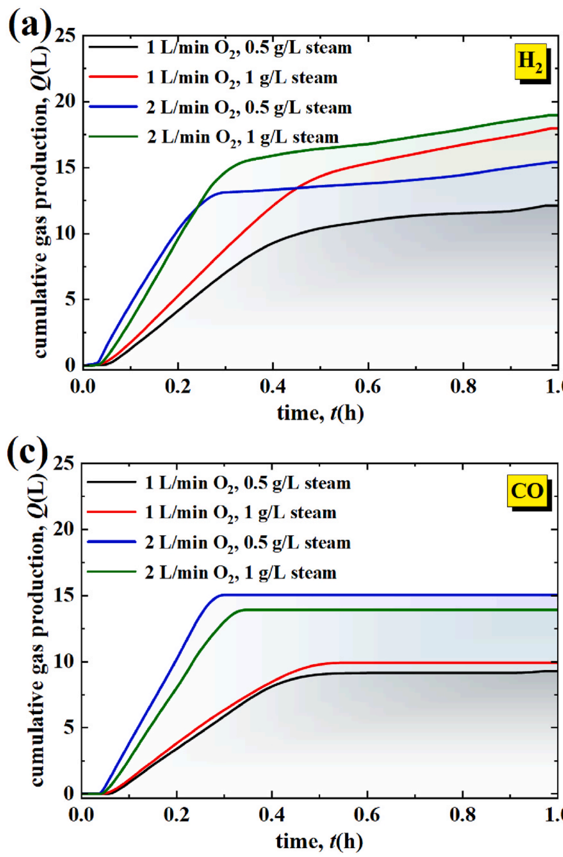

Fig. 8. Cumulative gas production for case 9–10. (a) H_2, (b) CH_4, (c) CO, (d) CO_2.

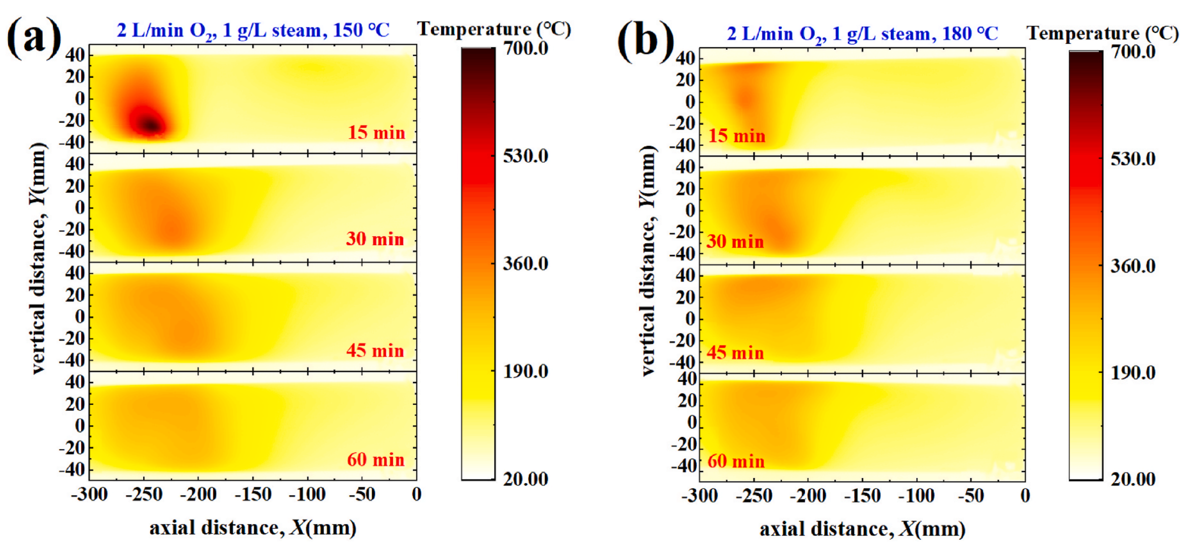

Fig. 9. Temperature distribution. (a) case 9, (b) case 10.

inward. Therefore, it comprehensively improves the consumption capacity of oxygen and steam, and produces more combustible gases.

According to Fig. 8 (b) ~ (c), influence of steam and oxygen on CH_4 and CO production is similar to that on H_2 production. According to Fig. 8 (d), more oxygen leads to an increase of the yields of combustible gas and CO_2 at same time, which is different from that with a straight flow injection in Fig. 5. This is because compared to the straight flow injection, the swirl flow injection induces a severe turbulence effect, which leads to improve the mass transfer capability and reaction efficiency. It can promote the generation of combustible gas and CO_2 simultaneously within the designated reaction time, rather than just in a short period of time.

In summary, when the injection is swirl flow (45° nozzle), H_2 production increases with steam addition for both 1 L/min and 2 L/min oxygen. Swirl flow shows a larger oxygen consumption capacity and H_2 production potential. The best parameters with 45° nozzle are 2 L/min

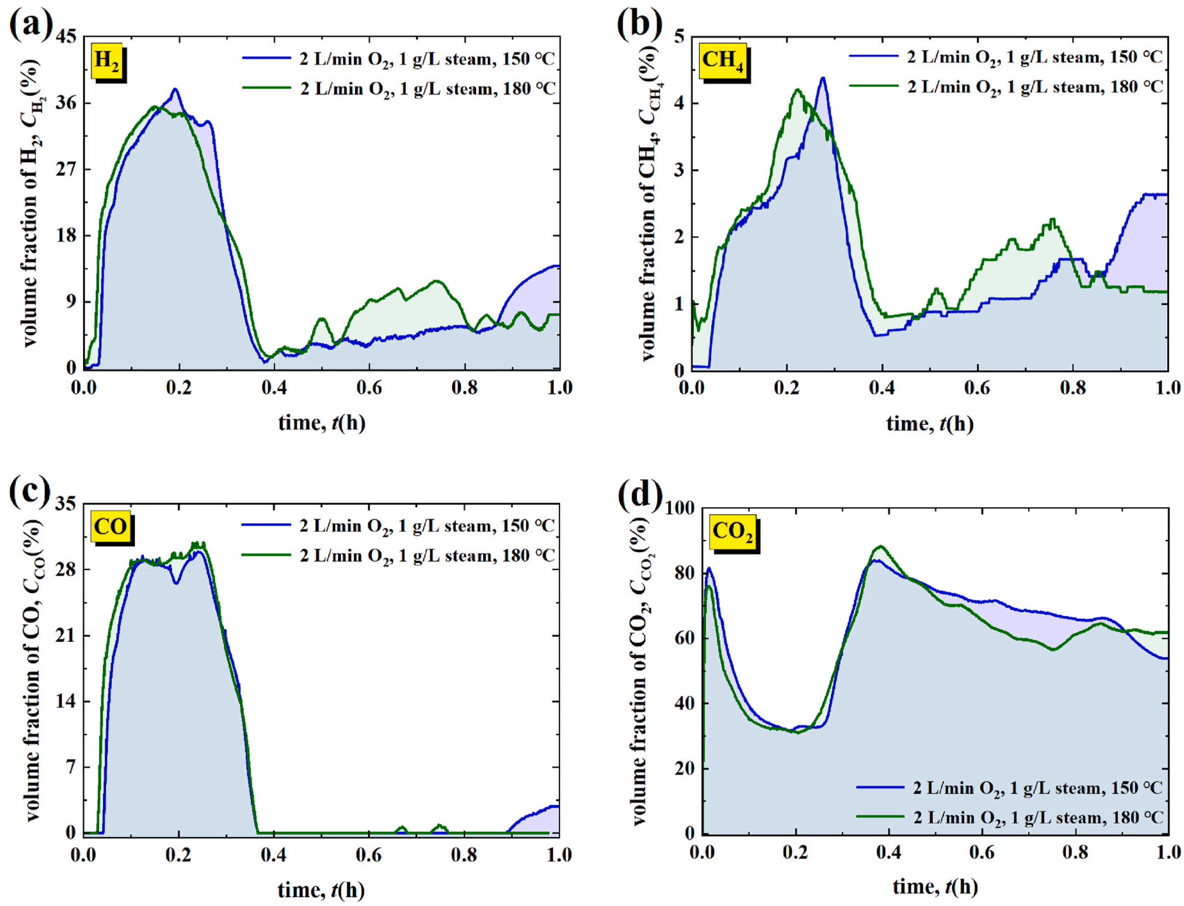

Fig. 10. Gas content in products for case 9–10. (a) H_2, (b) CH_4, (c) CO, (d) CO_2.

oxygen and 1 g/L steam, with a cumulative H_2 production of 19 L.

3.3. Effect of steam temperature

For case 9 and 10 in Table 2, 45° nozzle was used to form a swirl flow at inlet. Fig. 9 shows the temperature distribution for case 9 and 10 with different steam temperature. For 150 °C case, the maximum temperature decreases with time and the reaction zone expands towards the downstream. Compared to that, for 180 °C case the temperature is lower, and the area of reaction zone is almost the same.

The composition of gas products for case 9 and 10 are compared in Fig. 10. Basically, the gas production behaviors of these two cases are very similar, and also similar to that of case 8 (120 °C steam) in Fig. 7. The difference is at the late stage since 0.5 h, where the H_2 and CH_4 have a sudden increase for 180 °C case. This may be caused by the fracture effect of high temperature steam on the coal structure, which leads to the exposure of more fresh coal.

Based on the gas product flow rate and composition, the cumulative gas production of H_2, CH_4, CO, CO_2 at different time is calculated, as shown in Fig. 11. For 150 °C case in Fig. 11(a), the final H_2 yields is 16 L, similar to that of 120 °C case in Fig. 8(a); while that for 180 °C case is 23 L, much higher than the former cases. The production of CH_4, CO and CO_2 for 180 °C case are also more, indicating a larger flow rate of total gas products.

In summary, an increase in steam temperature barely affects the composition of products but apparently increases the amount of products. The fracture effect of high temperature steam might cause the exposure of more fresh coal and a sudden increase of H_2 and CH_4 at the late stage.

3.4. Discussion on H_2 production performance

3.4.1. Maximum hydrogen content in products

In this work, the maximum hydrogen content in products is 43.5 %, which is compared with the results from literature as shown in Fig. 12, including field tests [19,27,28], laboratory model experiments [29–31] and ground gasification (SCG) [32,33]. The results in this work is better than most of the similar studies, with a high hydrogen content caused by optimal swirl injection, proper steam addition and temperature. The maximum hydrogen content from ground gasification by Xiao [33] is the highest (50.90 %), due to the fact that the fuel used is pulverized coal and the catalyst is also used. For UCG, the gasification target is a large block of raw coal, rather than fine coal powder. Due to the difficulty in fully mixing the large block of raw coal with injected catalyst, coupled with the high cost of efficient catalyst and the impracticality in recycling it underground, the application of catalyst in UCG is not an effective method. In addition, the maximum hydrogen content of the experiment by Yang [31] is also higher than that of this work. It is because the injection position is adjusted immediately during gasification to control the expansion of reaction zone, which is a promising approach and could be considered for future research, especially in conjunction with swirl flow injection to enhance the gas performance. As for other research results with hydrogen content lower than that of this work, it is mainly attributed to two aspects. On the one hand, this is due to the difference in the types of coal used. On the other hand, it is related to the injection conditions. In these studies, traditional straight flow injection is often employed, with inappropriate steam-oxygen ratio and superheated steam temperature, leading to a lower hydrogen content. In summary, for the industrial application of UCG, optimization of injection direction,

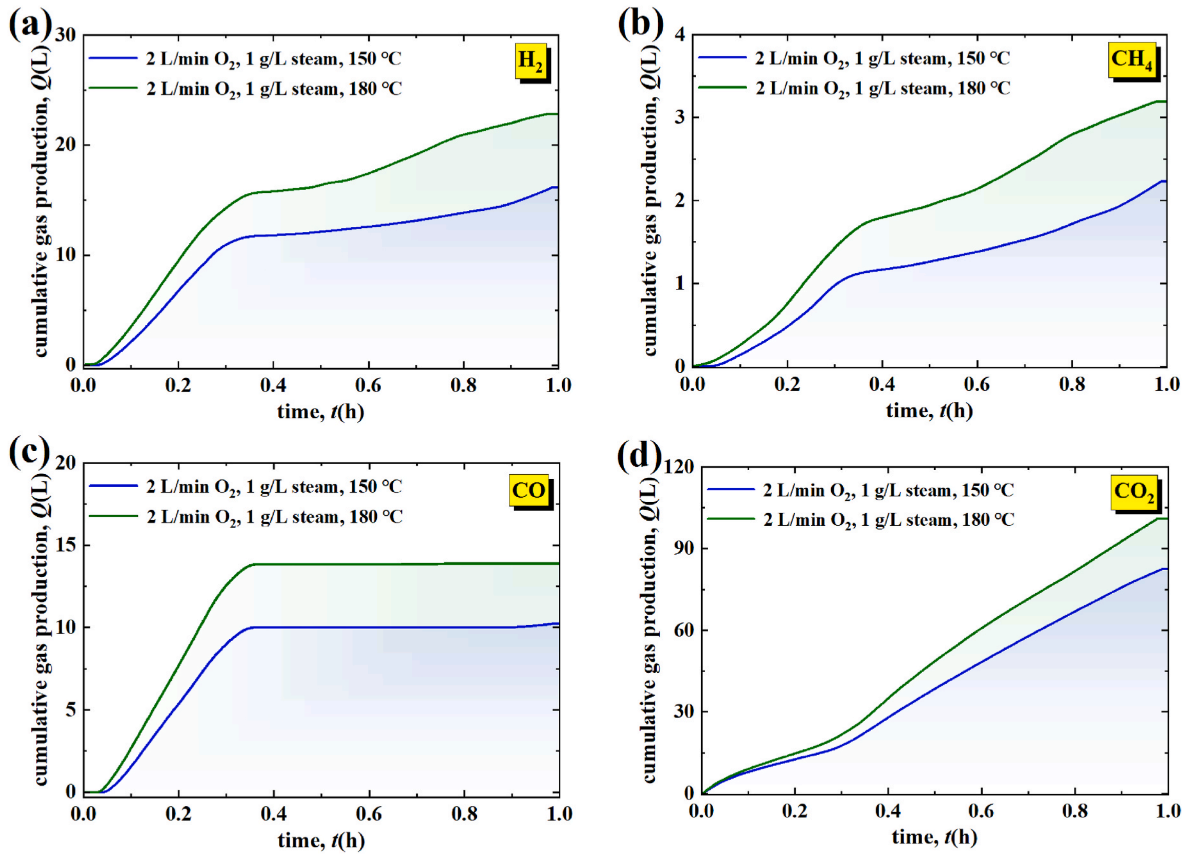

Fig. 11. Cumulative gas production for case 9–10. (a) H_2, (b) CH_4, (c) CO, (d) CO_2.

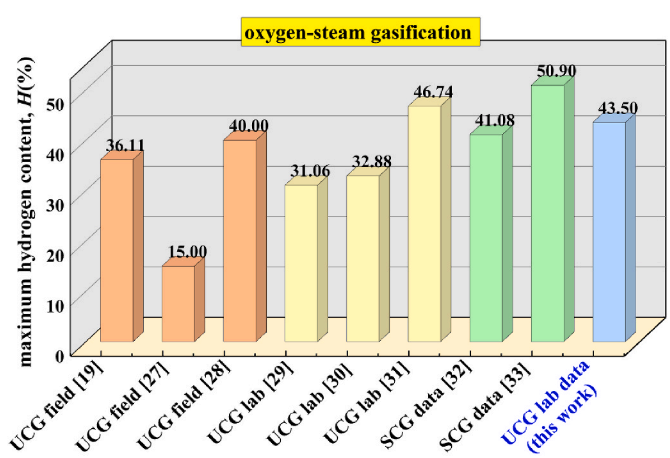

Fig. 12. Summary of maximum hydrogen content in products.

position, steam addition and temperature are important for improving H_2 production.

3.4.2. Future application of this work

Based on the results of this work, a new UCG technology with high H_2 production is designed as shown in Fig. 13. The gasification agents such as oxygen and steam are prepared in a factory above ground and then transported to the underground reaction zone via injection well. The injection pipeline is composed of the insulating material and the outer wall, which effectively prevents the condensation of steam. At the front part of the inlet, the injection head is a swirl nozzle with at least two independent swirl grooves to form a stable gasifying agent swirl flow. Subsequently, it is injected into the empty gasification channel hole and undergoes the gasification reaction with the coal wall. Compared with the straight flow, the swirl flow has a smaller axial velocity, resulting in a larger residence time for the reaction; meanwhile, the swirl flow has a larger tangential velocity, which can promote the expansion of the combustion zone and improve the utilization rate of coal. The syngas products are transported to the surface through the production well, and then undergoes filtration treatment, gas separation and purification, then are transported to the storage tanks. In order to increase the hydrogen production, the traditional methods are to increase the steam/oxygen ratio and inject the superheated steam. However, the novel methods are focus on a matchup between steam and oxygen and a proper choice of steam temperature. It is worth noting that the cost of insulation materials is closely related to the steam temperature, thus the choice of steam temperature is not only based on the hydrogen production efficiency, but also the investment cost.

4. Conclusion

In this work, a lab scale reactor was used to study the effect of steam addition on H_2 production in UCG. Temperature field and gas products under different injection direction, oxygen flow rate, steam mass flow and temperature are compared. The main conclusions are summarized below.

With a straight flow injection, the effect of steam addition on gasification performance depends on the oxygen flow rate. The good match between steam and oxygen is essential for H_2 yields. For straight flow injection, the highest H_2 production is 14.6 L under 1 L/min oxygen and 1 g/L steam.

With a swirl flow injection, H_2 production increases with steam addition for both 1 L/min and 2 L/min oxygen, which shows a larger H_2

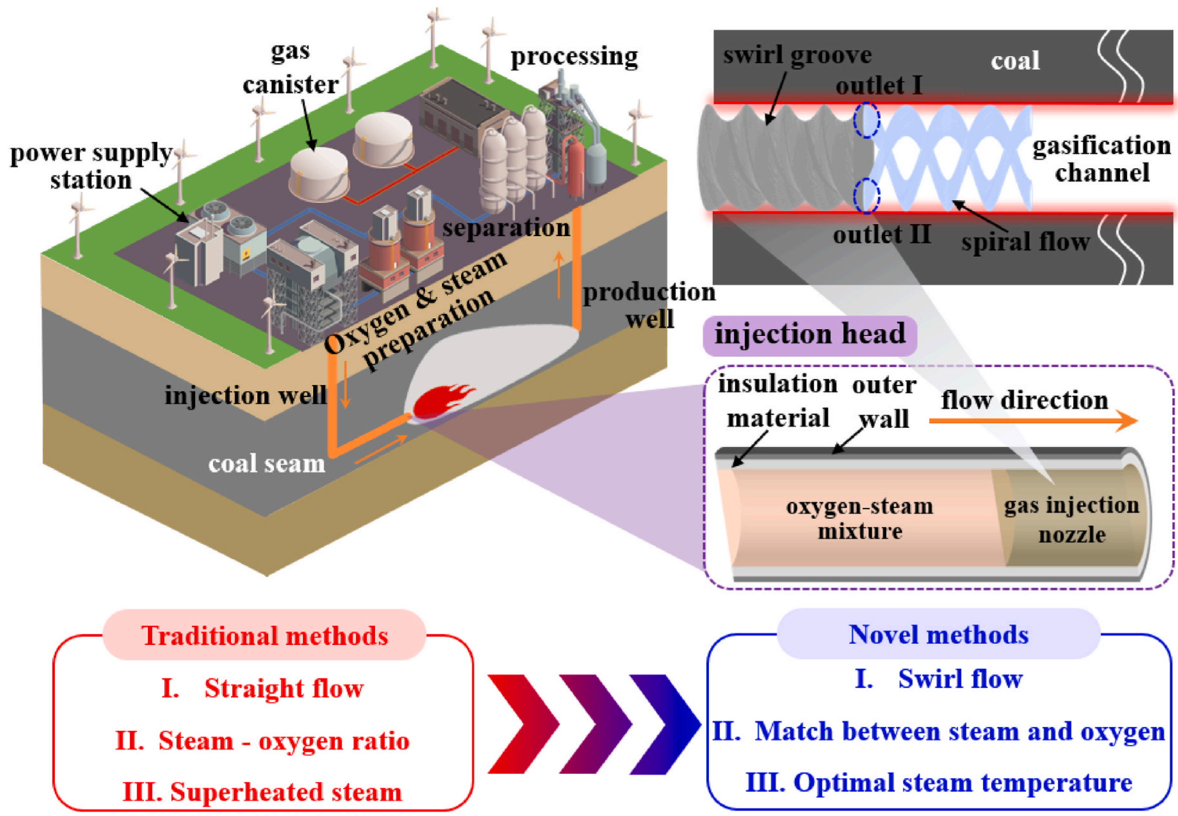

Fig. 13. A new UCG technology with high H_2 production.

production than straight flow injection. The highest H_2 production for swirl flow injection is 19 L under 2 L/min oxygen and 1 g/L steam.

An increase in steam temperature barely affects the composition of products but apparently increases the amount of products. The fracture effect of high temperature steam might cause the exposure of more fresh coal and a sudden increase of H_2 and CH_4 at the late stage.

In the future, the influence mechanism of swirl flow should be further investigated. From the perspective of numerical simulation, it focuses on discussing how swirl flow strengthens the strong coupling effect between gas-solid two-phase fields, as well as the variations in the gas production component field and temperature field of underground coal gasification under different swirl flow injection conditions (swirl angle, number, area, and position of swirling ports, etc.)

CRediT authorship contribution statement

Lele Feng: Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Validation, Visualization, Writing - review & editing. **Maifan Dong:** Conceptualization, Data curation, Writing - original draft. **Botao Qin:** Conceptualization, Funding acquisition. **Jiabao Pang:** Conceptualization. **Saeideh Babaee:** Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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