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Bio-methanol from Bio-oil Reforming Syngas Using Dual-reactorTong-qi Ye^a, Shi-zhi Yan^a, Yong Xu^a, Song-bai Qiu^a, Yong Liu^b, Quan-xin Li^{a*}*a. Department of Chemical Physics, Anhui Key Laboratory of Biomass Clean Energy, University of Science and Technology of China, Hefei 230026, China**b. Hefei Tianyan Green Energy Development Co., Ltd., Hefei 230026, China*

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A dual-reactor, assembled with the on-line syngas conditioning and methanol synthesis, was successfully applied for high efficient conversion of rich CO₂ bio-oil derived syngas to bio-methanol. In the forepart catalyst bed reactor, the catalytic conversion can effectively adjust the rich-CO₂ crude bio-syngas into the CO-containing bio-syngas using the CuZnAlZr catalyst. After the on-line syngas conditioning at 450 °C, the CO₂/CO ratio in the bio-syngas significantly decreased from 6.3 to 1.2. In the rearward catalyst bed reactor, the conversion of the conditioned bio-syngas to bio-methanol shows the maximum yield about 1.21 kg/(kg_{catal}·h) MeOH with a methanol selectivity of 97.9% at 260 °C and 5.05 MPa using conventional CuZnAl catalyst, which is close to the level typically obtained in the conventional methanol synthesis process using natural gas. The influences of temperature, pressure and space velocity on the bio-methanol synthesis were also investigated in detail.

Key words: Bio-methanol, Bio-syngas, CuZnAlZr catalyst, On-line syngas conditioning

I. INTRODUCTION

Methanol is an important starting raw material for a number of fuels and chemicals or can be directly used as a feed for fuel cell applications by on board reforming [1]. Methanol is produced worldwide by the methanol synthesis with syngas, derived from natural gas, refinery off-gas, coal or petroleum at present [2]. Methanol synthesis from syngas uses a Cu/ZnO/Al₂O₃ catalyst currently, which is a well established technology [3]. Catalytic synthesis of methanol from syngas is a classic high-pressure exothermic equilibrium limited synthesis process. The first high-temperature and high-pressure methanol synthesis catalyst was ZnO/Cr₂O₃ (containing 20%–75% Zn), which was operated at 350 °C and 25–35 MPa [4]. A more active catalyst of Cu/ZnO/Al₂O₃ can synthesize methanol at a low temperature (220–290 °C) and low pressure process (4.0–6.0 MPa) [4]. The modified Cu-based catalysts, such as Cu/ZrO₂, Cu/M_{0.3}Zr_{0.7}O₂ (M=Ce, Mn, and Pr), and Cs-Cu/ZrO₂, have been explored for the syngas conversion to methanol [5, 6]. In addition, the methanol synthesis from a CO₂-rich syngas has been explored using the modified Cu-based methanol synthesis catalysts [7–10] as well as the noble metal catalysts such as Pd, Pt, and Re [11, 12]. The synthesis efficiency from CO₂-rich syngas seems to be much lower than that from CO-rich syngas.

Biomass is a rich, environmentally friendly and renewable resource which is globally available, and can be used as an alternative feedstock for energy source or chemicals [13–15]. Methanol synthesis via biomass has already been suggested as a potential and environmentally friendly method for renewable biomass utilization [16]. However, the conversion of biomass to bio-methanol remains challenging, because bio-methanol synthesis is a more expensive process compared with natural gas-based methanol synthesis at present [17]. To produce bio-methanol from biomass, the main procedures generally include bio-syngas production, syngas conditioning, methanol synthesis and separation. Bio-syngas can be produced by biomass gasification technologies [18, 19]. Crude bio-syngas derived from biomass gasification contains numerous of gas compositions, generally including H₂, CO, CO₂, CH₄, N₂ and a small amount of water and hydrocarbons [20]. The composition of biomass-based syngas mainly depends on biomass types, pretreatment, reactor types, gasification environment, operating conditions and purification processes. As shown in Table I, the composition of bio-syngas derived from biomass gasification is different from that derived from coal gasification and natural gas reforming [21, 22]. The latter syngases consist mainly of H₂ or CO, with a small amount of CO₂, while bio-syngas from biomass gasification consists much more of CO₂ and less of H₂, resulting in a low H/C ratio and a high CO₂/CO ratio [23]. Therefore, the composition of raw bio-syngas is not favorable for methanol synthesis under the conventional method. It needs to be purified and adjusted in the downstream process by water-gas shift (WGS) reaction, methane reforming, CO₂ removal, or

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TABLE I Typical compositions of syngases derived from biomass gasification, coal gasification, natural gas (NG) reforming, and bio-oil reforming.

Route	Main composition of syngases/%					
	H ₂	CO	CO ₂	H ₂ O	CH ₄	Refs.
Biomass gasification	22–32	28–36	21–30	Dry	8–11	[20]
Coal gasification	1–10	5–50	0.5–5	0.1–10	0.1–10	[21]
NG reforming	30–60	10–25	1–10	10–15	0.1–7	[22]
Bio-oil reforming	60–73	2–10	20–35	Dry	0.1–4	[27–30]

H₂ supplement before methanol synthesis.

Alternatively, bio-syngas can also be produced from bio-oil reforming process [24]. Bio-oil, generated from biomass via fast pyrolysis process, generally contains numerous and complex oxygenated organic compounds including acids, alcohols, aldehydes, ketones, substituted phenolics and other oxygenates derived from biomass carbohydrates and lignin [25]. Probably, bio-syngas from bio-oil reforming is one of the most promising options because it can get a higher H₂ yield, and has the advantages of collection, transportation and storage. Bio-syngas derived from bio-oil reforming is rich in H₂ and CO₂ with a much higher CO₂/CO ratio (Table I). In principle, CO₂-rich bio-syngas is feasible for bio-methanol through CO₂ hydrogenation [26], but the methanol yield is significantly lower than those from CO-rich syngas. In order to obtain a higher methanol yield, the composition of crude bio-syngas derived from bio-oil reforming process should be adjusted to meet the conventional methanol synthesis composition by decreasing CO₂ content and increasing CO content. Although there is a growing worldwide interest in bio-methanol recently, as far as we know, no commercial process exists up to now. Significant improvements are essential for bio-methanol synthesis from biomass to make this conversion close to commercial attraction.

In our previous work, attention has been paid to produce bio-syngas from biomass gasification and bio-oil reforming, and produce hydrogen from biomass or bio-oil, both in lab and pilot plant scales [27–30]. In this work, a dual-reactor, assembled with the on-line syngas conditioning and methanol synthesis, was successfully applied for high efficient conversion of CO₂-rich bio-oil derived syngas to bio-methanol. The influences of temperature, pressure and space velocity on the bio-methanol synthesis were also investigated in detail. Potentially, present bio-methanol synthesis may be one of the promising routes to produce the bio-methanol from bio-oil.

II. EXPERIMENTS

A. Catalysts and characterization

Two types of catalysts including self-made CuZnAlZr mixture oxide catalyst and commercial CuZnAl catalyst were employed for the conversion of bio-oil-based

syngas to bio-methanol. The commercial CuZnAl catalyst was supplied by Jingjiang Co. in China. While the CuZnAlZr catalyst was prepared by co-precipitation method using respective metal nitrates solution as precursors and Na₂CO₃ solution as precipitator. The metal nitrates solution was added quickly to the sodium carbonate solution at about 70 °C with pH of 7.0±0.2. The precipitate was aged at 80 °C for 2 h, washed with the deionized water, dried in air at 100 °C for 24 h and 120 °C for 12 h, and calcined at 350 °C for 4 h in air to obtain the corresponding mixed oxides catalyst. The mixed oxides catalyst was finally made into granules with 40–60 mesh sizes.

The contents of metal oxides in catalysts were measured by inductively coupled plasma and atomic emission spectroscopy (ICP/AES, Atom scan Advantage of Thermo Jarrell Ash Corporation, USA). The Brunauer-Emmett-Teller (BET) surface area and pore volume was determined by the N₂ physisorption at –196 °C using a COULTER SA 3100 analyzer. X-ray diffraction patterns (XRD) from the catalysts were recorded on an X'pert Pro Philips diffractometer, using a Cu K α radiation ($\lambda=0.15418$ nm). The measurement conditions were in the range of $2\theta=10^\circ-80^\circ$, step counting time 5 s, and step size 0.017° at 298 K.

B. Feedstocks for bio-methanol synthesis

In this work, two different bio-syngases, *i.e.*, crude bio-oil-based syngas and conditioned bio-oil based syngas, were used for bio-methanol synthesis. Crude bio-oil-based syngas was produced from wood sawdust via two serial fluidized bed reactors (*i.e.*, the pyrolysis fluidized bed reactor and the reforming fluidized bed reactor) using steam as the carrier gas in small pilot-plant scale [31]. Crude bio-oil-based syngas was a CO₂-rich syngas with a CO₂/CO ratio of 6.33. The conditioned bio-oil-based syngas was produced by present catalytic conversion approach through RWGS reaction. The conditioned bio-oil-based syngas contained less CO₂ with CO₂/CO ratio nearly 1.

C. Reaction system for bio-methanol synthesis

Performance of bio-methanol synthesis from selected bio-oil-based syngases over CuZnAl catalysts was eval-

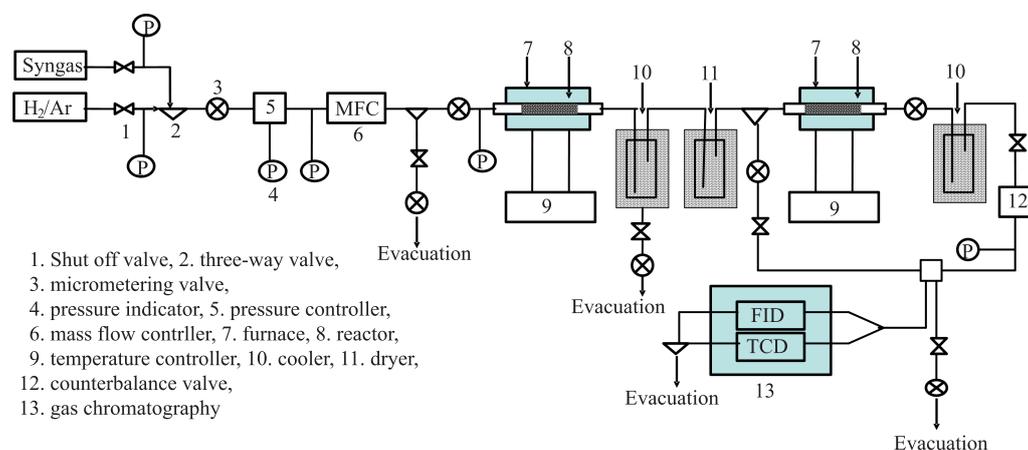


FIG. 1 The schematic experimental setup for the conversion of bio-syngas to bio-methanol.

uated in a dual fixed-bed continuous-flowing reactor (Fig.1). The two cylindrical reactors were both constructed from 316L with 40 cm length and an internal diameter of 1 cm. Gas flow rates were regulated using Seven Star 17B mass flow controllers. Reactor pressure was maintained by a back pressure regulator. The reactor temperature was maintained by an external, electrical heating block and a PID temperature controller. The catalyst bed temperature was measured during reactions using a type K thermocouple positioned within the reactor itself, near the center of the catalyst bed. The steam produced from the forepart reactor firstly condensed in the cooler, and then adsorbed by the 3A molecular sieve in the dryer. The compositions of the conditioned syngas could be *in situ* detected through the side-road.

Usually, 1.0 mL commercial CuZnAl catalyst, diluted with 2.0 mL Pyrex beads, was loaded in the rearward reactor in any case. While in the case of double-bed experiments, 1.0 mL CuZnAlZr catalyst, diluted with 2.0 mL Pyrex beads was loaded in the forepart reactor. The catalyst pretreatments in the dual reactors required a stepwise procedure. Initially, the CuZnAlZr catalyst in the first reactor was treated under a flowing 5% H₂/N₂ mixture at 250 °C for 16 h. When the reduction was completed, the CuZnAl catalyst in the second reactor was subsequently reduced at 523 K for 16 h.

Then, bio-oil-based syngas was conducted to the reactor for bio-methanol synthesis under a setup synthesis condition. Quantitative product analysis from the reactor outlet stream was on-line sampled every 15 min using two on-line gas chromatographs (GC1 and GC2) analysis. The gases of H₂, CO, and CO₂ were detected by GC1 (model: SP6890, column: TDX-01) with a thermal conductivity detector (TCD), and other gaseous hydrocarbons were detected by GC2 (model: SP6890, column: PorapakQ-S, USA) with a flame ionization detector (FID). The condensable vapors (mainly consisting of methanol and water) were cooled into a liquid

tank and then detected off line by GC2 with a FID. The performance of bio-methanol synthesis was evaluated by carbon conversion C_{carbon} , space time yield of bio-methanol (STY), selectivity of methanol ($S_{\text{CH}_3\text{OH}}$) *etc.*, according to the following equations:

$$C_{\text{carbon}} = \frac{x_{\text{in}} - x_{\text{out}}}{x_{\text{in}}} \times 100\% \quad (1)$$

$$\text{STY} = \frac{M_{\text{CH}_3\text{OH}}}{M_{\text{catal}}t} \times 100\% \quad (2)$$

$$S_{\text{CH}_3\text{OH}} = \frac{x_{\text{CH}_3\text{OH}}}{x_{\text{in}} - x_{\text{out}}} \times 100\% \quad (3)$$

where x_{in} , x_{out} , and $x_{\text{CH}_3\text{OH}}$ are the moles of (CO+CO₂) in and out of reactor and CH₃OH, respectively; $M_{\text{CH}_3\text{OH}}$ and M_{catal} are weight of CH₃OH and catalyst; and t is reaction time.

III. RESULTS AND DISCUSSION

In this work, the CuZnAlZr and CuZnAl catalysts were employed for the conversion of bio-oil based syngas to bio-methanol. The CuZnAlZr catalyst, containing 58.6%CuO, 30.7%ZnO, 5.5%Al₂O₃, and 5.2%ZrO₂, was selected for conditioning CO₂-rich bio-syngas. The CuZnAl catalyst, containing 62.3%CuO, 31.8%ZnO, and 5.9%Al₂O₃, was employed for methanol synthesis from the bio-syngases. The XRD patterns of the two catalysts are shown in Fig.2. Phase due to CuO and its reflections at $2\theta=38.6^\circ$ and 48.8° (ICDD: 48-1548) were observed in the fresh CuZnAl catalyst. The characteristic peaks of ZnO (ICDD: 36-1451) were also identified. However, the fact that none of ZrO₂ signals was found in the CuZnAlZr catalyst suggesting a high dispersion of ZrO₂. Additionally, the peaks of CuO in the CuZnAlZr catalyst are wider than in the CuZnAl catalyst shows a higher dispersion of CuO. BET surface area S_{BET} , pore volume (PV), and the crystallite size d were summarized in Table II.

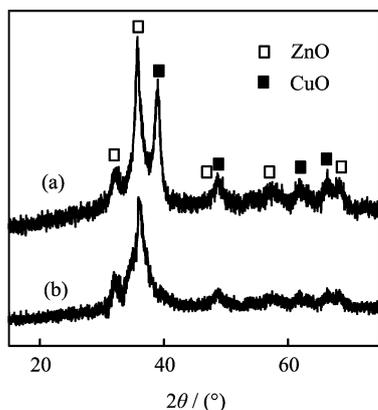


FIG. 2 XRD patterns of (a) CuZnAl catalyst and (b) CuZnAlZr catalyst.

TABLE II Physical and chemical properties for catalysts employed for the conversion of bio-syngas to bio-methanol.

Catalysts	$S_{\text{BET}}/(\text{m}^2/\text{g})$	$\text{PV}/(\text{cm}^3/\text{g})$	d^{a}/nm
CuZnAlZr	82	0.34	14.2
CuZnAl	91	0.27	13.6

^a Mean crystallite size was estimated from the peaks of XRD by the Scherrer equation.

The original bio-oil based syngas, produced from wood sawdust via two serial fluidized bed reactors [31], mainly contains 68.59% H_2 and 25.97% CO_2 together with small amount of CO , N_2 , and CH_4 (Fig.3). The crude bio-syngas was rich in CO_2 with CO_2/CO ratio of 6.33. However, presence of a large amount of CO_2 in the bio-syngas has a significant influence on the performance of bio-methanol synthesis, and leads to a prominent decrease of bio-methanol yield. In order to increase the yield of bio-methanol, an on-line syngas conditioning followed by methanol synthesis was carried out in the dual-reactor.

The on-line conditioning of the crude bio-syngas was tested in the forepart bed reactor using the CuZnAlZr catalysts at 350–500 °C, 5.0 MPa, and GHSV=6000 h^{-1} . Figure 3 shows the effect of temperature on the gas compositions in the conditioned bio-syngas. The performance of bio-syngas conditioning is significantly enhanced by increasing temperature in the forepart catalytic bed. In the range of 350–500 °C, the CO_2 conversion steadily increases from 18.9% to 38.8% with a CO selectivity of 91.2%–99.8% through the RWGS reaction ($\text{CO}_2 + \text{H}_2 \rightarrow \text{CO} + \text{H}_2\text{O}$, $\Delta H^\circ = 41.1 \text{ kJ/mol}$), accompanied by the formation of a small amount of methane through the methanation reaction via the hydrogenation of CO_2 and/or CO . The gas compositions after the catalytic conditioning are sensitive to temperature. The concentration of CO in the bio-syngas significantly increases from 9.5% to 15.2% with increasing temperature from 350 °C to

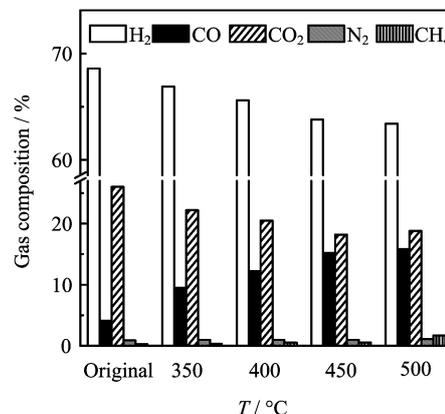


FIG. 3 Online conditioning of the CO_2 -rich bio-syngas through RWGS reaction over CuZnAlZr catalyst. Reaction conditions: 350–500 °C, 5.0 MPa, GHSV=6000 h^{-1} .

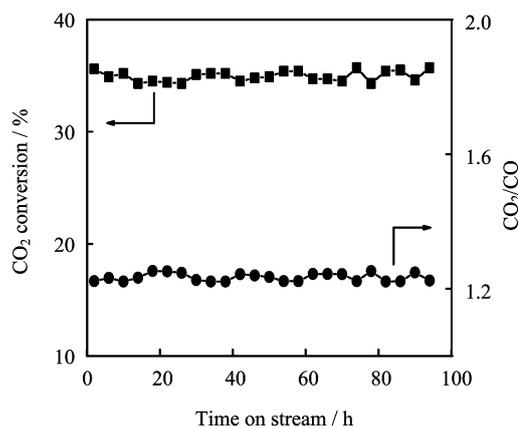


FIG. 4 Stability of CuZnAlZr catalyst in the RWGS reaction (450 °C, 5 MPa, GHSV=6000 h^{-1}).

450 °C, accompanied by a synchronous decrease of the CO_2 content. In particular, the CO_2/CO ratio remarkably drops from 6.3 to 1.2 after the catalytic conditioning at 450 °C. When the temperature increased to 500 °C, the CO_2/CO ratio nearly has no change, while methane, an unexpected by-product, sharply increased from 0.56% to 1.71%. Therefore, the condition of 450 °C was selected for RWGS reaction in this work.

Moreover, the catalytic stability in the RWGS reaction was tested by measuring the CO_2 conversion and the CO_2/CO ratio in the effluent gas. As Fig.4 shows, the RWGS reaction activity on the CuZnAlZr catalyst and the CO_2/CO ratio are almost constant in our tested 100 h.

As a comparison, Fig.5 shows the behavior of bio-methanol synthesis over CuZnAl catalyst using the original bio-syngas and the conditioned one (conditioning temperature: 450 °C), respectively. For the original CO_2 -rich bio-syngas, the total carbon conversion was very low (1%–10%) and gradually increased with temperature. When the content of CO in the bio-oil-

based syngas increased after conditioning by RWGS reaction, both CO and CO₂ conversion was increased. As Fig.5 shows, both the carbon conversion and the bio-methanol yield were significantly higher than those from the unconditioned one after the on-line syngas conditioning. The synthesis products distribution from the conditioned bio-syngas is roughly the same as that from the CO₂-rich crude bio-syngas. The different performance between two bio-syngases should be attributed to the different gas compositions [32, 33] and distinct synthesis mechanisms. Although the mechanism of methanol synthesis from CO/CO₂ hydrogenation is still controversial, the viewpoint that methanol mainly derived from the hydrogenation of CO₂ has most supporters. According to Lee *et al.*, CO₂ is the primary source of methanol with CO-CO₂-H₂ feed, and methanol synthesis was much faster with CO₂-H₂ than that with CO-H₂ in this system [26]. The role of CO in the system may be ascribed to three aspects. First, it is the removal of the oxygen adsorbed on the catalyst surface, while the adsorbed oxygen is a product of reaction (*i.e.*, HCOO(a)+3H(a)=CH₃OH(g)+O(a)), which is believed to be the rate-controlling step of methanol synthesis [34]. Secondly, the water produced by the hydrogenation of CO₂ is an inhibitor of the hydrogenation reaction in reverse [35], while the CO could enhance the WGS reaction to decrease the water content. Thirdly, the addition of CO to the CO₂/H₂ system greatly decrease the activation energy for methanol synthesis [33], however, has no significant effect on the activation energy for RWGS reaction. Although methanol was derived mainly from CO₂ hydrogenation, the rate of methanol formation is very sensitive to the CO content. As shown in Fig.5 the crude bio-syngas has a quite low conversion of both CO and CO₂. Even when the temperature increased to 280 °C, the conversion of CO and CO₂ are only 12% and 10% respectively. After conditioning, the high concentration of CO promoted the conversion of CO₂, and the CO conversion was also lifted through the CO₂ channel. When temperature increased to 260 °C, the conversion of CO and CO₂ increased to their utmost of 46% and 19%, respectively.

Table III shows the performance of bio-methanol synthesis using the conditioned bio-syngas over the CuZnAl catalyst under the synthesis conditions: 220–300 °C, 1–5 MPa, and GHSV=6000–12000 h⁻¹. The maximum STY of bio-methanol reaches 1.2 kg/(kg_{catal}·h) MeOH with a methanol selectivity of 98% within our investigated range, which is close to the level typically obtained in the conventional methanol synthesis process using natural gas. Commonly, temperature is one of the most critical reaction parameters in the fuels synthesis, which significantly influences the rate of kinetically controlled synthesis reactions. As shown in Table III, the carbon conversion significantly increases from 14.17% to 31.36% with a rising temperature from 220 °C to 260 °C, and decreases as temperature further increases over 260 °C. A similar trend is also observed for the

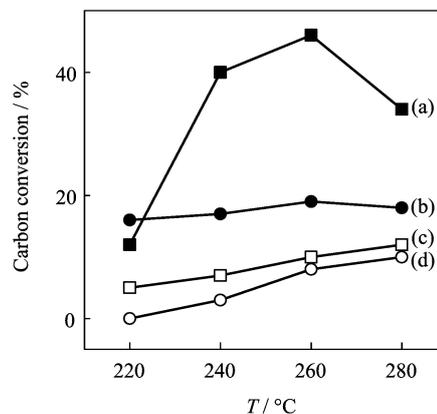


FIG. 5 Comparison of carbon conversion using two bio-oil-based syngases (the original bio-oil based syngas and the conditioned one) over the CuZnAl catalyst under typical synthesis condition: 220–280 °C, 5.0 MPa, and GHSV=6000 h⁻¹. (a) CO conversion after conditioning, (b) CO₂ conversion after conditioning, (c) CO conversion before conditioning, and (d) CO₂ conversion before conditioning.

TABLE III Performance of bio-methanol synthesis using the conditioned bio-syngas over CuZnAl catalyst under different synthesis conditions.

T/°C	P/MPa	GHSV/h ⁻¹	C _{Carbon} /%	STY ^a	S _{MeOH} /%
220	5	6000	14.17	359.6	99.1
240	5	6000	27.53	702.2	98.9
260	5	6000	31.36	794.3	98.4
280	5	6000	25.32	636.2	97.5
300	5	6000	22.41	557.7	96.4
260	1	6000	6.34	157.4	96.1
260	3	6000	19.87	497.1	97.1
260	5	9000	24.99	953.1	98.6
260	5	12000	24.04	1213.8	97.9

^a In mg/(mL_{catal}·h).

STY (bio-methanol), giving a maximum value around 260 °C. In lower temperature region, increasing temperature is conducive to increase the reaction rates of hydrogenation of CO and CO₂. However, another characteristic of methanol synthesis is highly exothermic and exorbitant temperature will inhibit the generation of methanol thermodynamically and shorten the catalyst lifetime. Consequently, to maximize the bio-methanol yield, an appropriate temperature needs to be closely controlled at the value of 260 °C in the reactor. On the other hand, pressure and GHSV are another two important factors that affect the bio-methanol synthesis. As shown in Table III, the carbon conversion and the STY ascend as pressure increases. Meanwhile, the increasing pressure enlarges the equilibrium concentration of methanol from the hydrogenation of CO and CO₂ because the synthesis reactions involve a decrease in the

TABLE IV Comparison of the methanol synthesis derived from different syngases and reactors.

Reactor	$T/^{\circ}\text{C}$	P/MPa	$\text{GHSV}/\text{h}^{-1}$	$\text{H}_2/\text{CO}_2/\text{CO}$	$\text{C}/\%$	$\text{STY}/(\text{mg}/(\text{mL}_{\text{catal}}\cdot\text{h}))$	$S/\%$	Reference
B/CuZnAl	SR ^a	250	5	10000	75/22/3	636		[7]
Zr/CuZnAl	SR	250	5	10000	75/22/3	679		[8]
GaZr/CuZnAl	SR	250	5	18000	$\text{H}_2/\text{CO}_2=3$	785		[9]
Ga/CuZn	SR	250	5	18000	$\text{H}_2/\text{CO}_2=3$	738	53.2	[10]
PdGa/CuZnAl	SR	270	8	18800	75/22/3	1300	84.2	[11]
Pd/Zn/CNTs	SR	250	3	1800	69/23/8	37.1 ^d	86.0	[12]
Raney Cu/Zr	SR	250	5	18000	$\text{H}_2/\text{CO}_2=3$	941	98.4	[36]
Cu/ZnO/Al ₂ O ₃	MR ^b	206	2	6000	$\text{H}_2/\text{CO}_2=3$	186	75.0	[37]
Cu/ZnO/Al ₂ O ₃	DR ^c	260	5	12000	69/26/4	1213	97.9	This work

^a SR=single reactor.

^b MR=membrane reactor.

^c DR=dual reactor.

^d In $\text{mg}/(\text{g}_{\text{catal}}\cdot\text{h})$.

number of molecules (*e.g.*, from 3 to 1 in the CO hydrogenation to methanol: $\text{CO}+2\text{H}_2\rightarrow\text{CH}_3\text{OH}$). In contrast, the carbon conversion decreases with increasing GHSV, which is accompanied by an increase of STY. The negative impact of GHSV on the carbon conversion may result from shortening residual time in the catalyst bed, while the positive impact on the methanol yield can arise from the increase of the turnover frequency of the synthesis products with increasing GHSV. The selectivity towards methanol (*S*) ranges from 96% to 99%, indicating that the bio-methanol was the dominating product in the synthesis process.

Finally, Table IV shows the comparison of the methanol synthesis derived from different syngases and different reactors. In viewpoint of the methanol yield and the methanol selectivity from CO₂-rich syngas, present dual-reactor method remarkably improved the performance of methanol synthesis, compared with single-bed reactor and membrane reactor.

IV. CONCLUSION

This work reported a dual-reactor for high efficient conversion of CO₂-rich bio-oil-based syngas to bio-methanol. The compositions of the crude CO₂-rich bio-syngas, derived from the bio-oil reforming, were firstly adjusted in the forepart catalyst bed reactor through RWGS reaction using CuZnAlZr catalyst. After the on-line syngas conditioning at 450 °C, the CO₂/CO ratio in the bio-syngas decreased from 6.33 to 1.20. Both the carbon conversion and the bio-methanol yield were greatly enhanced after the on-line conditioning. The influences of the most important parameters (*e.g.*, temperature, pressure and space velocity) on the synthesis process of bio-methanol were also investigated. The maximum bio-methanol yield reached about 1.21 kg/(kg_{catal}·h) MeOH with a methanol selectivity of 97.9%. The bio-oil used as the bio-methanol synthesis

raw material, has the advantages of collection, transportation and storage. In particular, the bio-methanol synthesis is unstinted by the feedstock of biomass, and potentially, may be one promising route to produce bio-methanol in future.

V. ACKNOWLEDGMENTS

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