

# Microwave Plasma Dry Reforming of Methane at High CO<sub>2</sub>/CH<sub>4</sub> Feed Ratio

Nabil Majd Alawi, Gia Hung Pham, Ahmed Barifcani

**Abstract**—Dry reforming of methane that converts two greenhouses gases (CH<sub>4</sub> and CO<sub>2</sub>) to synthesis gas (a mixture of H<sub>2</sub> and CO) was studied in a commercial bench scale microwave (MW) plasma reactor system at atmospheric pressure. The CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub> conversions; H<sub>2</sub>, CO selectivities and yields, and syngas ratio (H<sub>2</sub>/CO) were investigated in a wide range of total feed flow rate (0.45 – 2.1 L/min), MW power (700 – 1200 watt) and CO<sub>2</sub>/CH<sub>4</sub> molar ratio (2 – 5). At the feed flow rates of CH<sub>4</sub>, CO<sub>2</sub> and N<sub>2</sub> of 0.2, 0.4 and 1.5 L/min respectively, and the MWs input power of 700 W, the highest conversions of CH<sub>4</sub> and CO<sub>2</sub>, selectivity and yield of H<sub>2</sub>, CO and H<sub>2</sub>/CO ratio of 79.35%, 44.82%, 50.12, 58.42, 39.77%, 32.89%, and 0.86, respectively, were achieved. The results of this work show that the product ratio increases slightly with the increasing total feed flow rate, but it decreases significantly with the increasing MW power and feeds CO<sub>2</sub>/CH<sub>4</sub> ratio.

**Keywords**—Atmospheric pressure, methane dry reforming, microwave plasma, synthesis gas production.

## I. INTRODUCTION

CURRENTLY, the demand for the development of alternative, clean energy and the reduction of greenhouse gas emissions (CO<sub>2</sub> and CH<sub>4</sub>) are becoming urgent to reduce the risk of global warming and climate change. It is therefore necessary to find modern and cost-effective technologies to convert these undesirable gases to valuable products such as synthesis gas [1]. Synthesis gas (syngas) is an important intermediate for the production of synthetic fuels and value-added chemicals through Fischer-Tropsch Synthesis (FTS) [2]. There are different methane reforming processes used to produce syngas as summarised below [3]-[5]:

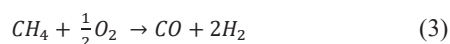
Steam Reforming of Methane (SRM):



Dry Reforming of Methane (DRM):



Partial Oxidation of Methane (POM):



SRM produces a syngas with the high ratio of H<sub>2</sub>/CO.

However, POM has attracted more interest than SRM, due to its mild exothermicity and a perfect H<sub>2</sub>/CO ratio of 2, and a desirable ratio for Fischer-Tropsch (F-T) synthesis. DRM is environmentally favourable and promising way to produce syngas from CO<sub>2</sub> and CH<sub>4</sub> [6], [7]. Dry reforming of methane yields a lower syngas ratio (H<sub>2</sub>/CO=1), which is suitable for the synthesis of oxygenated chemicals, hydrocarbons and liquid fuels from (F-T) process [7].

Plasma is considered to be the fourth state of matter, consisting of the highly reactive species such as electrons, ions, radicals and neutral particles [8]. Two main methods are used to convert chemical to plasma state and they are non-thermal (cold) such as dielectric barrier discharge (DBD), corona discharge (CD), atmospheric pressure glow discharge (APGD), gliding arc discharge (GAD), MW discharge (MWD) and thermal (hot) plasma discharge such as direct current heating [9]. The non-thermal plasma discharge processes offer some important advantages as they are cheap and easy to build at any scale for research and production [10].

In order to improve the product H<sub>2</sub>/CO ratio in plasma DRM process, the reducing of feed ratio CO<sub>2</sub>/CH<sub>4</sub> was studied [11]-[13]. Unfortunately, carbon formation during the reaction at the feed ratio ≤ 2 leads to an instability of the plasma. As a consequence, the study of the plasma DRM is very complicated and has some unavoidable errors.

In this paper, the effects of input parameters (the total feed gas flow rate, the microwave power, the ratio of CO<sub>2</sub>/CH<sub>4</sub>) on the performance of processes such as conversions of CH<sub>4</sub>, CO<sub>2</sub> and N<sub>2</sub>, the product selectivities and yields of H<sub>2</sub> and CO, and H<sub>2</sub>/CO ratio, respectively were investigated under microwave plasma at atmospheric pressure. The results could be important information for closing the knowledge gap of plasma stability, plasma condition and side reactions in complex microwave plasma DRM reaction zone.

## II. EXPERIMENTAL

The schematic diagram of the experimental set-up is shown in Fig. 1; MW plasma system fundamentally consists of gas cylinders, mass flow controllers, gas mixer, feed gas system, plasma reactor, MW generator, and gas chromatographic (GC-MSD and GC-TCD) analysis system. A commercial MW reactor system (Alter, SM 1150T, Canada) was used in this

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study. The three gases CH<sub>4</sub> (99.99%), CO<sub>2</sub> (99.99%) and N<sub>2</sub> (99.99%) were controlled by a mass flow controller and sent into the gas mixer prior entering the plasma zone. All experiments were performed at atmospheric pressure. The quartz reactor has a size of 1.68 mm wall thickness, 25.5 mm outer diameter and length of 126 mm. The feed and product gas samples were collected and analyzed by the GC/MSD. Each measurement was repeated three times for the data accuracy improvement purpose. The experimental conditions are presented in Table I. The calculations of H<sub>2</sub>/CO ratio are presented by:

$$CH_4 \% Conversion = \frac{\text{moles of CH}_4 \text{ converted}}{\text{moles of CH}_4 \text{ introduced}} \times 100 \quad (4)$$

$$CO_2 \% Conversion = \frac{\text{moles of CO}_2 \text{ converted}}{\text{moles of CO}_2 \text{ introduced}} \times 100 \quad (5)$$

$$H_2 \% Selectivity = \frac{\text{moles of H}_2 \text{ produced}}{2 \times \text{moles of CH}_4 \text{ converted}} \times 100 \quad (6)$$

$$CO \% Selectivity = \frac{\text{moles of CO produced}}{[\text{moles of CH}_4 + \text{moles of CO}_2] \text{ converted}} \times 100 \quad (7)$$

$$H_2 \% Yield = \frac{\text{moles of H}_2 \text{ produced}}{2 \times \text{moles of CH}_4 \text{ introduced}} \times 100 \quad (8)$$

$$CO \% Yield = \frac{\text{moles of CO produced}}{[\text{moles of CH}_4 + \text{moles of CO}_2] \text{ introduced}} \times 100 \quad (9)$$

$$\frac{H_2}{CO} \text{ Ratio} = \frac{\text{moles of H}_2 \text{ produced}}{\text{mole of CO produced}} \quad (10)$$

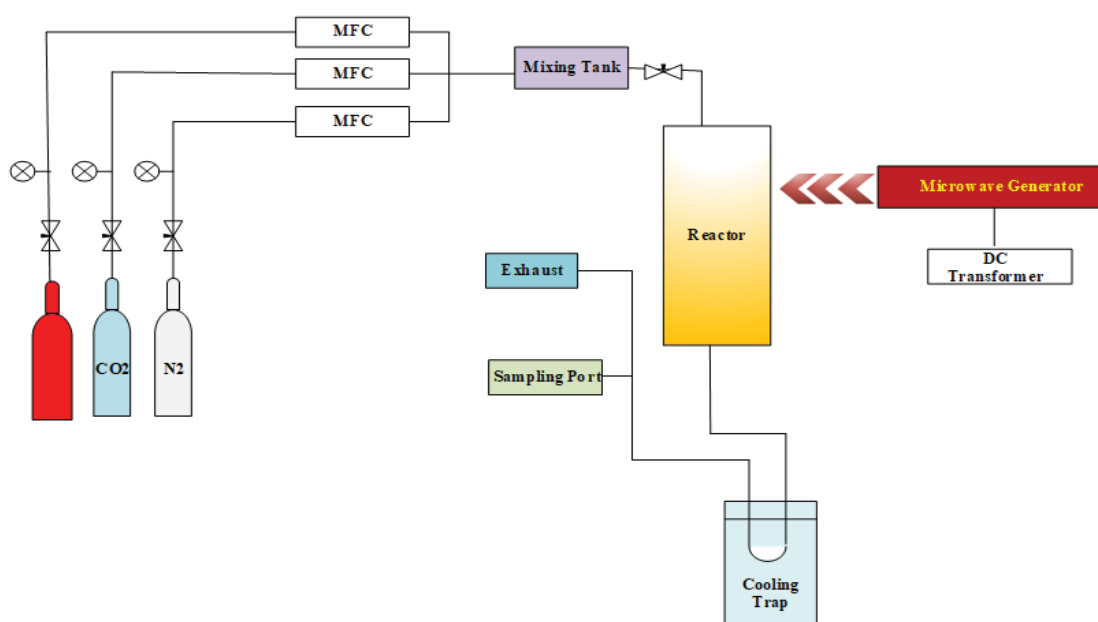


Fig. 1 Schematics Diagram of the experimental process

TABLE I  
EXPERIMENTAL CONDITIONS FOR DRM

Experimental Approach	Flow Rate [Lmin <sup>-1</sup> ]			Total feed flow Rate [L min <sup>-1</sup> ]	CO <sub>2</sub> /CH <sub>4</sub> Ratio	MW Power [W]
	CO <sub>2</sub>	CH <sub>4</sub>	N <sub>2</sub>			
Effect of Total Flow Rate	0.1	0.05	0.3	<b>0.45</b>	2/1	700
	0.15	0.075	0.5	<b>0.725</b>		
	0.2	0.1	0.7	<b>1</b>		
	0.25	0.125	0.9	<b>1.275</b>		
	0.3	0.15	1.1	<b>1.55</b>		
	0.35	0.175	1.3	<b>1.825</b>		
	0.4	0.2	1.5	<b>2.1</b>		
Effect of MW Power	0.4	0.2	1.5	2.1	2/1	700
						800
						900
						1000
						1100
Effect of CO <sub>2</sub> /CH <sub>4</sub> Ratio	0.4	0.2	1.5	2.1	2/1	700
	0.5			2.2	2.5/1	
	0.6			2.3	3/1	
	0.7			2.4	3.5/1	
	0.8			2.5	4/1	
	0.9			2.6	4.5/1	
	1			2.7	5/1	

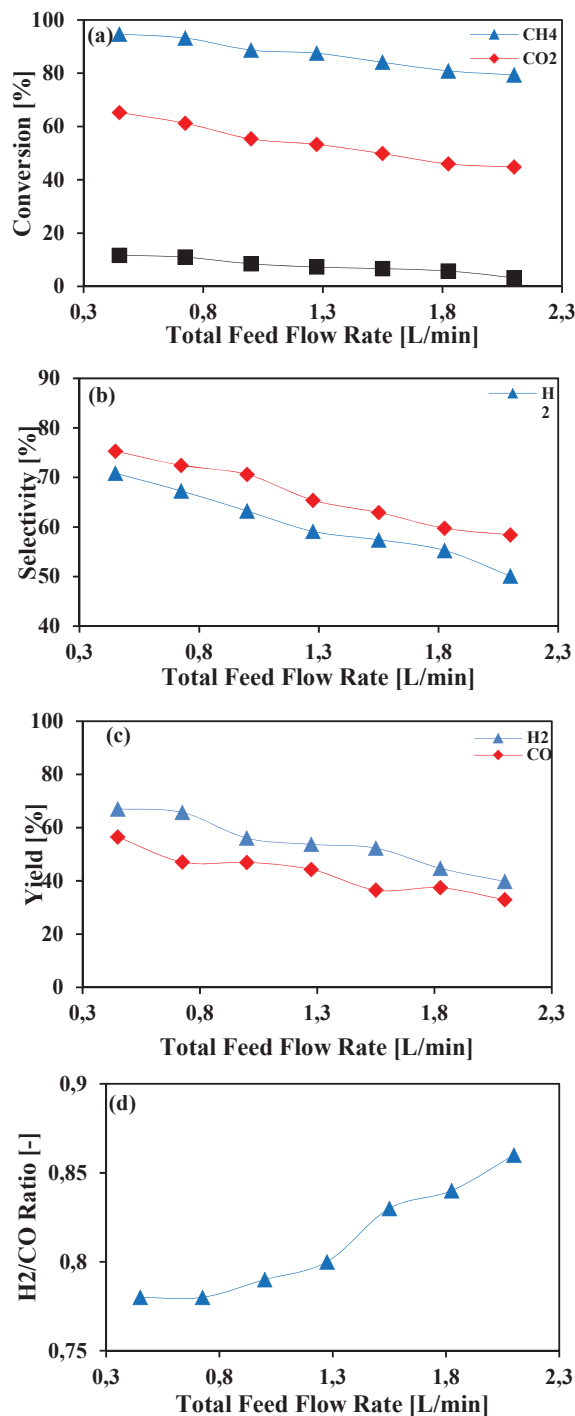


Fig. 2 Effect of Total Gas Feed Flow Rate on the Performance MW Plasma Dry Reforming Reaction; (a) CH<sub>4</sub>, CO<sub>2</sub> and N<sub>2</sub> Conversions; (b) Selectivity of H<sub>2</sub> and CO; (c) Yield of H<sub>2</sub> and CO; and (d) H<sub>2</sub>/CO Ratio (CO<sub>2</sub>/CH<sub>4</sub>: 2/1; input MW Power: 700 W)

### III. RESULTS AND DISCUSSIONS

#### A. Effect of Total Feed Flow Rate

The influence of the feed gas mixture flow rates on the conversion of CH<sub>4</sub>, CO<sub>2</sub> and N<sub>2</sub>, selectivities and yields of H<sub>2</sub>

and CO, and H<sub>2</sub>/CO ratio under MW plasma discharge were determined at constant molar ratio CH<sub>4</sub>/CO<sub>2</sub> of 2/1 and the input MW power of 700 W at atmospheric pressure, as shown in Figs. 2 (a)-(d). It can be seen from It can be seen from Figs. 2 (a)-(c) that the conversions of CH<sub>4</sub>, CO<sub>2</sub> and N<sub>2</sub>, selectivities and yields of H<sub>2</sub> and CO slightly decreased with increasing total flow rates while, the H<sub>2</sub>/CO ratio reveal opposite trends and increased slightly with increasing the feed flow rates, as shown in Fig. 2 (d). The CO<sub>2</sub> and CH<sub>4</sub> are very stable species, so that they need to absorb enough energy to form plasma. As a result, the shorter MW absorption time the less CO<sub>2</sub> and CH<sub>4</sub> reacted [14].

#### B. Effect of MW Power

The input power is one of the most important factors influencing the reaction were used for this experiment. The input microwave power was used as a function of the conversions of CH<sub>4</sub>, CO<sub>2</sub> and N<sub>2</sub>; the selectivity and yield of H<sub>2</sub>, CO, and the H<sub>2</sub>/CO ratio under experimental conditions such as the CO<sub>2</sub>/CH<sub>4</sub> molar ratio of 2/1, and the CH<sub>4</sub>, CO<sub>2</sub>, and N<sub>2</sub> flow rates of 0.2, 0.4 and 1.5 L/min respectively, as shown in Figures 3 (a)-(d). Experiments were performed in wide range of input power from 700 to 1200 W to get better understanding of the effect of input power on the conversions of CH<sub>4</sub>, CO<sub>2</sub> and N<sub>2</sub>, the selectivities and yields of H<sub>2</sub>, CO and the molar ratio of H<sub>2</sub>/CO.

The CH<sub>4</sub>, CO<sub>2</sub> and N<sub>2</sub> conversions, the CO selectivity and yield increased, while the selectivity and yield of H<sub>2</sub> and the ratio of H<sub>2</sub>/CO decreased with increasing the input power, as shown in Figs. 3 (a)-(d). The increase of input MW power could provide more energy to dissociate the CH<sub>4</sub> and CO<sub>2</sub> molecules and then lead to cause cracking of molecules deeply of CH<sub>4</sub> and CO<sub>2</sub>. At high MW power a side reaction, which consumes H<sub>2</sub> ( $H_2 + CO_2 \rightarrow H_2O + CO$ ), occurs and provides enough energy to activate CO<sub>2</sub> to form CO. As a consequence, the product ratio H<sub>2</sub>/CO decreases with the increasing MW power [15].

#### C. Effect of CO<sub>2</sub>/CH<sub>4</sub> Ratio

For better understanding of the feed composition on the reaction, test series with varying the molar ratio of carbon dioxide to methane from 2/1 to 5/1 in the feed gas at MW power of 700 W were performed. The conversions to CH<sub>4</sub>, N<sub>2</sub> and selectivity to CO escalated when increasing CO<sub>2</sub>/CH<sub>4</sub> ratio, as shown in Figs. 4 (a) and (b). Conversely, the increase of CO<sub>2</sub>/CH<sub>4</sub> ratio leads to decreasing the conversion of CO<sub>2</sub>, which leads to the selectivity of H<sub>2</sub>, the yields of H<sub>2</sub>, CO and H<sub>2</sub>/CO ratio. The induction of high amount of CO<sub>2</sub> in the reactor resulted in larger amount of carbon atoms, which are cracked by electron collision. These radicals are then reacts with oxygen atoms to form carbon mono oxide ( $C + O \rightarrow CO$ ) while the hydrogen is low because of the formation of water as a consequence of the reaction of hydrogen atoms with oxygen atoms ( $H_2 + O \rightarrow H_2O$ ). So, the selectivity and yield of H<sub>2</sub>, CO and the H<sub>2</sub>/CO ratio significantly decreased when the CO<sub>2</sub> content in the gas mixture increased, as shown in Figs. 4 (a)-(d) [16].

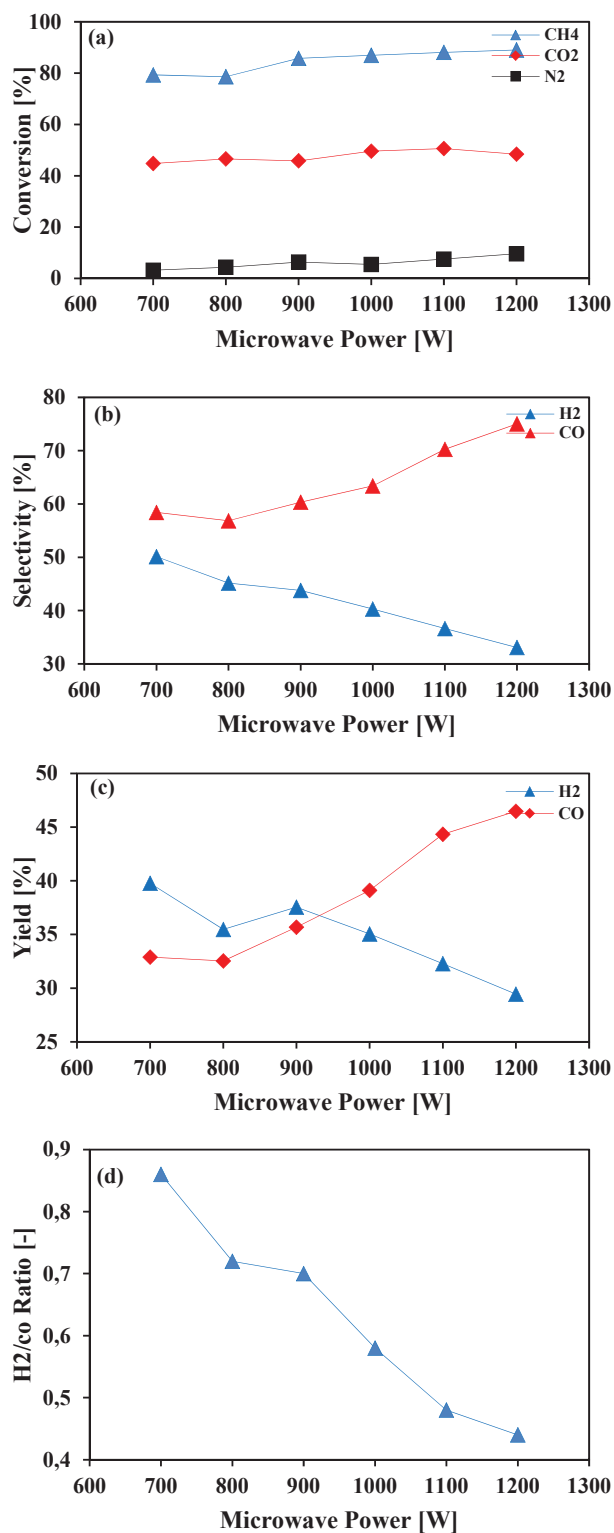


Fig. 3 Effect of Input MW Power on the Performance MW Plasma Dry Reforming Reaction; (a) CH<sub>4</sub>, CO<sub>2</sub> and N<sub>2</sub> Conversions; (b) Selectivity of H<sub>2</sub> and CO; (c) Yield of H<sub>2</sub> and CO; and (d) H<sub>2</sub>/CO Ratio ( $\text{CO}_2/\text{CH}_4$ : 2/1; the feed gas rate at  $2.1 \text{ L min}^{-1}$ )

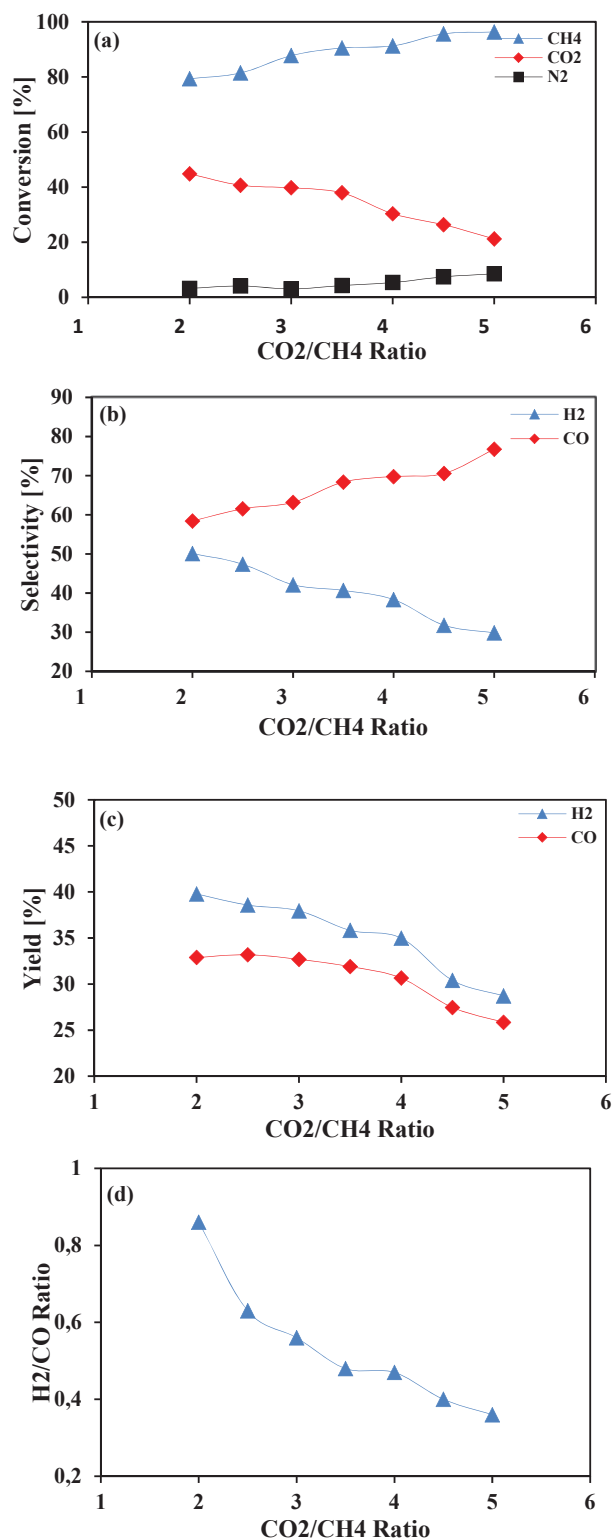


Fig. 4 Effect of  $\text{CO}_2/\text{CH}_4$  Ratio on the Performance MW Plasma Dry Reforming Reaction; (a) CH<sub>4</sub>, CO<sub>2</sub> and N<sub>2</sub> Conversions; (b) Selectivities of H<sub>2</sub> and CO; (c) Yield of H<sub>2</sub> and CO; and (d) H<sub>2</sub>/CO Ratio (input MW power: 700 W)

## IV. CONCLUSIONS

In this work, nitrogen-plasma dry methane reforming was investigated for MW reactor at atmospheric pressure. The effects of different reaction conditions such as total feed flow rate, MW power and CO<sub>2</sub>/CH<sub>4</sub> molar ratio on the conversions of CH<sub>4</sub>, CO<sub>2</sub> and N<sub>2</sub>, selectivities and yields of H<sub>2</sub>, CO, and H<sub>2</sub>/CO ratio were demonstrated. The total reactant flow rate slightly affects the conversions of CH<sub>4</sub>, CO<sub>2</sub> and N<sub>2</sub>, the selectivities and yields of H<sub>2</sub> and CO. Meanwhile, the H<sub>2</sub>/CO ratio was sharply increased with increasing the total feed flow rate from 0.45 to 2.1 L/min at 700 W and CO<sub>2</sub>/CH<sub>4</sub> of 2/1. The study also found that the MW power significantly affects the CH<sub>4</sub>, CO<sub>2</sub> and N<sub>2</sub> conversions, the selectivity and yield of CO. On the other hand, the MW has a negative effect on the H<sub>2</sub>, CO selectivity and yield, and the H<sub>2</sub>/CO ratio. The CO<sub>2</sub>/CH<sub>4</sub> molar ratio increased from 2/1 to 5/1 at 700 W, the conversion of CH<sub>4</sub>, N<sub>2</sub> and the selectivity of CO increased rapidly, while the conversion of CO<sub>2</sub>, the selectivity of H<sub>2</sub>, the yield of H<sub>2</sub> and CO, and the ratio of H<sub>2</sub>/CO exhibited an opposite behaviour.

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