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Simulation of Synthesis Gas Production by Using a Plasma Reactor

Elnaz Valizade*, Hamid Reza Bozorgzadeh, Mohammad Irani
Faculty of Engineering, North Tehran Branch, Islamic Azad University, Tehran, Iran
*E-mail: el.valizade@gmail.com

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Abstract

There are multiple methods for producing synthesis gas and one of the most important of these methods is dry reforming in which two preparations of carbon dioxide and methane are converted into synthesis gas. Carbon dioxide as one of the destructive environmental factors and methane as the main component of natural gas exist in copious amounts in the world, especially in Iran, which has the second largest gas resources of the world after Russia. Therefore, the importance of this method is in converting pollutants into an intermediate substance known as synthesis gas which has considerable applications. In this study, first, synthesis gas production by using dry reforming with the use of plasma technology is studied and for this purpose, glow electric discharge plasma at atmospheric pressure with DC power supply was used. Feed flow rate and the distance between the electrodes were studied as the parameters. In addition, voltage effect on optimal conditions was studied as well. Next, by using fluent software, dynamic simulation of computational fluid of this system was performed which gives us velocity and pressure distributions in the system. For optimization of laboratory conditions, it was assumed that our system has two incoming paths instead of one and the results obtained from this assumption showed that this assumption increases the residence time of the material between the two electrodes which in turn increases the percentage of conversion.

Key words: Synthesis gas, plasma reactor, electric discharge of gliding arc, CFD simulation

Introduction

Simultaneous with the growth and development of industries in all the countries and following the increasing emission of greenhouse gases, the necessity of using fuels with the least pollutant effects and at the same time with the highest level of efficiency is felt more than ever. Considering this situation, natural gas can be referred as one of the most abundant and cleanest resources of available energy in the world which has a high level of importance (Liu, C.-j., G.-h. Xu, and T,1999, York, A.P., T. Xiao, and M.L. Green, 2003).

Natural gas fuel is a clean and appropriate feed for chemical industries and in fact, is a mixture of hydrocarbon preparations together with minimal amounts of non- hydrocarbon preparations like (CO2-N2-H2S-He) that is either in gas phase or is extracted from underground resources of crude oil. Conversion of light hydrocarbons to synthesis gas is one of the most important chemical conversion processes (Liu, C.-J., et al.2001, Liu, C., et al.1997). Synthesis gas is a preparation of hydrogen and carbon monoxide which is the most major intermediate substance for producing hydrogen and some other chemical compounds including methanol, ammonia, liquid fuels and solvents (Czernichowski, 2001).

From an industrial point of view, synthesis gas production can be performed by using a number of methods including: catalytic conversion of methane with steam, partial oxidation of methane, and conversion of methane by carbon dioxide and so on (Chaker, Moisan, and Zakrzewski,1986).

Results of previous studies show that the use of chemical plasma reactor for producing synthesis gas from methane is an advanced technology with an acceptable energy efficiency which is also compatible with the environment.

Cold plasma, due to its non-equilibrium feature and its simple functional conditions, that is, low pressure and temperature, is a very appropriate instrument for starting reactions including the reaction of converting methane to synthesis gas (Liu, at al. ,1999,2001). Considering the operating pressure and shape of electrodes, gold plasma is divided into various types of radiation, calm, corona, radio frequency, microwave and gliding arc plasma reactors (Yao, et al.2002). There are two characteristics in plasma which are of a special importance: Thermal plasma and non-thermal plasma (Sreethawong, 2007).

Advantages of using non-thermal plasma are related to its lower temperature which leads to less energy consumption and less electrode erosion. While, there is no need to cool down the electrodes as well. In addition, size and weight of non-thermal electrodes are rather low (Liu & Xu,1999).

The main aim of non-equilibrium plasmas is to control the flow intensity and discharge capacity. These parameters can with controlled by working on feed source, flow velocity and design. All these parameters are related to one another (Eliasson & Kogelschatz,1999).

There are two methods for creating non-thermal plasma:

- Using static discharge which is for Corona or DBD discharge.
- Using dynamic discharge with is put under pressure by gas flow through the length of reactor and this technique is used in gliding and microwaves arc (Chaker, Moisan, & Zakrzewski,1986).

Gliding arc technology is one of the most appropriate techniques for producing hydrogen. This technology is not so much complex and has a high level of stability and work in a high range of flow velocity. The main advantage of this instrument is that we can easily change the capacity of discharge by working on electrodes and voltage level. This reactor can work with an alternating or direct voltage and power supply technology has less complexity comparing to corona or microwave technology. Gliding arc reactors specially are used in eliminating gas pollution, gas conversion and another number of chemical processes (Czernichowski, 2001).

Major products in methane plasma conversion process are CO and H_2 and some other C2 compounds (ethane, ethylene and acetylene), heavier compounds and coke are also seen in these products. With adjusting the operating conditions inside a reactor we can direct the methane plasma conversion process toward producing synthesis gas (Co, H_2) or hydrocarbons. The biggest disadvantage of plasma reactors is electric energy consumption by them and in case of availability of electric energy, using plasma reactor technology for producing synthesis gas seems to be so much desirable (Huang, et al.,2000; Krall,1973).

In this study, we first study the production of synthesis gas by dry reforming by using plasma technology. For this purpose, glowing electric discharge plasma in atmospheric pressure with DC power supply is used. Parameters of incoming flow rate and distance between electrodes were studied. In addition, voltage effect on optimum conditions was studied. Next, by fluent software, dynamic simulation of computational fluids of this system was performed which gives us velocity and pressure distribution in the system. For optimizing in vitro conditions it was assumed that the system has two inlets instead of one.

Laboratory studies and their results

Cold plasma reactor with DC electric discharge was used (figure 1). Measurement system is consisted of high voltage probe Tektronix p6015 HV, Oscilloscope Tektronic TDS2024B, multimeter and gas chromatography. Pulse DC power supply can be set as per need. RG plasma model IRPS70 has a maximum outgoing voltage of 20 KW and its maximum outgoing frequency is 40 KHz.

In each experiment, the incoming feed and the produced product were analyzed and identified by gas chromatography. The used gas chromatography of Agilent6890N is consisted of two Reagents: FID flame ionization reagent for analyzing hydrocarbons like ethane, ethylene, acetylene and so on; TCD which has the ability to identify and analyzed the molecule of substances like Argon, nitrogen, carbon dioxide, carbon monoxide, hydrogen, methane and so on.

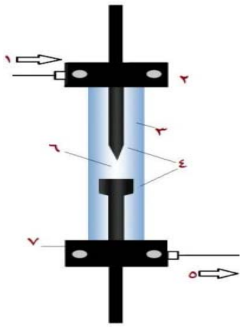


Figure 1: **Plasma reactor: 1- Incoming location of feed gas; 2 & 7- Teflon preservative; 3- Quartz pipe; 4-Needle-shape flat electrode of quartz material; 5- Products discharge; 6- Electric discharge space.**

Calibration of mass control device

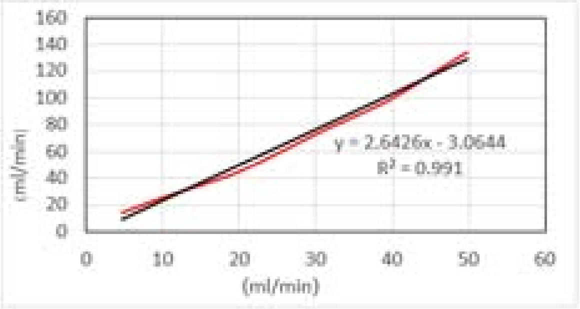


Figure 2: Calibration of argon gas.

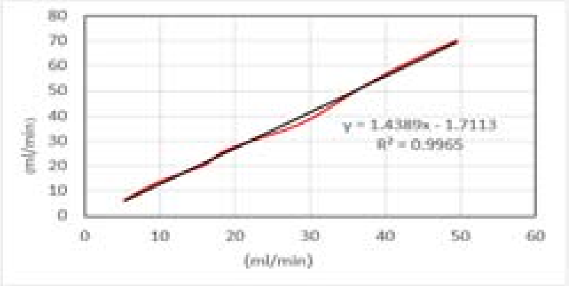


Figure 3: Calibration of methane gas.

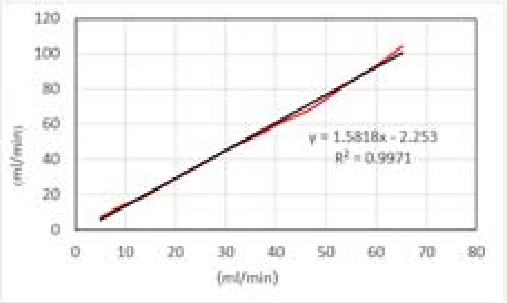


Figure 4: Calibration of carbon dioxide gas.

The important thing in measuring flow rate of gases is the calibration of MFCs. Before the feed gas enters the reactors, there is a specific MFC on its way. With the passage of one gas and with the valve of the other gases being closed, its nominal flow rate is red by the screen. Next, the actual value of the passing gas flow is measured by soap flowmeter from outgoing MFC.

In this way, we obtained a diagram. One of the axes of this diagram is nominal flow rate and its other axis is the measured flow rates which are known as calibration diagram. The obtained diagrams are shown in figures 2 to 4.

Preliminary experiments

The amount of undesirable produced gases in preliminary experiments like Ethane, ethylene and propylene has been inconsiderable. With increase molar proportion of CO_2/CH_4, Carbon leakage reduces inside the reactor which makes us to conclude that carbon production is due to C atom of CH4 molecule and C atom in CO_2 molecule doesn’t have any role in carbon production; because, if carbon production was due to atom c of CO_2 molecule, the amount of carbon should have increased by increased molar proportion of CO_2/CH_4, but this is not the case and $C+O_2 \rightarrow cCO_2$ reaction doesn’t occur in plasma reactor medium. Lack of production of O2 molecule in reactor’s outgoing products also proves this claim.

Relationships between methane and dioxide carbon conversion percentage and selectivity of synthesis gas

Methane conversion percentage:

$$CH_4\ conversion = \frac{mole\ of\ CH_4\ converted}{mole\ of\ CH_4\ \mathrm{int}roduced} \times 100\%$$

Dioxide Carbone conversion percentage:

$$CO_2\ conversion = \frac{mole\ of\ CO_2\ converted}{mole\ of\ CO_2\ \mathrm{int}roduced} \times 100\%$$

Selectivity of monoxide carbon gas:

$$CO\ selectivity = \frac{mole\ of\ H_2\ produced}{mole\ of\ CH_4\ consumded + mole\ of\ CO_2\ consumded} \times 100\%$$

Molar proportion of CO/H_2:

$$\frac{H_2}{CO} = \frac{mole\ of\ H_2\ produced}{mole\ of\ CO\ consumded} \times 100\%$$

Energy efficiency:

$$Energy\ coversion\ efficiency\ (ECE) = \frac{n_{H_2} \times LHV_{H_2} + n_{CO} \times LHV_{CO}}{P + n_{CH_4} \times LHV_{CH_4}}$$

After the stage of designing and developing the laboratory system and performing preliminary experiments of the target parameters, incoming flow rate and electrode distance were determined. The target level of feed gas enters plasma reactor after mass control device calibration and general flow rate of incoming and outgoing gases are measured again by bubble flowmeter. The applied voltage to the reactor by pulse DC power supply is seen by Oscilloscope. The frequency is also measured by multimeter. Flow also is obtained by ciphering multimeter in the circuit. Then, we can calculate the capacity. Finally, reactor's products are entered into GC for analysis which is calibrated by standard gas calibration column with known percentage of compound. Every data is extracted after 2 to 3 minutes of starting the reactor and every experiment is performed for 4 to 5 times and in case of repeating, the result is reported.

Studying the effect of incoming feed flow rate and electrode distance on methane gas conversion percentage

In the conducted experiments, distances of 2 and 2.5 cm for electrodes, 22 watts for power, 10 KV for the applied voltage and 30 KHz for frequency have been considered.

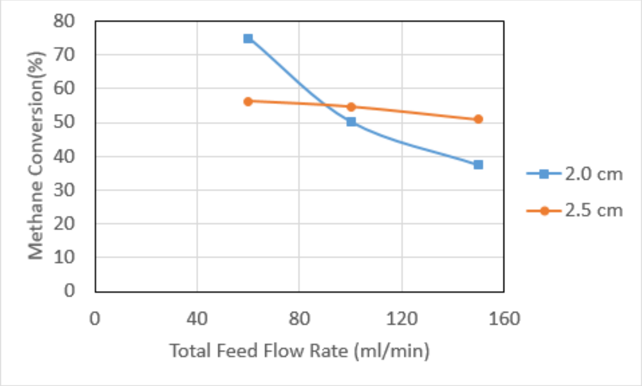


Figure 5: Comparison of methane conversion percentage at d= 2 and 2.5 cm distance on total incoming flow of F=145, 97, 60(ml/min) at power.

As we can see from figure (5), increased incoming gas flow leads to reduced methane gas conversion percentage and the gradient of methane conversion percentage reduction at electrode distance of 2 cm is more than the gradient of its reduction at 2.5 cm, which indicated that at higher flows 100ml/min and 150 ml/min) methane conversion percentage at 2.5 cm of distance is more than its conversion percentage at 2 cm of distance. It also indicated that at the distance of 2.5 cm, the value of methane conversion percentage doesn't reduce so much with increasing the incoming feed and this can be of great importance from economic point of view; because, power is fixed during the reaction.

Studying the effect of incoming feed flow rate and electrode distance on dioxide carbon gas conversion percentage

With comparing the two diagrams in figure (6), we can see that the percentage of dioxide carbon gas conversion reduces with increasing incoming feed flow; however, the percentage of dioxide carbon gas conversion at the distance of 2.5 cm is larger than its conversion percentage at the distance of 2 cm. This is because at larger electrode distance, gas contact with plasma is more and gas has more opportunity for residing in plasma environment. Therefore, better results have been achieved at electrode distance of 2.5 cm.

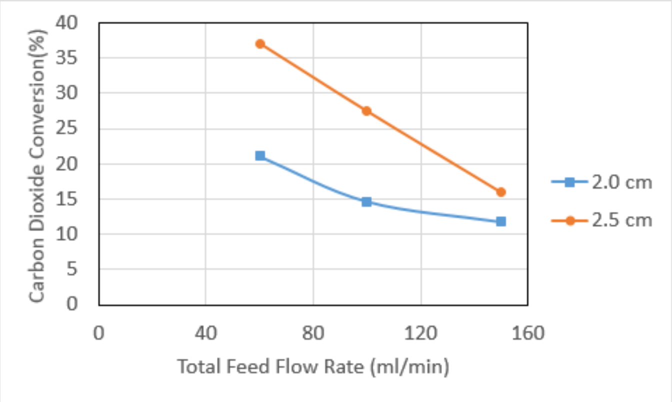


Figure 6: Comparing the percentage of dioxide carbon conversion percentage at d=2 & 2.5 cm on total incoming flow F=145, 97, 60 (ml/min) at fixed power of p=22(w).

Studying the effect feed flow rate on hydrogen and monoxide carbon selectivity

Selectivity of one of the reaction's products which is hydrogen gas, at 2.5 cm electrode distance reduces with increased incoming feed flow rate. However, we expected this to happen with reduced percentage of methane gas conversion in high flow rate. However, at the distance of 2 cm at 97 ml/min flow, hydrogen selectivity increases and even it surpasses its value at 2.5 cm of distance. Hence, this point can be considered as the optimal point. However, as we can see in figure (7), with increasing the flow to 145 ml/min, we witness a reduction in selectivity of hydrogen gas. Results obtained in 2.5 cm of distance (of course, with the exception of the optimal point) are better than the distance of 2 cm. However, these results are due to the fact that methane conversion percentage is higher at 2.5 cm of distance; therefore, the product resulting from the conversion, that is hydrogen gas, is produced much more at this distance as well.

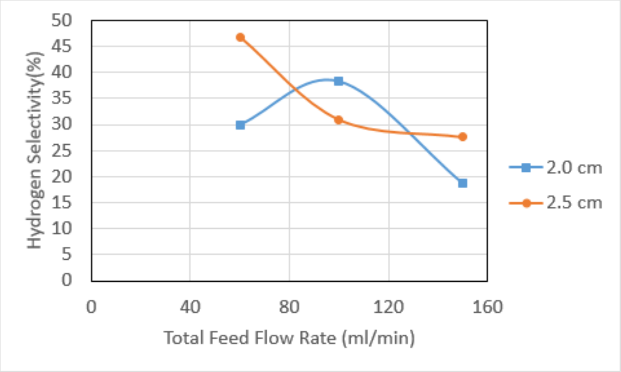


Figure 7: Comparison of hydrogen selectivity at d= 2 cm and 2.5 cm on total incoming flow F=145, 97, 60 (ml/min) at fixed power of p=22(w).

As we can see in figure (8), CO gas selectivity reduces with increased flow rate. However, its slowing gradient at 2 cm of distance is more than its slowing gradient at 2.5 cm of distance. Also, at 2 cm distance at 60 ml/min flow rate, CO production is considerable. However, with increasing flow rate to 97 & 145 ml/min, dioxide carbon gas selectivity at 2.5 cm electrode distances increases. Since, plasma medium has the necessary energy for performing $CO_2+e \rightarrow CO+O+e$ reaction, with increased residence time of gas in plasma medium and occurrence of the above reaction, CO selectivity increases as well.

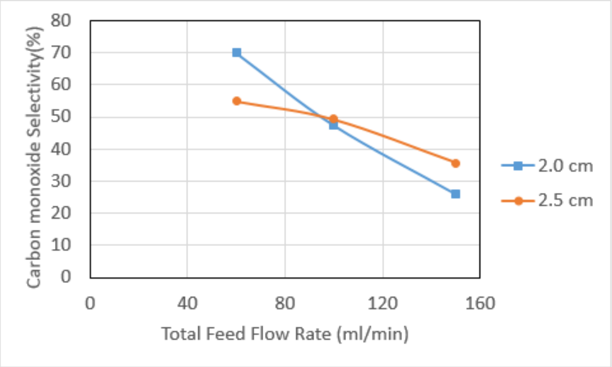


Figure 8: Comparison of hydrogen selectivity at d= 2 cm and 2.5 cm on total incoming flow F=145, 97, 60 (ml/min) at fixed power of p=22(w).

In methane reforming of CO_2, a major problem is the issue of coking and formation of carbon in reactor environment and on electrodes. Both in terms of thermodynamic and experimental observations, we can see that the main reason for coking is the reaction of $2CO \rightarrow C+CO_2$. Specially, so much coke is produced in molar proportions close to $CO_2/CH_4=1$ and for removing it from experiments, nitric acid 30% is used and carbon is removed from electrodes by soft sandpaper. In $CO_2/CH_4=3$ proportion, the problem of carbon production is much less. With selecting this proportion, as we can see in diagrams, desirable results are obtained at 2.5 cm electrode distance. Plasma formation in this electrode distance has two major advantages: first, incoming gas feed has more space for contacting with plasma electric discharge and gas residence time in plasma electric discharge environment increases. Second, with increased electrode distance, we can obtain higher voltage. With increased voltage, degree of ionization increases and in turn, methane and dioxide carbon conversion percentages increases with increased number of active particles and electrons which is due to increase voltage. This was confirmed by conducting Preliminary experiments at 1 and 1.5 cm of distance and considering other parameters like incoming flow, frequency and molar proportion as fixed which gave us much weaker results. For example, in preliminary experiments with molar proportion of $CO_2/CH_4=3$, total flow of 60 ml/min, voltage of V=10 kv, frequency of F=30kHz and electrode distance of d=1.5 cm, methane conversion percentage was obtained to be equal to 10%. With repeating experiments at these conditions, it was found that this distance is not appropriate. It was also indicated that distances more than 2.5 cm are also not appropriate, because, in this case a very high voltage would have been needed (more than 16 kv) and on the other hand, it was not possible to conduct this experiment at lower voltage like less than 10 kv, because, at this voltage, plasma wouldn't have produced at the glowing area. Therefore, 2 cm and 2.5 cm were considered as the best distance for electrodes.

Studying conversion percentage and selectivity of methane gas and dioxide carbon in different feeds at 2.5 cm electrode distance

Conversion percentage of methane is always higher than the conversion percentage of dioxide carbon. For studying this we should pay attention to the fact that the energy required for Breaking the molecular bonds of dioxide carbon (O-CO=5.52 ev) is larger than the energy required for breaking the molecular bonds of methane ($H-CH_3=4.55$ ev). On the other hand, we need more energy for breaking O-CO comparing to $H-CH_3$. Therefore, we always witness a higher value for methane conversion percentage comparing to dioxide carbon conversion percentage in diagrams.

The second thing which should be considered is the very low speed of Fluctuating energy loss of dioxide carbon molecular bonds which leads to high concentration of dioxide carbon molecules with high fluctuating energy in reaction medium. According to the conducted experiments, the more the distance between electrodes, the percentage of dioxide carbon conversion increases. CO_2 molecules with high fluctuating energy are existed in plasma environment. With increased electrode distance, CO_2 contact with energy source, which is the plasma electric discharge, increases and this increases the chance of receiving electron from plasma environment which leads to complete break of CO_2 and formation of CO and O and this is confirmed by formation of some amount of steam.

The third thing is that with increased incoming feed flow rate, contact time between electric discharge and reacting materials' molecules reduces; therefore, probability of molecules breaking into intermediate active substances reduces. However, on the other hand, the number of dioxide carbon molecules with a high level of fluctuating energy, increases. In fact, active environment/medium of reactor increases.

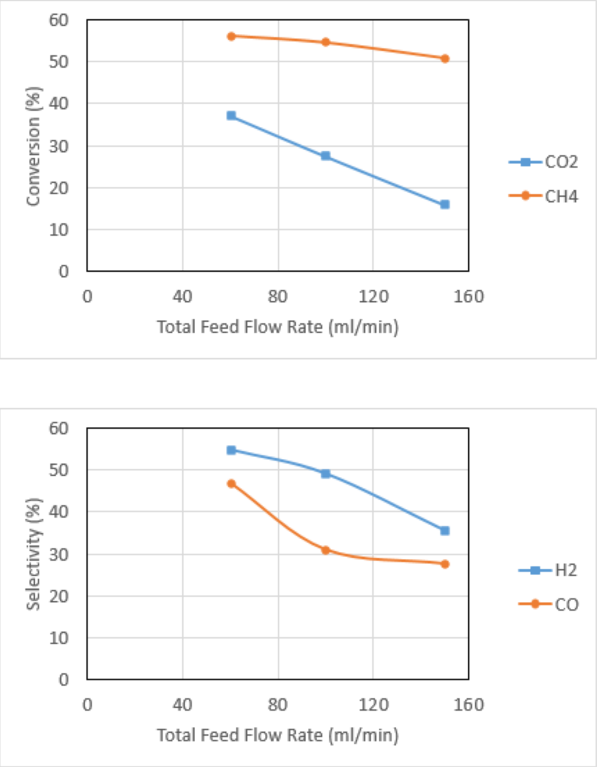
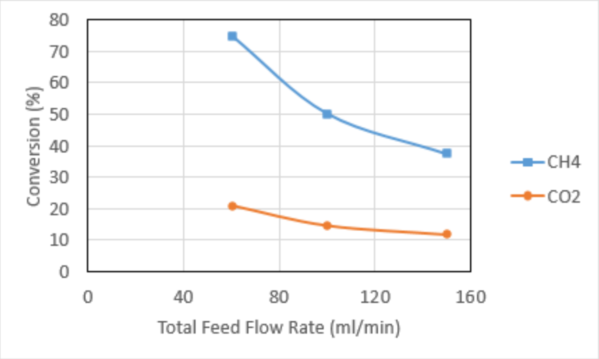


Figure 9: Comparing selectivity (a) and conversion percentage (b) at distance. Comparison of methane conversion percentage at d=2.5 cm on total incoming flow of F=145, 97, 60(ml/min) at fixed power of p=22(w).

With conducting preliminary experiments and considering 3 molar proportions for incoming feed (proportions of O_2/CH_4=1, 2 , 3), it is concluded that with increasing molar proportion CO_2/CH_4=3, probability of electron collisions between high-energy electrons and dioxide carbon molecules increases. Therefore, the extent of dioxide carbon conversion to monoxide carbon and Atomic oxygen increases and consequently, due to reaction between methane and atomic oxygen, we witness an increase in methane conversion percentage. In general, with increased gas flow, we witness a reduction in methane and dioxide carbon conversion percentage and it is clear that with increased gas flow, particles are less affected by plasma. With increased gas flow, incoming feed molecules, pass plasma area faster and their residence time in this area reduces.

Studying methane and dioxide carbon conversion percentage and selectivity of hydrogen and monoxide carbon in different feeds at 2 cm electrode distance



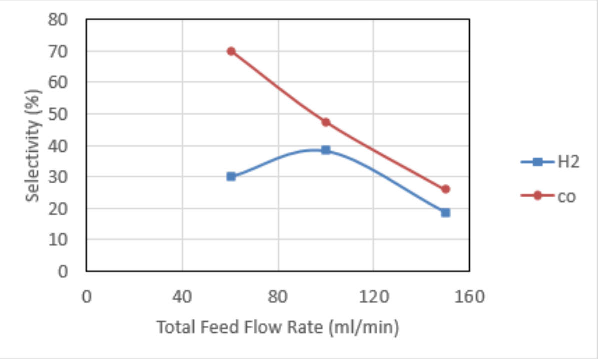


Figure 10: Comparison of conversion percentage and selectivity; comparison of methane conversion percentage at d= 2cm distance on total incoming flow of F=145, 97, 60 (ml/min) at fixed power of p=22(w).

Studying the proportion of produced products to incoming flow increase

Studying the proportion of produced products is of great importance for us. The reason behind this importance is that different proportions of produced products are appropriate for different usages in different industries. For example, $H_2/CO=2/1$ proportion is appropriate for methanol synthesis and $H_2/CO=1$ proportion is appropriate for Methyl and acetic acid synthesis and it is also highly appropriate for Fischer-Tropsch synthesis.

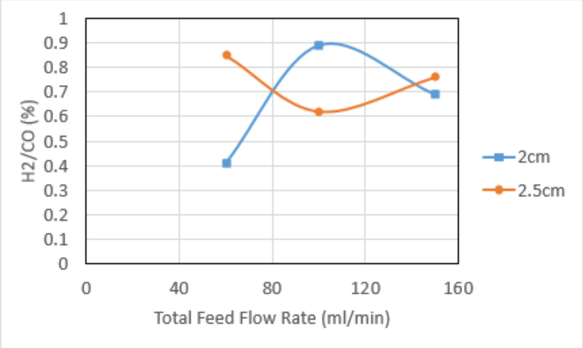


Figure 11: Studying the proportion of produced products of CO/H_2 on incoming flow of feed gas.

The used feed with molar proportion of $CO_2/CH_4=3$ was interred into the system and it was expected that the outgoing proportion of CO/H_2 products from the reactor to be reduced. Since, the proportion of less than one of CO/H_3 is so much appropriate for liquid hydrocarbons synthesis and we also witnessed that in this proportion, coking phenomenon has reduced considerably. In this proportion, $CO_2/CH_4=3$ feed is appropriate for producing monoxide carbon and therefore, we expect the product proportion of less than 1 for CO/H_2. The proportion of the produced products at 60 ml/min flow and at 2.5 cm distance has its highest value and this proportion has the highest value for 2 cm distance at 100 ml/min flow.

Studying the effect of voltage on incoming feed conversion percentage and products' selectivity

In all the previous experiments, voltage was fixed and equal to $V_{p-p}=10(kv)$. While conducting these experiments, considering the obtained results regarding the conversion percentage and selectivity of products, one of the results was selected as the best result and voltage effect was studies on it.

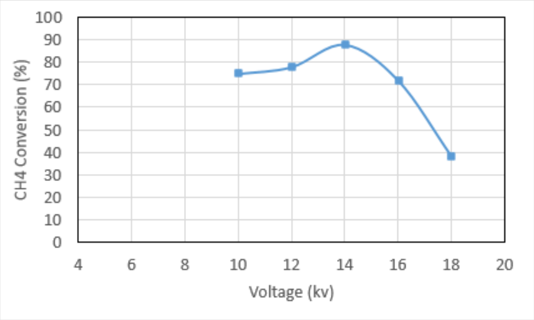


Figure 12: Studying the effect of voltage on methane conversion percentage.

Therefore, all the conditions like frequency (F=30 kHz), feed molar proportion ($CO_2/CH_4=3$), flow (Flow=60ml/min) and electrode distance (d=2cm) were considered as fixed values and only the only parameter which is variable is voltage.

With increasing voltage from 10 to 14 kv, methane conversion percentage increases and reaches 87.6%; however, with increasing it up to 18kv, methane conversion percentage reduces and reaches 36.95%. Therefore, we conclude that increasing voltage beyond 14kv reduces conversion percentage. With increasing voltage at the time of conducting the experiments, we witness tht with increasing voltage; plasma comes out of its uniform state which leads to a reduction in conversion percentage of Reactants and eventually, reaction's products.

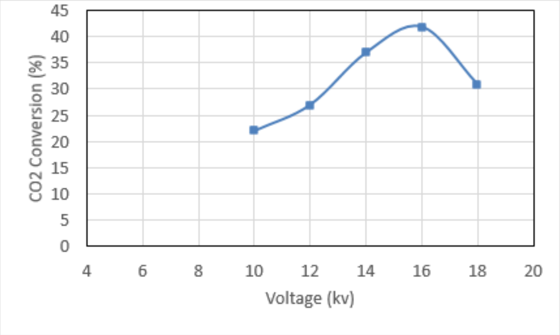


Figure 13: Studying the effect of voltage on dioxide carbon conversion percentage.

With increasing voltage from 10 to 16kv, we witness an increase in dioxide carbon conversion percentage up to 46.3%; however with continuing this increase in voltage up to 18kv, conversion percentage decreases to 30.18%.

Considering the data in methane conversion percentage diagram, we witness in reduction from 14 to 18kv voltage; therefore, it is expected that hydrogen selectivity also reduces considerably with increasing voltage to beyond 14kv.

Products' selectivity reduces with increasing voltage and the reason for this is the production of by-products like Ethylene, acetylene, water vapour, or reproduction of methane or CO2. As these diagrams show, increasing voltage is not useful for products' selectivity, which is synthesis gas. Also, in preliminary experiments we worked with lower voltages (8 kv) and no good results were reported. Reforming process requires energy and in plasma method this energy is supplied by electricity.

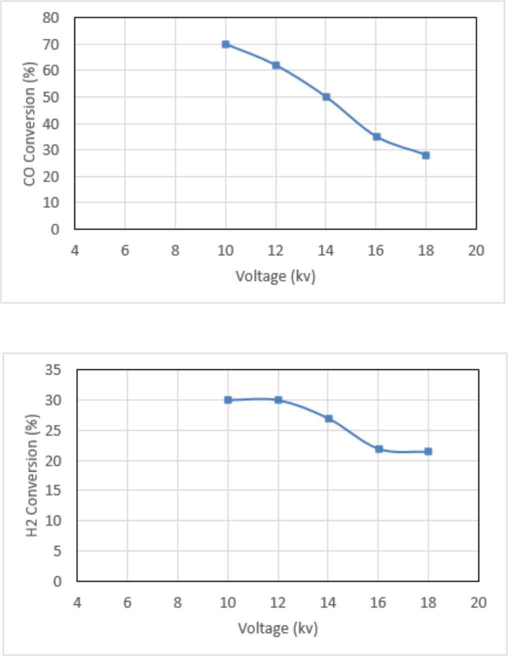


Figure 14: Studying the effect of voltage on selectivity of monoxide carbon

Studying energy efficiency in plasma method

For evaluating plasma method in methane dry reforming, its efficiency in methane conversion should be studied and this value can be calculated according to ECE formula.

In the following table, minimum thermal value of the required gases for ECE calculation is presented.

Table 1: Minimum thermal value for CH_4, CO, H_2

LHV of CO	kJ.mol 283.502
LHV of H_2	kJ.mol 242
LHV of CH_4	kJ.mol 801.363

Calculated energy efficiency (ECE) in this study is 54%. For comparing it with other methane dry reforming methods with the use of plasma method, all the information of these studies have been presented in table 2 together with their references.

Results of CFD simulation

Considering the reaction occurring between the two electrodes, the aim is to increase the reaction amount by increasing the residence time between the two electrodes, because, conversion percentage in a system is a function of residence time and reaction rate.

In the following, a number of cases are studied:

1. One incoming and one outgoing flows (laboratory system)
2. Two incoming and one outgoing flows from electrode
3. Two incoming and one outgoing flows from Porous Electrodes

Table 2: Comparing different plasma methods and studying their efficiency

Plasma type	Feed (mL.min)	Molar proportion CH_4/CO_2	power (W)	Conversion percentage (%)		Selectivity (%)		Molar proportion H_2/CO	ECE (%)
				CH4	CO2	CO	H2		
Corona electric discharge	43	1.1	46.3	62.4	47.8	66.8	70	1.2	13
Corona electric discharge	60	1.2	63	94.1	77.9	97	69.4	0.6	21
Corona + Zeolite	25	1.1	84	56.3	22.8	9.1	-	2.1	4
DBD	150	2.1	500	64.3	55.4	33.3	-	1.7	3
DBD+ Ni/Al_2O_3	30	1.1	130	55.7	33.48	60.9	51.9	1	3
MW	200	3.2	60	70.8	68.8	75	-	1.5	47
Glow discharge	120	1.1	23	61	50	63	77.5	1.4	44
Cold jet plasma	830	4.6	770	45.6	34	85.4	78.1	0.8	63
GAD electric discharge	1000	1.1	190	40	31	62	50	0.9	28
Thermal electric discharge	21700	4.6	85000	87.9	84.3	82.2	43.48	0.4	36
The present study	60	1.3	22	75	21.05	70	30	0.4	54

Mode 1: One incoming and one outgoing paths

In this state, we have one incoming path with a velocity of 2128 m/s which is turned into an outgoing path on the other side of the calculation field. Figure 15, shows the residence time in calculation range:

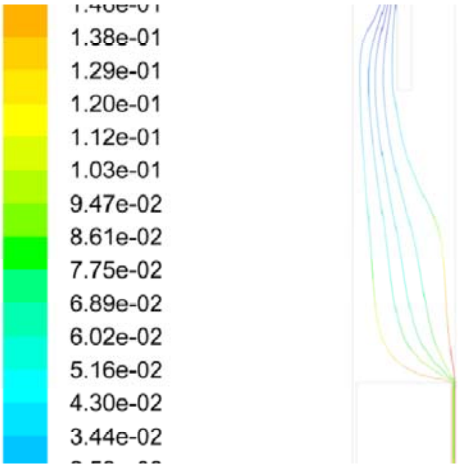


Figure 15: Total residence time in mode 1.

Lateral flow paths have a higher residence time comparing to middle flow paths, because they pass through a longer path. Residence time in this mode includes all the area, however, the important thing is the residence time between the two electrodes and when it passes through the small space between the electrode and flow wall, it is not important for us that how much time passes, because in this area no reaction occurs.

Therefore, we calculate the residence time between the two electrodes and for this purpose, we calculate the residence time between the bottom of the first electrode and the top of the second electrode which is presented in the flowing figure. On the other hand, we continue increasing the number of flow paths until the value of target parameters in the table, doesn't change between two consecutive values.

Table 3: Total residence time for 1st mode.

	The number of considered flow path	Minimum residence time	Maximum residence time	Average residence time	Standard deviation of residence time
One incoming path and one outgoing path	5	8.69e-2	1.721e-01	1.204e-1	3.524e-02

Table 4: Optimal residence time of 1st mode

	The number of considered flow path	Minimum residence time	Maximum residence time	Average residence time	Standard deviation of residence time
One incoming path and one outgoing path	250	7.038e-02	4.327e-01	1.189e-01	6.966e-02
	300	7.039e-02	4.327e-01	1.187e-01	6.943e-02

As we can see in table 4, with increasing the number of flow paths to 300 paths, no considerable change occurs. Therefore, there is no need to increase the number of paths beyond this.

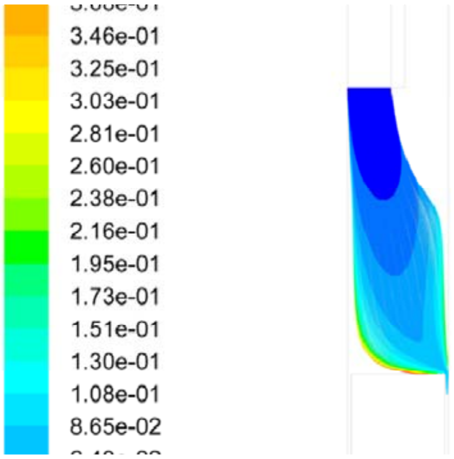


Figure 16: **Optimal residence time for the 1st mode.**

Mode 2: Two incoming and one outgoing paths from electrode

In this mode, we have two incoming paths with the velocity of 1064 from two sides of the first electrode and one outgoing path which is on the electrode. Figure 17, shows the residence time in the whole calculation area.

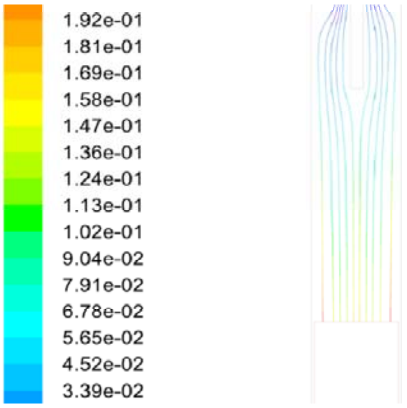


Figure 17: Total residence time for the 2nd mode

Since, there is symmetry, the average residence time and other parameters for one side and for the whole calculation area is also the same value. The following figure shows the residence time between the two electrodes for one side.

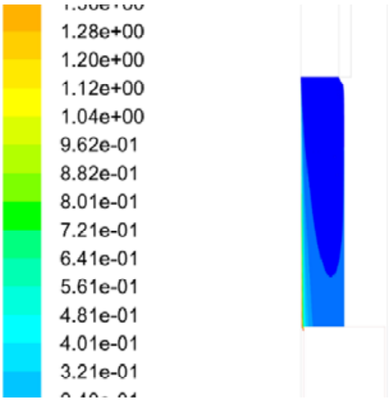


Figure 18: Optimal residence time of one of the sides of the 2nd mode.

Table 5: Optimal residence time of the second mode

	The number of considered flow path	Minimum residence time	Maximum residence time	Average residence time	Standard deviation of residence time
Two incoming paths and one outgoing path	300	9.965e-02	1.603	0.01826	2.163e-01

As we can see in table 5, the average of the residence time has increased; however, standard deviation has also increased. The reason of this increase in standard deviation is the flow near the wall that comparing to the previous mode, it is more inclined toward the walls and due to friction with the wall its velocity has reduces and its residence time has increased.

Mode 3: Two incoming paths and one outgoing path from porous electrode

In this mode, a part of the bottom electrode has become porous.

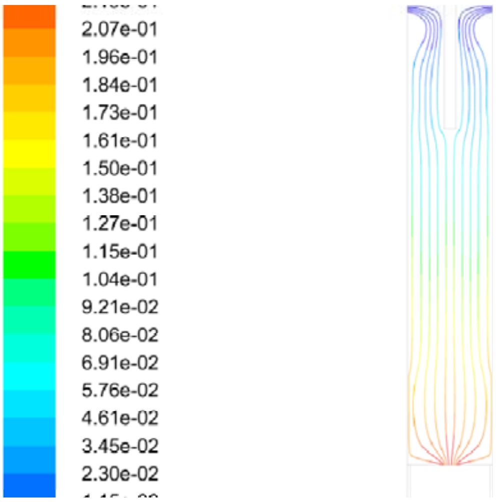


Figure 19: Residence time in the whole calculation area of the third mode

As we can see in figure 19 in the bottom area, in the porous part, flow paths close to the wall are more close to each other and in the bottom part, they have more distance with one another. This means that flow has a higher inclination to go toward the wall, because, resistance of the porous area prevents the passage of the flow. In figure 20, you can see the optimal residence time.

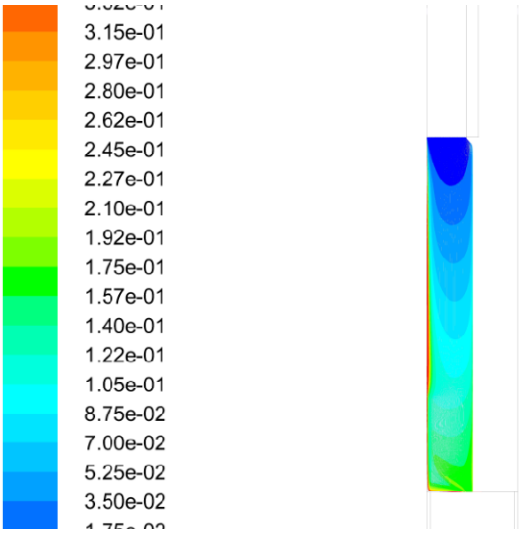


Figure 20: Optimal residence time of one side of the third mode

Table 6: Optimal residence time of 3rd mode

	The number of considered flow path	Minimum residence time	Maximum residence time	Average residence time	Standard deviation of residence time
two incoming paths and one outgoing path	300	1.616e-01	4.315e-01	0.1841	3.854e-02

Considering the fact that with making the bottom electrode porous, the path length has been increased a little bit; the average time of residence and standard deviation has been increased, because, flow is not uniform in the porous part of the electrode (table 6).

Conclusion

Considering the results obtained from the conducted studies in laboratory and CFD simulation we can say that in general the average time of residence is of priority and the more it is, it would be better. Therefore, the third case is preferred to the second case and the second case is preferred to the first case. However, at the same average of residence time, lower standard deviation is desirable.

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