Exploring Ethylene Generation in a Micro-Flow Reactor with Controlled Temperature

Profile

by

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ABSTRACT

Ethylene is one of the most widely used organic compounds worldwide with ever increasing demand. Almost all the industries currently producing ethylene globally use the method of steam cracking, which, though highly selective and cost effective, is energy intensive along with having a high carbon footprint. This study aims to analyze micro-scale partial oxidation of propane as a novel approach towards ethylene generation which is simpler, less energy consuming, operates at lower temperatures and causes minimum CO_2 emission. The experimental study endeavors to maximize the ethylene production by investigating the effect of variables such as temperature, flow rate, equivalence ratio and reactor diameter. The micro-scale partial oxidation of propane is studied inside quartz tube reactors of 1 mm and 3 mm diameter at a temperature range of 800 to 900 ^oC, at varying flow rates of 10 to 100 sccm and equivalence ratios of 1 to 6. The study reveals ethylene yield has a strong dependence on all the above factors. However, the factors are not completely independent of each other. Adjusting certain factors and levels results in greater ethylene yields as high as 10%, but propane to ethylene conversion efficiency is approximately constant for most conditions. Low CO_2 concentrations are also recorded for most of the factor and level combinations, indicating the potential to achieve lower CO_2 yields compared to conventional approaches. The investigation indicates promise for application in the field of ethylene generation.

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CHAPTER 1

INTRODUCTION

Ethylene, the simplest alkene, and a colorless flammable gas is one of the widely used hydrocarbons. It finds its usage in polyethylene (a popular plastic) production, fruit ripening as a plant hormone and production of ethanol. As per the reports, over 150 million tons of ethylene were used worldwide in 2021 and its consumption is supposed to reach up to 260 million tonnes by 2035 [1]. Owing to the ever-growing demands for ethylene, new methodologies of its production must be investigated and especially those methods with low greenhouse gas emissions.

Currently, steam cracking of ethane and naphtha is a primary method of industrial ethylene production. This process is overly endothermic, requiring temperatures in a range of $1100^{o}C$ and energy consumption of about 26-31 GJ per tonne of ethylene [2]. Excessive carbon emissions which are in the range of 2 tonne of CO_2 per tonne of ethylene are also a drawback of production via steam cracking. Although, the conversion rate of feed fuel to ethylene is impressive and the process is continuously improved and sophisticated with over a century of research, aspects of immoderate energy usage and emissions increase the need for alternative, novel techniques of achieving similar goals. Extensive research has established new processes of ethylene generation such as chemical looping, oxidative coupling of methane (OCM), and catalytic partial oxidation, among others. This research shows affirmative results in reduced emissions, energy intensity and complexity of the process [3]. However, a lot of effort is needed to increase the ethylene intensity as well as to improve industrial profitability of these processes.

In the present study, operating conditions for micro-scale thermal partial oxidation of propane are investigated. To determine the approach leading towards better ethylene yield, experiments were conducted with four important variables which are reactor diameter, wall temperature, flow rate and equivalence ratio. The process calls for investigation as it is devoid of a catalyst and the associated costs, although an external heat source is required just to maintain specific wall temperature. The reactor is as simple as a quartz tube and no processing of fuel or air is necessary prior to the reaction chamber. The nature of reaction is partial oxidation and hence less carbon dioxide emission and possibility of deriving other important hydrocarbons or hydrogen are other key points which makes this process attractive.

CHAPTER 2

LITERATURE REVIEW

This chapter will examine the ethylene production technologies currently in use. Specifically, we will examine the steam cracking process used in industry as well as other promising new techniques like chemical looping, oxidative coupling of methane, catalytic partial oxidation and at last thermal partial oxidation. Table 1 can also be used to summarize all the discussion in this chapter comparing various processes.

Key performance parameters are needed to compare the ethylene production processes. Conversion rate (Eq. 1) informs us about how much of injected fuel has converted into products. It can be mathematically defined as the ratio of the difference between the amount of fuel at inlet and outlet to the amount of fuel at inlet.

$$Conversion\ Rate = \frac{(Feed_{in} - Feed_{out})}{Feed\ in} \tag{1}$$

Selectivity is calculated to measure the output of the desired compound with respect to the fuel utilized. It is the ratio of product output to the fuel utilized, i.e., the difference in the amount of fuel fed in and amount of fuel at the output.

$$Selectivity = \frac{Product\ output}{Feed_{in} - Feed_{out}} \tag{2}$$

Table 1:
Comparison of various ethylene producing technologies

Process	Feed	Catalyst	Conv. Rate	Selectivity in %	Heat GJ/T C_2H_4	Temp. (°C)	By Products	CO_2 T/ton C_2H_4
Cracking	Naptha	Zeolite	NA	29-34[3]	26-31 [2]	~1100[2]	olefins, CH_4, H_2	1.8-2 [2]
	Ethane	NA		80-84[3]	17-21 [2]			1-1.2 [2]
Chemical Looping	Methane	MeO	91 [4]	39 [4]	5	500 [4]	H_2O, H_2, CH_4	0.45 [5]
Oxidative Coupling of Methane	Ethane	NA	85 [5]	NA	NA	NA	NA	NA
	Methane	Mn-Na_2WO_4/SiO_2	20-30 [6]	70-80 [6]	NA	NA	NA	~1 [7]
		Sn,Pb,Sb,Bi,Tl,Cd,Mn-Al_2O_3	~5–11 [8]	50 [8]		500-1000 [8]	CO, CO_2, C_2H_6	
		Pd-based catalyst	~10–40 [9]	80 [9]		350 [9]	H_2, C_2H_2, BZ	
		PtBi/HZSM5	~1-6 [10]	80-99 [10]		600-700 [10]	H_2, BZ Coke	
		Fe@SiO_2	48 [11]	48.4 [11]		950-1090 [11]	H_2, BZ	
		Fe@SiO_2	~5-25 [12]	~50-85 [12]		950-1090 [12]	H_2, C_2H_2, BZ	
		alkali-Mg_6MnO_8	36.7 [13]	63.2 [13]		840 [13]	CO, CO_2, C_2H_6	
		doped nanowire	40 [2]	55 [2]		520 [2]	CO, CO_2, C_2H_6	

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Process	Feed	Catalyst					Products	
		alkali-Mg_6MnO_8	36.7 [14]	63.2 [14]		840 [14]	CO, CO_2, C_2H_6	
		$Bi_{1.5}Y_{0.3}Sm_{0.2}O_{3-\delta}$	44 [15]	62 [15]		900-1000 [15]	CO, CO_2, C_2H_6	
		alkali earth-La_2O_3	26 [16]	61 [16]		800 [16]	CO, CO_2, C_2H_6	
		Sr-La_2O_3	30 [17]	66 [17]		850 [17]	CO, CO_2, C_2H_6	
Catalytic Partial oxidation	Ethane	Pt	64 [18]	69 [18]	NA	950 [18]	NA	NA
	Ethane, H_2	Pt-Sn	73 [18]	83 [18]	NA	950	NA	NA
Thermal Partial Oxidation	Propane	None	NA	6[19]	NA	900[19]	H_2, CO, CO_2	<1%*
	Ethane	None	NA	7[20]	NA	900[20]	H_2, CO, CO_2	<1%*
	CH_4	None	NA	1.25[21]	NA	900[21]	H_2, CO, CO_2	~1%*
	n-butane	None	NA	10[22]	NA	800[22]	H_2, CO, CO_2	<2%*

* CO_2 represented as percentage value present in the exhaust

2.1 Cracking:

Cracking, also known as the steam cracking process, is widely used in the petrochemical industry to produce ethylene. Steam cracking is a thermal process that involves the breakdown of hydrocarbons such as ethane, propane, naphtha and sometimes gasoline in the presence of steam at high temperatures to produce lighter hydrocarbons, mainly ethylene and propylene. It consumes nearly 8% of the total energy consumed by

the industrial sector globally, making it one of the most energy intensive processes in the chemical industry [2]. It is well known that steam cracking is used for almost all commercial production of ethylene worldwide. The method offers a cost-effective and highly efficient means of producing ethylene. However, the process is also accompanied by tremendous amounts of greenhouse emissions. The high amount of energy per unit of ethylene produced requires critical examination of alternative processes of ethylene production. Below is the fundamental chemical reaction of conversion of ethane to ethylene, during steam cracking.

$$C_2H_6 \xrightarrow{\text{Superheated Steam}} C_2H_4 + H_2 \tag{3}$$
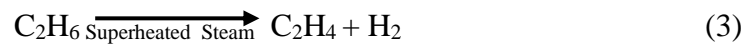
Eq. 3 is an endothermic process and typically consumes 17 to 21 GJ of energy per ton of ethylene production [2]. This energy accounts for preheating of fuel, heating of the superheated steam and pyrolysis. Steam cracking involves 3 main processes namely pyrolysis, compression, and separation. Pyrolysis is carried out in a reactor where preheating of fuel, heating with superheated steam and pyrolysis in absence of a catalyst are sequentially performed with the help of heat exchangers. Compression is only done to generate liquid fuels and involves condensation and fractionation of the oil streams. A separation process follows to collect the desired product through distillation, refrigeration, and extraction.

Although steam cracking results in around 84 percent selectivity of ethylene when ethane is used as fuel, it is highly energy intensive involving high temperatures up to 1100 ^{o}C and critical as well as high energy intensive separation process. Demand for steam is
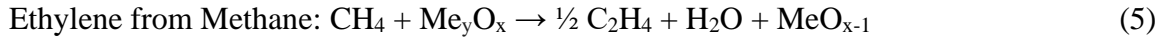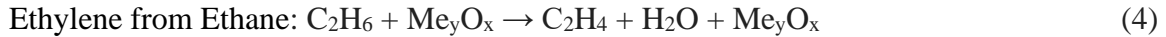
also remarkably high [2]. In addition, this process releases about 1 ton of CO_2 per ton of ethylene production [2]. The ability to mass produce ethylene with such a high selectivity leaves industries with few other options but to incorporate steam cracking. Nevertheless, research is being conducted to develop a methodology which will replace the energy demanding and carbon intensive steam cracking. We shall discuss such endeavors in further sections.

2.2 Chemical Looping

Chemical looping (CL) is a promising substitute to steam cracking for ethylene production. Chemical Looping or catalytic oxidative dehydrogenation (CL-ODH) of ethane is a way to achieve ethylene with tremendous reduction in carbon emission and energy requirements. Ethane ODH can lower energy usage by 30% as compared to steam cracking process [4]. ODH does not need gaseous oxygen which adds to its advantages. Additionally, ODH requires fewer separation units than the conventional steam cracking method which in turn reduces by-products and energy demands [23].

In this method, ethane is selectively oxidized to ethylene and water in an exothermic and catalytic environment. It uses a solid oxygen carrier to enable ethylene generation through selective oxidation and re-oxidation reactions. Oxygen is transported from a solid oxygen carrier to a fuel in a cyclical manner. This eliminates the need for gaseous oxygen, which can reduce energy consumption and emissions. Under these oxidative conditions, dehydrogenation lowers the reaction temperature below 550 °C. Also, Recent studies have reported the use of various oxygen carriers, such as metal oxides and perovskites, for the chemical looping process of ethane.[24]

Below is the reaction for the CL-ODH :

Ethylene from Ethane: $C_2H_6 + Me_yO_x \rightarrow C_2H_4 + H_2O + Me_yO_x$ (4)

Ethylene from Methane: $CH_4 + Me_yO_x \rightarrow \frac{1}{2} C_2H_4 + H_2O + MeO_{x-1}$ (5)

As a general strategy, chemical looping can be used to lower energy consumption and carbon emissions from processes involving total or reactive partial oxidations [24].

Overall, chemical looping is a promising technology that has the potential to improve efficiency and reduce the environmental impact of combustion processes. However, more research is needed to develop and optimize the technology for specific applications.

In chemical looping, the second law thermodynamic efficiency is improved and reflects in terms of reduced exergy losses [5]. A study by Neal L et al., compares performance of steam cracker and ODH reactor and regenerator at 850 °C and 950 °C, respectively. The chemical looping ODH system outperforms in terms of decrease in CO_2 emission which are about 78% as well as exergy reduction up to 0.9 GJ/ton exergy compared with steam cracking [5]. When compared to steam cracking energy demands also show a significant reduction of 80%. In addition to that, the study also shows a high ethylene selectivity of 85%. These energy savings are majorly at the reactor level which in turn helps further processing on the outlet stream. Per-pass ethane conversion is also better than achieved in steam cracking.

Although, the above study reports comparative ethylene yields CL-ODH needs to be investigated more for it to be considered as a replacement of steam cracking. Even though the reaction and downstream separation reduces the complexity, incorporation of

multiple reactors can lead to higher capital and operating cost. The involvement of oxygen carrier is crucial for the process which can add up to its complexity.

2.3 Oxidative coupling of Methane

In 1990 Amenomiya et al. [25] reported difficulties in direct conversion of methane to heavier molecules due to thermodynamic disadvantages and high stability of the methane molecule. They proposed a new way of conversion by introducing methane to an oxidant to gain a thermodynamic advantage. The reaction to produce ethane by oxidizing methane is given below,

$$2\ CH_4 + ½\ O_2 = C_2H_6 + H_2O \qquad\qquad \text{….(6)}$$
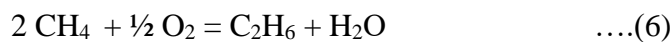
In addition, the same study indicates that theoretically oxidation of such kind can also produce higher hydrocarbons, while in practice only conversion until C_2 hydrocarbons is possible. The condensation presented in the above reaction is termed as oxidative coupling of methane. This reaction is exothermic and releases 121.6 kJ/mol [6]. The study of Wang et al. [6] mentions oxidative coupling reaction to extract ethylene from methane. This reaction (Eq. 7) is exothermic as well, releasing 152.5 kJ/mol of energy.

$$2\ CH_4 + O_2 = C_2H_4 + 2\ H_2O \qquad\qquad (7)$$

Wang et al. also promotes the use of suitable catalyst in this reaction to enable formation of C_2 hydrocarbons and to reduce occurrences of combustion in the reactor. Detailed analysis of ethylene selectivity, conversion rates and byproducts achieved from various catalysts are presented in Table 1.

Alkathiri et al. [26] gives us a generalized step by step process of achieving ethylene through OCM process with methane as feed fuel. Streams of methane and oxygen are supplied directly into the reactor which has an operating temperature of 800 – 900 °C. The ratio of the fuel and oxidizer determines the selectivity and conversion. High fuel/oxygen ratio increases selectivity but at the cost of conversion. While oxidizing this feed some by products are naturally formed such as CO, CO_2, C_2H_6, H_2 and H_2O. After this a rigorous separation process follows to purify the outlet stream of the reaction chamber. Water is removed first as it can easily be condensed. OCM produces equal amounts of ethylene and carbon dioxide per ton of methane [7]. In general, absorption in liquid form by means of a solvent is employed for extraction of CO_2. Finally, ethane and ethylene are separated from lighter gases. Ethane and ethylene are further separated from each other. Methane is also taken out from products of combustion and recycled back into the reaction chamber or used as fuel for relevant usage.

Khojasteh et al. [27] undertakes a study involving 6 sub sections in the OCM process to co-produce ethylene and electricity with the aim of achieving negligible carbon dioxide emissions. Here as well they mention the most important property affecting the selectivity and conversion is the ratio of methane to oxygen at the inlet. It is also reported that it is not worth recycling the unburnt methane back to reactor because of poor selectivity. This simulation-based study indicates slightly profitable process selection and remarkable reduction in carbon dioxide emissions.

A particular study by Fini et al. [28] tries to evaluate the performance of OCM as an industrialized process by performing simulation analysis assuming one billion pounds output of ethylene per year, examination of various industrial factors such as cost and its

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dependency, and evaluation of environmental effects. The report concludes OCM to be a marginally profitable method of producing ethylene with 6.8% return on investment. It is observed that in terms of investment and capital, OCM is like current ethylene plants, operating on steam cracking method, however, withdraws less profit.

Although considered a promising alternative for steam cracking for over 3 decades, the OCM method has a long way to go until it finds its place in commercial ethylene production units. Ethylene production through OCM is very challenging, especially at large scale where industry can see profit. The main reason is that ethylene and methane tend to oxidize at the temperatures involved in the reaction, reducing selectivity ultimately. Higher selectivity is constrained due to thermodynamic limitations and it's crucial for successful OCM adaptation by ethylene producers. A 20% ethylene yield can be considered as the upper limit for most advanced OCM reactors and that's not attractive enough for commercial manufacturing of ethylene.[29]

The problems encountered in alternative approaches to steam cracking make the search for alternative technologies have two primary goals 1) either increase selectivity in OCM or 2) use a completely different phenomenon which can lead to ethylene generation.

2.4 Other evolving technologies

2.4.1 Partial oxidation of methane

A study conducted by Luo et al. [30] shows the partial oxidation of methane provides the necessary heat for pyrolysis of remaining methane. It assumed that the oxidation reaction is much faster than the pyrolysis reaction and that pyrolysis is independent of the oxidation reaction. There is another method called partially decoupled

oxidation of ethane to produce ethylene and acetylene. In this process cheap gases are combusted and used as heat carrier. Ethane is further added in this heat carrier, and it goes under pyrolysis at high temperature. As high as 42% of ethylene plus acetylene yield were reported in this simulation-based study [31].

2.4.2 Partial oxidation of ethane

Another study by Bodke et al. [18] examines partial oxidation of ethane, or in other terms oxidative dehydrogenation of ethane, with use of a catalyst. It is basically catalytic partial oxidation by adding large amounts of hydrogen in the reactor mixture at high temperature. Hydrogen might react with oxygen explosively at these temperatures but with the use of a suitable catalyst there is no evidence of such reaction. Olefin selectivity higher than 85% was observed with appropriate amount of H_2. The amount of hydrogen at the outlet is more than what is being fed, and therefore the initial feed system is hydrogen sustainable.

2.5 Thermal Partial Oxidation

Thermal partial oxidation is a process that utilizes high temperatures and oxygen to break down organic compounds into simpler molecules. Micro-combustion takes place in small tubes in a non-catalytic environment utilizing heat recirculation. This process has many potential applications, including the treatment of wastewater and the production of hydrogen gas [32]. The use of micro-combustion is also investigated comprehensively for cogeneration of power and heat [19].

A 2019 study conducted by Milcarek et al. explored propane micro-combustion for flame assisted fuel cells power and heat co-generation. The study explored fuel-rich mixtures as high as equivalence ratios of 5.5 and a wall temperature ranging from 750 to 900 °C. The study suggests high utilization of fuel up to 50% at an equivalence ratio of 4.6 and demonstrates the method can be used as fuel reformer for hydrocarbons to syngas. It also goes on to state that formation of syngas is sensitive to the wall temperature and denotes the importance of changing flow rate and equivalence ratio. Additionally, Significant amount of ethylene, methane and hydrogen were observed in this investigation which makes one wonder upon simultaneous use of this method with hydrocarbons for heat generation as well as production of important industrial hydrocarbon fractions such as ethylene and other gases like hydrogen. Another important feature to be considered is low concentrations of carbon dioxide were observed.

A subsequent study by the same authors [20] examined the effects of micro combustion on ethane reformation into syngas at equivalence ratios from 1 to 5 and wall temperatures of 800, 900 and 1000 °C along with varying flow rate of 10 to 250 mL/min. Once more, a strong link between maximum wall temperature, total flow rate, equivalence ratio and micro combustion reforming was asserted. It has been noted that higher temperature and higher flow rate result in substantial increase in hydrogen concentration. Furthermore, as high as 7% of ethylene formation can be observed in this literature.

Afterwards, Skabelund et al. conducted similar research on *n*-butane[22] and natural gas and methane [21]. Both the studies present micro-scale partial oxidation as a promising method to reform hydrocarbons with fuel-rich air mixtures. Higher flow rate resulted in higher reactivity for methane and natural gas. Also, lowering the flow rate improved

thermal partial oxidation reaction at lower temperature. The temperature dependency of reaction is consistent in these studies as well. A maximum ethylene fraction of 10% was recorded for *n*-butane at an equivalence ratio of 5 and wall temperature of 800 °C.

Given the above information, micro-scale thermal partial oxidation appears to be an interesting methodology for ethylene generation owing to a few of the features. Foremost the simplicity of the reactors and lack of complicated catalysts, which were mandatory in the previously studied methods. Another critical aspect is the large reduction in CO_2 emissions observed, indicating the method can be adapted at large scale. It is anticipated that there is no need for a large external energy source to the reactor as the wall temperatures can be maintained electrically at lower cost.

2.5.1 Thermal Partial Oxidation Reaction Mechanism:

The stochiometric global reaction for propane takes the following form,

$$C_3H_8 \;+\; 5\,(\,O_2 + 3.76\,N_2\,) \;\;=\;\; 3\,CO_2 \;+\; 4\,H_2O \tag{8}$$
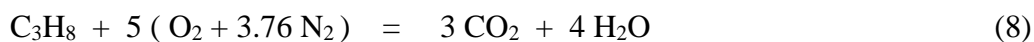
However, this is the overall balanced chemical equation of combustion which goes through various stages, or elementary reactions, involving breaking and formation of chemical bonds giving rise to different molecules and radicals at each stage. In the first few steps the single covalent bond of carbon present in alkanes is broken at high temperature and heavier hydrocarbons are split into smaller hydrocarbons. Also, the fuel molecule is broken down by oxygen and hydrogen atoms to partially form alkenes and hydrogen.

Step 1: The heavier propane molecule is split as one of three single covalent bonds (C-C) of carbon is broken (Eq 9)

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$$C_3H_8 + M \rightarrow C_2H_5 + CH_3 + M \tag{9}$$

Step 2: The radicals are further stripped off a hydrogen molecule to form alkenes and hydrogen,

$$C_2H_5 + M \rightarrow C_2H_4 + H + M \tag{10}$$

This is the stage where ethylene shows up in the oxidation of propane. In the thermal partial oxidation, the residence time of fuel in the reactor is small due to the high flow rate of air fuel mixture which does not allow the fuel to go through the further stages of combustion which results in the high percentage of hydrogen, methane and ethylene in the exhaust and less carbon dioxide as well. Rich fuel mixture keeps the hydrocarbons away from oxygen, and helps in partial combustion.

CHAPTER 3

METHODS

3.1 Quartz Tubes:

The quartz tube serves as reactor chamber in this study. The reaction of air and fuel is supposed to take place in a no catalyst environment. The nature of quartz tubes makes them a good candidate for such applications. The quartz does not have any effect on the hydrocarbon combustion process and the transparent tube allows observation of the propagation flames as well as soot formation. The size of the tubes, especially the diameter, has an important role in the experiments conducted. The diameter affects the heat transfer to the fuel/oxidizer and the residence time of the fuel air mixture which in turn impacts the completeness of the combustion reaction. Here we are trying to study the effect of micro-scale (<2 mm) partial oxidation and smaller tube diameters are desirable. Previous studies mentioned in section 2.5 have been conducted with a 3.6 mm diameter tube. Hence, we have selected smaller tubes of 1 mm, 2 mm and 3 mm diameter. To achieve a uniform current and temperature distribution we tried to maintain nearly equal radial thickness of the tubes from the available quartz tube dimensions. The tubes are 30 mm in length each with 1 mm, 2 mm and 3 mm inner diameter and 5 mm, 6 mm and 8 mm outer diameter, respectively. All the tubes are joined with 6.35 mm outer diameter pieces of quartz on both the ends to accommodate the inlet and outlet tubes and clutches for the stands. This attachment is done by one of the glass labs at ASU. Quartz tube of maximum diameter of 1 mm is shown in Figure 1.
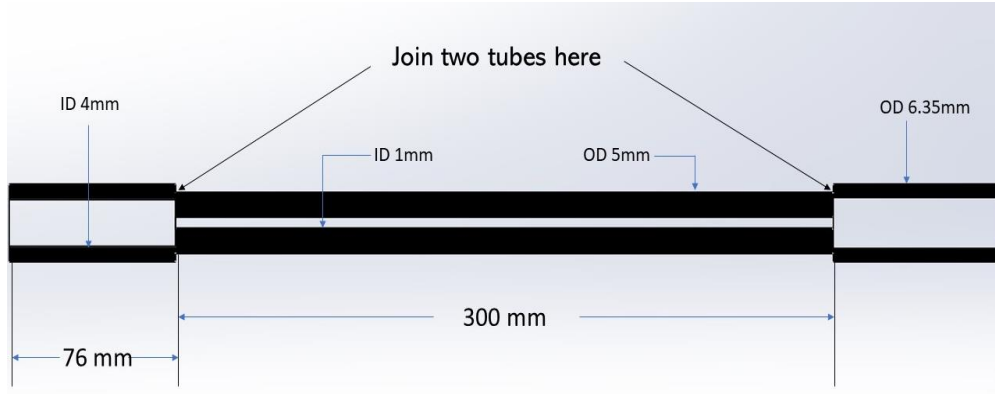
Figure 1: Schematic of quarts tube reactor 1mm inner diameter
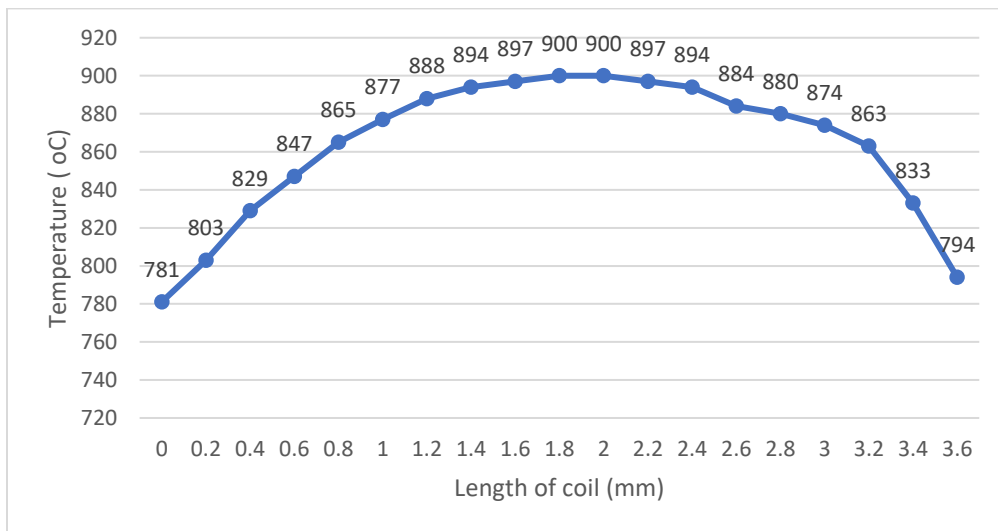
3.2 Temperature Mapping:

It is very important to ensure the consistency of the temperature inside the reactor at all stages of the experiment. Temperature is one of the variables which affects the outcome of the partial oxidation process as we have seen in section 2.5. We cannot have a thermocouple inside the reactor all the time, hence, mapping is necessary. It is done by regulating the voltage on a thermal resistance heater and measuring the inside temperature across the considerable length of the reactor using a thermocouple. The tube was heated using electric resistance coils which cover about 10 cm length of the coil, operating with voltage control. The voltage is regulated continuously to achieve a desired temperature while the inside of the tube is monitored with a thermocouple. The thermocouple was placed along the inside of the quartz tube reactor in direct contact with the bottom and then moved across the length of the heated section to check regularity of temperature. The maximum temperature is attained at the center point of the coil. A sufficient time was given

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to reach steady state before recording the voltage and current ratings at the given temperature. After that, the thermocouple was moved from one end of the coil to the other with a gradual increment of 2-5 mm while the temperature was recorded at every step. A gradual increase in the temperature was noted as we move from endpoint of coil to the center point and as we approach the center point, we can find the stabilization of desired temperature for a brief length. This part of the reactor can be considered as the reaction point in the reactor. It is critical to have this reaction length consistent to maintain consistency across all the tests. To maintain such consistency noting the voltage rating and time required to attain the desired temperature at that voltage rating is important. As we are maintaining the same thickness on all tubes, the above process needs to be done on one of the tubes and then verification on other tubes at similar voltage must be conducted.

In the present study we are testing with only two temperature points, 800 °C and 900 °C. Below are the graphs of temperature mapping along the reactor length at both 800 °C and 900 °C on the 3 mm internal diameter quartz tube. 800 °C as achieved at 13.75 V and 900 °C was achieved at 15.80 V. When similar mapping is done on 1 mm internal diameter tube, 800 °C is achieved at 13.75 V and 900 °C is achieved at 14.95 V.
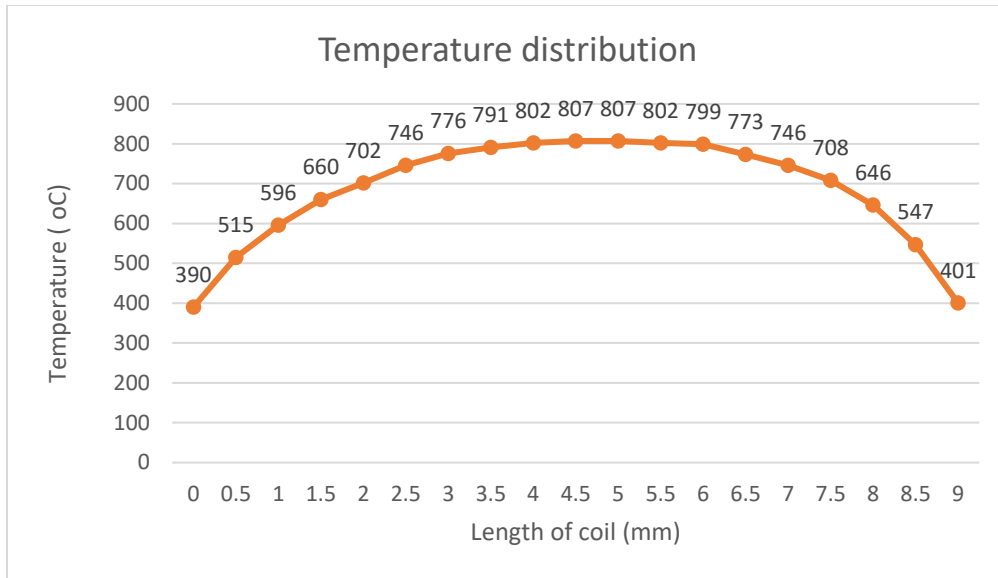
A)

B)

Figure 2: Temperature mapping for 3mm tube A) at 800 °C and 13.75 V. B) at 900 °C and 15.95 V.

3.3 Flow Control:

Mass flow controllers were used to regulate the flow of fuel and air into the reactor. The equivalence ratio impacts the outcome of oxidation process immensely as we have seen in section 2.5, hence various flow meters were needed to ensure the accuracy of the results at various equivalence ratios. A flowrate of as low as 0.5 sccm was applied with accuracy of ± 5%. In the present study, we tried to establish the effect of equivalence ratio on the generation of ethylene as well as other hydrocarbons through partial oxidation. Equivalence ratio is a measure of the fuel/air ratio of the mixture compared to the fuel/air ratio required for stoichiometric reaction. An equivalence of 1 represents the stoichiometric reaction ratio of the air fuel mass. Below an equivalence ratio of 1 gives leaner mixture whereas equivalence ratio of more than 1 gives richer mixture. Equivalence ratios ranging from 1 to 6 were used in the present study. In addition, the relative velocities are kept constant for tubes of different diameters. The reason for this is the residence time depends more on the velocity of moving fluid rather than the flow rate. The total flow rates are adjusted according to the relative velocity with changing diameter of the reactor tube. The relative velocities are calculated by simple continuity equation where product of cross-sectional area and velocity is constant. Here we keep the velocity constant and calculate the flow rate for varying diameter. The flow rate of 10 to 100 sccm are accounted for 3 mm tube whereas the relative flow rates for 1 mm tube are calculated according to the above discussion. The equivalence ratios are kept the same even though the total flow rates are different. The respective amount of flow rate for the range of equivalence ratios for different flow rates with respect to diameter is presented in the following tables 2 and 3.

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Table 1:
Composition of fuel and air for propane for 3 mm tube at varying
equivalence ratio at total flow rate of 25 sccm

equivalence ratio	Fuel	Air
1	1.00	23.9
2	1.93	23.0
3	2.79	22.2
4	3.59	21.4
5	4.34	20.6
6	5.03	19.9

Table 3:
Composition of fuel and air for propane for 1 mm tube at varying
equivalence ratio at total flow rate of 2.77 sccm

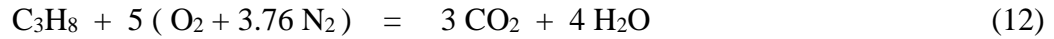| **equivalence ratio**	Fuel	Air
1	0.11	2.66
2	0.21	2.56
3	0.31	2.46
4	0.39	2.37
5	0.48	2.29
6	0.55	2.21

Equivalence ratios are calculated from the formula given below,

$$Equivalence\ Ratio\ (\emptyset) = \frac{n_{fuel}/n_{air}}{n^s_{fuel}/n^s_{air}} \tag{11}$$

Where, n = *number of moles,*

S = *stoichiometric ratio*

Deriving a generalized solution to find ratio of fuel and air flowrates for propane at different equivalence ratios can be completed as follows. First, stoichiometric reaction for Propane,

$$C_3H_8 + 5(O_2 + 3.76\ N_2) = 3\ CO_2 + 4\ H_2O \tag{12}$$

1 mole of Propane needs 5 x (1+3.76) moles of air for stoichiometric combustion.

Stoichiometric ratio = 1 / 5 x 4.76 = 0.042017 (13)

Now we can find air fuel ratio at any equivalence ratio for propane using relation in Eq. (9)

$$n_{fuel}/n_{air} = \text{Equivalence Ratio } (\emptyset) \times \text{Stochiometric Ratio}$$

$$n_{fuel}/n_{air} = \text{Equivalence Ratio } (\emptyset) \times 0.042017$$

$$n_{fuel} = [\text{Equivalence Ratio } (\emptyset) \times 0.042017] * n_{air} \tag{14}$$

Also,

$$Total\ Flow\ Rate = n_{fuel} + n_{air} \tag{15}$$

From (12) and (13) we can calculate exact flow rates of air and fuel for any given equivalence ratio for propane combustion. These calculations can be used for any gas as well if stoichiometric relations for that gas are used.

3.4 Gas Chromatograph:

We can determine the chemical composition of the partial oxidation exhaust coming out of the reactor with the help of a gas chromatograph (GC). Gas chromatography is used to separate and detect organic and inorganic chemical compounds in a mixture. For organic compounds, the gas chromatograph utilized in the lab can detect up to C6

hydrocarbons. We observed the presence of 7 hydrocarbon compounds in the following study: methane, ethane, ethylene, propane, cyclopropane, iso-butane, and *n*-butane. The gas chromatograph does not explicitly measure the number of hydrocarbons present in the mixture, but in the case of the flame-ionization detector it detects the ions formed during the combustion process of hydrocarbons in a hydrogen flame. These ions are collected on an electrode and its current is measured. Finally, the gas chromatograph delivers a graph of voltage against time. The peaks on the graph represent the hydrocarbon compounds in a timely order where the retention time determines which compound is exiting the gas chromatograph. We can calculate the area under these curves using tools developed in the gas chromatograph software. A special calibration is needed as these measured areas are directly proportional to the compound concentration in the gas stream. The linear proportionality of area and gas concentration of respective hydrocarbons for the gas chromatograph used in this study is given in table 4 after being determined through calibration.

Table 4:
Compounds and their linear relation with area on GC

Compound	Linear relation with Area(A) on GC
Methane	0.000000581253 x A + 0.603632
Ethane	0.000000319444 x A + 0.0440788
Ethylene	0.000000316934 x A + 0.0183542
Propane	0.000000214804 x A - 0.016749

3.5 Experimental Setup:

The schematic diagram of experimental set up is as shown in Figure 3. The gas cylinder is attached to a pressure regulator to maintain the feed fuel at constant pressure. Air is supplied either via a cylinder or the zero-grade air generator which gets the air supply from a compressor. The air pipe is also fitted with another mass flow controller. Both the lines are then joined to form the air fuel mixture and this mixture is then fed to the reactor that is a quartz tube. The lines in the inlet section are of copper tubing material. Before the reactor a flame arrester is placed to prevent any back propagation of flame towards the feed stock. The reactor is coiled with a thermal resistance heater. The coil is covered with glass wool insulation. The coil is around 10 cm long and is placed near one third length of the reactor from the end of the gas inlet. The output of the reactor is joined to a gas chromatograph using copper tubing. Copper tubing is used in the output section to handle the hot temperature exhaust. The reactor is held at a certain height using the lab stands and is placed inside a fire safe chamber.
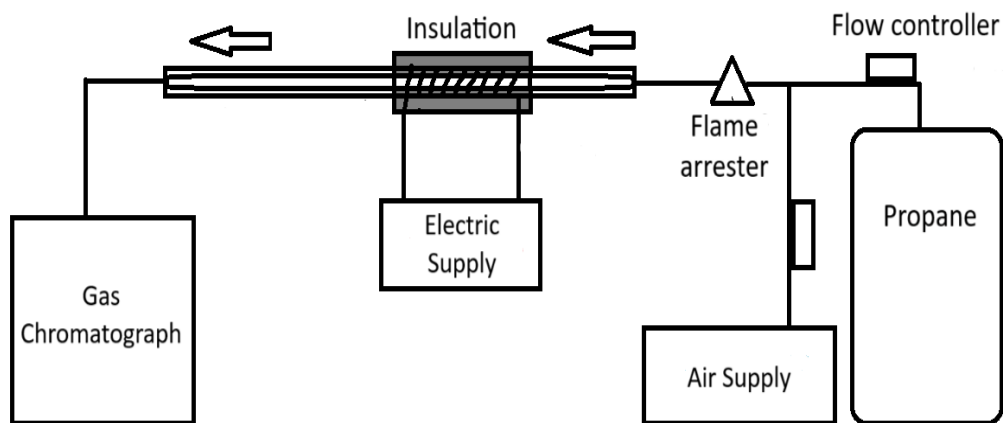

Figure 3: Schematic diagram of experimental setup

CHAPTER 4

RESULTS AND DISCUSSION

The results section is divided into several subsections which deal with different

variables that impact the amount of ethylene generated in the micro-flow reactor. There

can be numerous such variables and some of them are interdependent. For this research

we identified 4 of them of utmost importance for two reasons. First and foremost, they

have a direct impact on the ethylene concentration which we can guess intuitively and

second these variables are easy to measure and control. The rationale of these variable's

importance is provided in the previous section. The tables and graphs being discussed in

this section show the values of each gas component from Table 4 of the methods section.

For some important points the experiment was run several times. Due to the nature of the

experiment, it doesn't reproduce the values with greater accuracy. Therefore, to come to

conclusion in shorter period, statistical study of averages and error bars is included in

sections where we have multiple data points. The Five major factors under discussions

and their levels are shown in Table 5.

Table 5: Variables discussed and their range

Factors	Level
Diameter of reactor	1 mm and 3 mm
Temperature	800 and 900 °C
Flow rate	10, 25, 50, 75 and 100 sccm
Equivalence ratio	3, 4, 5 and 6

To analyze the effect of each we will set three out of four at a fixed value and keep modifying the other variable. The results from the gas chromatograph shall reflect the changes.

4.1 Analyzing the Impact of the Diameter of Reactor on Ethylene Production:

The temperature was fixed to $800\ ^{\circ}C$ and flow rate was set to 75 sccm for the 3 mm reactor with propane used as fuel. For the 1 mm reactor the flow rate was 8.33 sccm which is the equivalent of 75 sccm for 3 mm tube as discussed in section 3.3. For an equivalence ratio of 2 and below with the 1 mm reactor, the amount of fuel was not sufficient to trigger any significant reaction. GC results show no sign of any other by-products but propane, which is feed fuel. As the equivalence ratios were increased the ethylene starts to show up for the 3 mm tube and steadily increases thereafter. On the other hand, ethylene concentrations are present but on lower side for 1 and 2 equivalence ratios in 3 mm tube. We can notice a sudden increase at equivalence ratio of 3 and again steady increase thereafter.

It is evident from the Figure 4, for steady flow with a reactor wall temperature of $800\ ^{\circ}C$ and flowrate of 75 sccm, the diameter of the reactor plays a crucial role. There is consistent and stark difference in the ethylene concentrations in both the results at each data point. For rich mixtures at an equivalence ratio of 5 and 6 the difference is as high as 6.5 %.

The resulting maximum concentrations in the bigger tube can be accounted for by various factors. By intuition, we can say lower diameter of reactor helps in maximum reaction because it would help increase the residence time of fuel inside the reactor.

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However, the flow velocity is kept constant in this experiment which turns down the intuitive assumption. Also, the lower temperature not favoring oxidation can also be the reason for low ethylene concentrations in small tubes. It is not possible to arrive to conclusion from this data and above rationale.
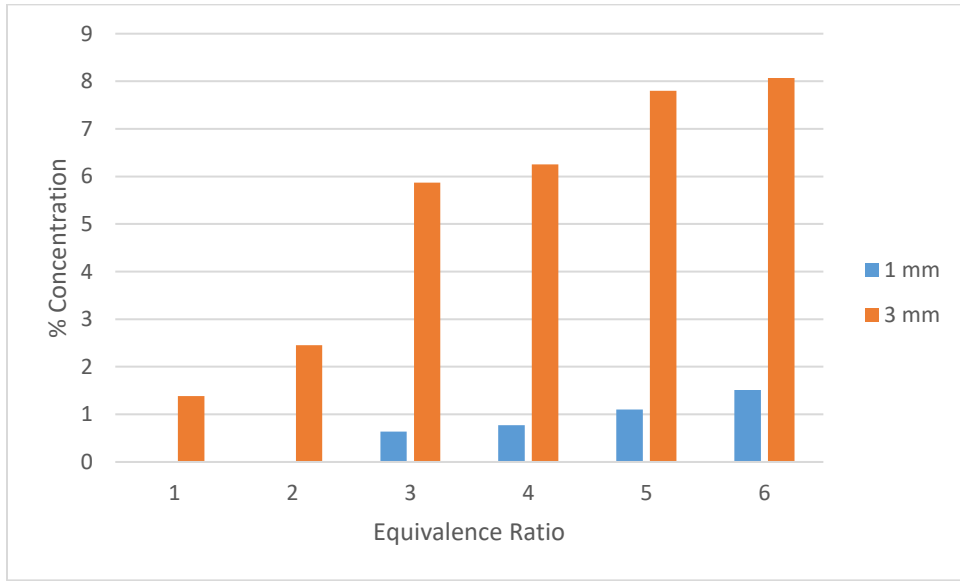

Figure 4: Mean ethylene concentration at temperature - 800 °C and flow rate - 75ccm

Figure 5 further analyzes the effect of diameter with varying temperature. This time an equivalence ratio of 6 is kept constant as we found maximum difference in ethylene and the peak of ethylene for both the tubes at $\Phi = 6$. Also, the results were taken at flow rate of 75 sccm which was the case in previous discussion. Results at 900 °C were compared to 800 °C. We can safely say that a wall temperature of 800 °C is sufficiently low as it generates little ethylene with the 1 mm reactor. However, ethylene concentrations as high as 10% were recorded at 900 °C in the smaller tube, approximately seven times higher than what observed at 800 °C. In comparison, there was not much difference in both data points

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in the larger diameter reactor. The important thing to note is that concentration of ethylene is higher in the smaller tube as compared to the bigger one at 900 °C. With an increase in temperature the smaller reactor had more efficient conversion to ethylene although we cannot comment if this is the peak of the reaction as we did not test temperature more than 900 °C.
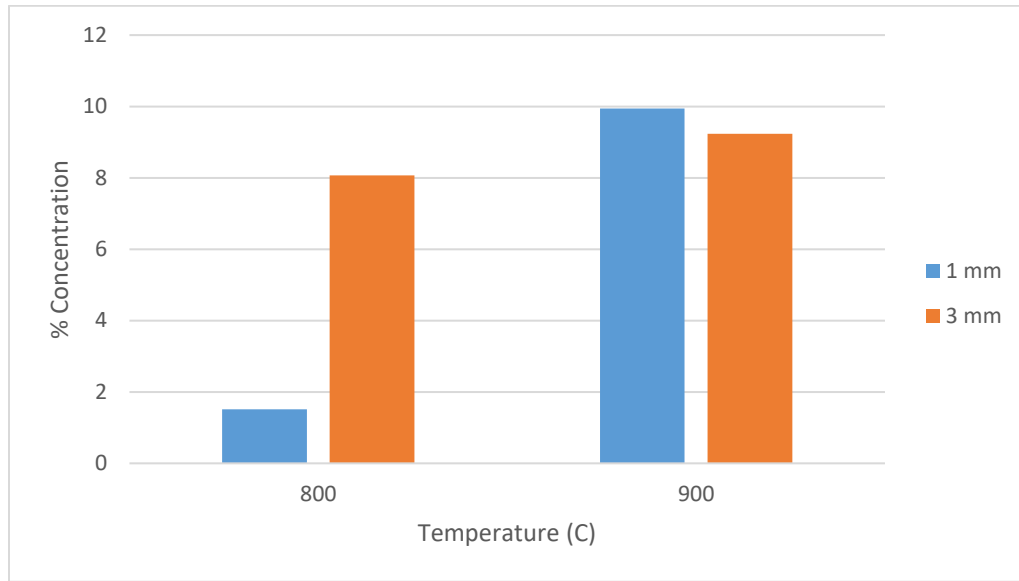

Figure 5: Mean ethylene concentration at Equivalence ratio - 6 and Flow rate - 75ccm

We also studied the effect of changing the total flow rate on the performance of both the tubes. The comparative analysis is presented in figure 6. For this study we kept the temperature at 900 °C as maximum ethylene was recorded at this temperature. Also, for the same reason the equivalence ration is kept at 6. The change in flow rate has contrasting effects on the different sized reactors. For the smaller reactor, the increase in flow rate shows an increase in ethylene concentration whereas, for the other reactor

ethylene percentage reduced with higher flow rate. These differences are minor for the 1 mm tube in comparison to the 3 mm tube. For 3 mm tube the ethylene concentration decreased by one third. Overall, we can say increased flow rate appears to be beneficial for this smaller tube, decreasing the residence time and thus increasing the byproducts. Higher flow rate, however, is not to the advantage for this larger tube.
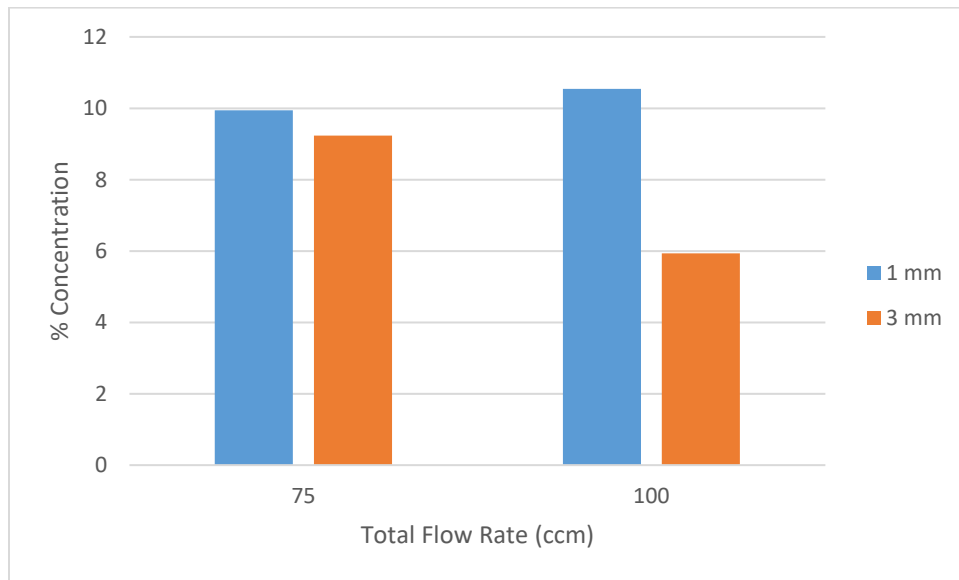

Figure 6: Mean ethylene concentration at temperature - 900 ^{0}C and equivalence ratio - 6

If we are just looking at maximizing the ethylene production, from the result we have seen till now, lower reactor diameter, higher temperature, higher flow rate and higher equivalence ratio are all important factors. The maximum ethylene concentration was recorded to be 10.54% at 900 °C, Ø 6, flow rate of 100 sccm when the 1 mm reactor was used.

While we came to an understanding of what is desirable in terms of the diameter of the reactor tube, the consequences of the other variables cannot be concluded from the above graphs. There might be other interdependence between the factors and therefore each of the three variables are separately studied in the following sections.

4.2 Analyzing the Impact of Temperature on Ethylene Production:

From the results of the previous section, the importance of temperature can be determined. In this section we shall further study the impact of temperature on both the tubes in detail. A total flow rate of 75 sccm and $\emptyset = 5$ and 6 were chosen for this study. As we know, lower flowrates and equivalence ratios do not produce as much ethylene and can be neglected.

First, we shall look at the results of the 1 mm tube. Equivalence ratio is kept constant at 6. We did not get multiple data points for this setting due to time constraints. Nevertheless, we can analyze the concentration of different gases in the outgoing exhaust stream. Figure 7 shows the difference in exhaust composition at 800 °C and 900 °C. All experimental results consistently showed the concentration of ethane is small enough that it is generally negligible compared to the other species.

Propane, the feed fuel, reduced drastically when the reactor wall temperature increased from 800 °C to 900 °C, indicating the occurrence of improved partial oxidation reactions. The decrease indicates that around 75% more propane took part in partial micro-combustion and was converted into something else. A similar trend shows up in both the methane and ethylene concentration which is absolute increase of 6% and 8%, respectively. An important point to notice is that at 900 °C propane percentage is lower than both

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methane and ethylene by a margin of at least 4% confirming greater propane reaction at higher temperature in the 1 mm reactor. Higher temperature is indeed more suitable for the smaller reactor tube.
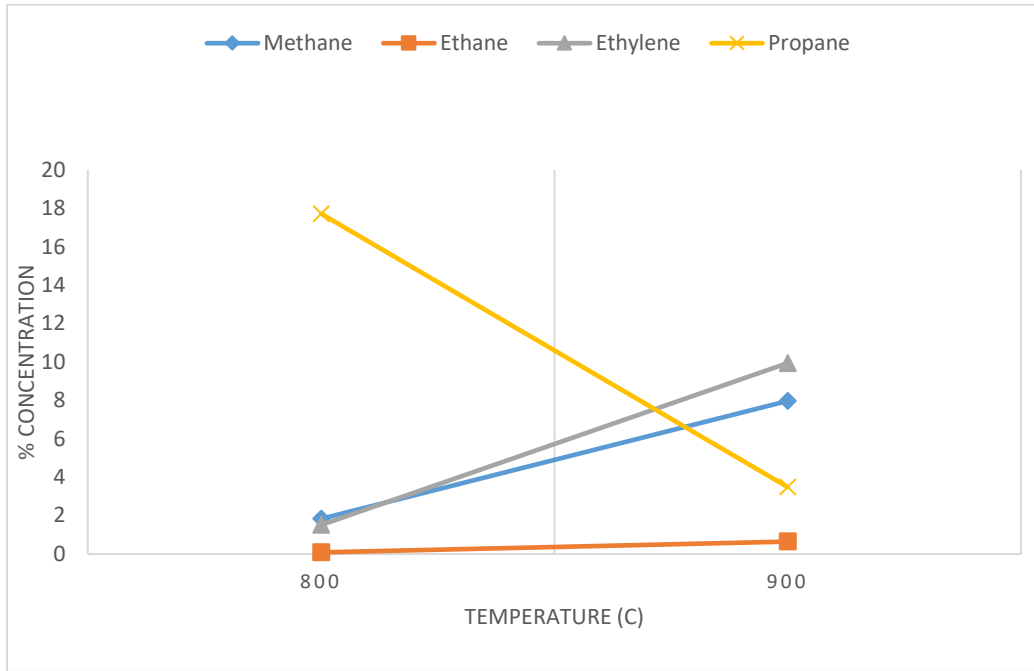

Figure 7: Mean ethylene concentration for 1mm tube at flow rate - 75ccm equivalence ratio - 6

The 3 mm reactor was studied with propane/air equivalence ratios of 5 and 6. We shall first explore an equivalence ratio of 5. Figure 8 shows the scatter plot of compositions at 800 °C and 900 °C. As shown, there is multiple test data for the reactor operating with a wall temperature of 800 °C, with a standard deviation of 2.5, 2 and 3, respectively, for methane, ethylene and propane. A maximum ethylene concentration of 10.53% was recorded in one experiment while the lowest was 6.1%. Methane and ethylene show similar

tendencies (increasing or decreasing together) in each data set while propane shows the opposite trend.
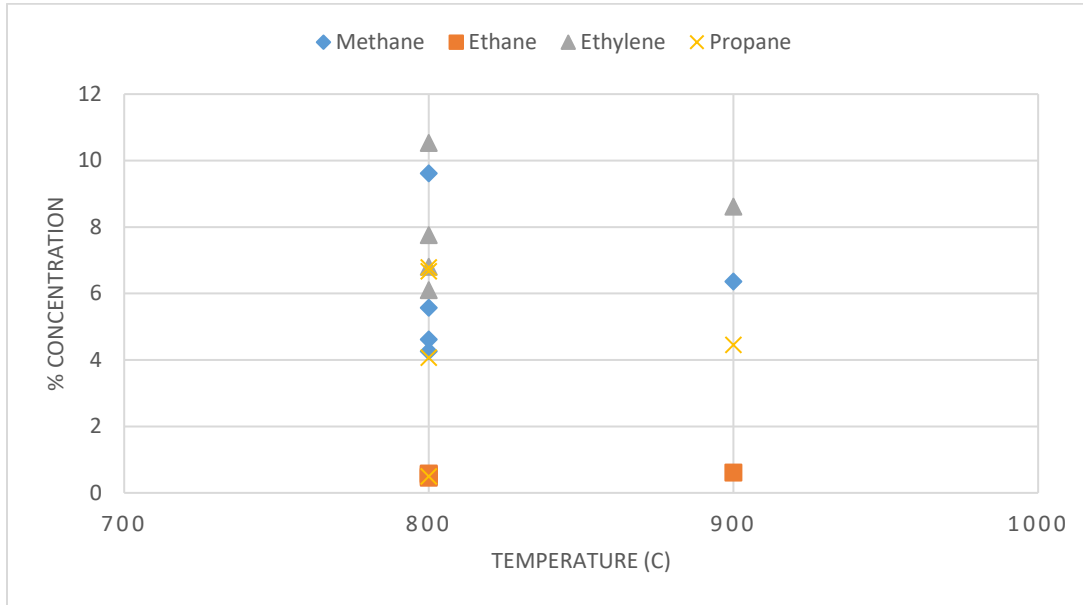

Figure 8: Scatter plot of species concentrations for 3mm tube at flow rate -6, Equivalence ratio - 5

When the averages of all the points are plotted the results are shown in figure 9, and not much difference is noticed as the wall temperature changes. A careful examination, however, demonstrates a slight increase in methane and ethylene with the increase in temperature. Figure 9 has the uncertainty of 0.48 for the data sets at 800 °C. We do not have multiple results for 900 °C but the difference of ethylene ratio is more than the standard error. Propane concentration, as predicted, drops with rise in temperature. Propane concentration at both 800 °C and 900 °C remains low compared to methane and ethylene concentrations. This result signifies that for the 3mm tube with propane micro-combustion

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operating at an equivalence ratio of 5, temperature in the range of 800-900 °C does not have much of an influence.
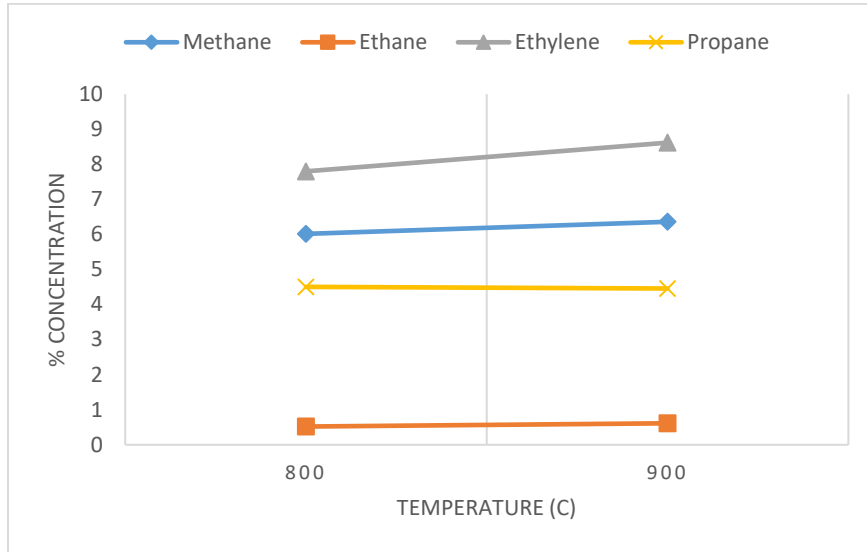

Figure 9: Mean species concentrations for 3mm tube at flow rate - 75sccm and Ø - 5
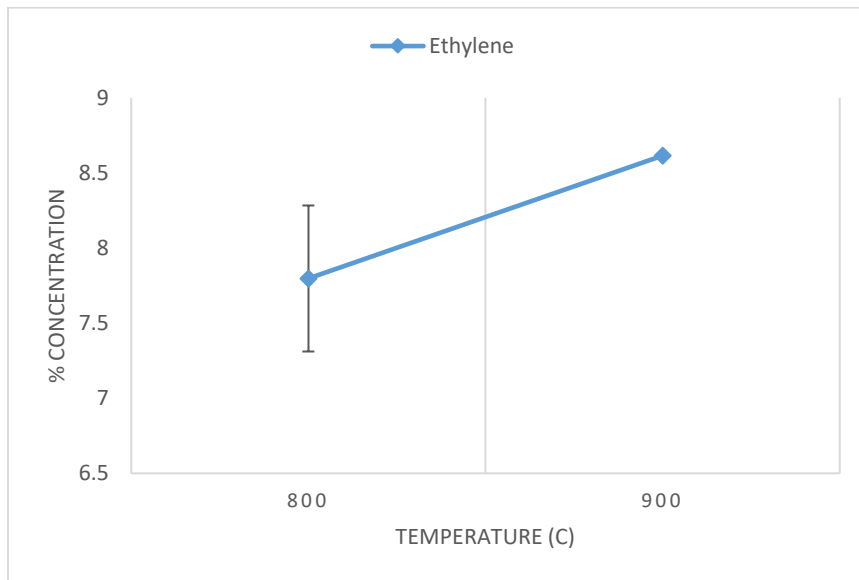

Figure 10: Mean ethylene concentration with error bar for 3mm tube, flow rate – 75sccm, Ø - 5

Similar results can be obtained from the micro reactor for propane/air reactions at an equivalence ratio of 6. In this case, we have multiple data points for both the temperature values. The scatter plot in Figure 11 is like the results obtained for the micro-reactor operating at Ø=5. One remarkable thing to notice is the maximum ethylene concentration observed at 900 °C is almost 11%. All the data sets show a large concentration of ethylene with the lowest being 6.64%. Propane has a higher concentration than ethylene at a few points, but the difference is not noticeable. The standard deviation of the scatter for ethylene data is 0.92 and 2.17 for 800 °C and 900 °C, respectively.
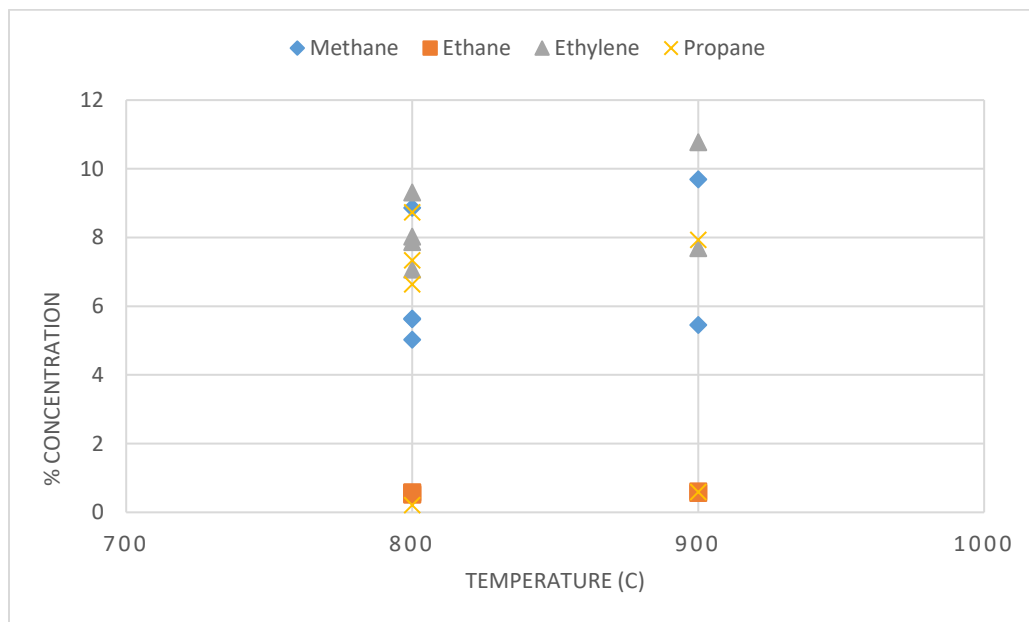

Figure 11: Scatter plot of species concentrations for 3mm tube, flow rate – 75 sccm, Ø - 6

In Figure 12, the results show a similar trend to those observed at an equivalence ratio of 5 when the averages are plotted for the data sets. There is not much distinction in

the concentration of gases with changing temperature in the 3 mm reactor. Ethylene and methane show increasing trends while propane decreases as temperature rises. At 900 °C, however, ethylene and methane are significantly higher than that of propane indicating additional reaction.
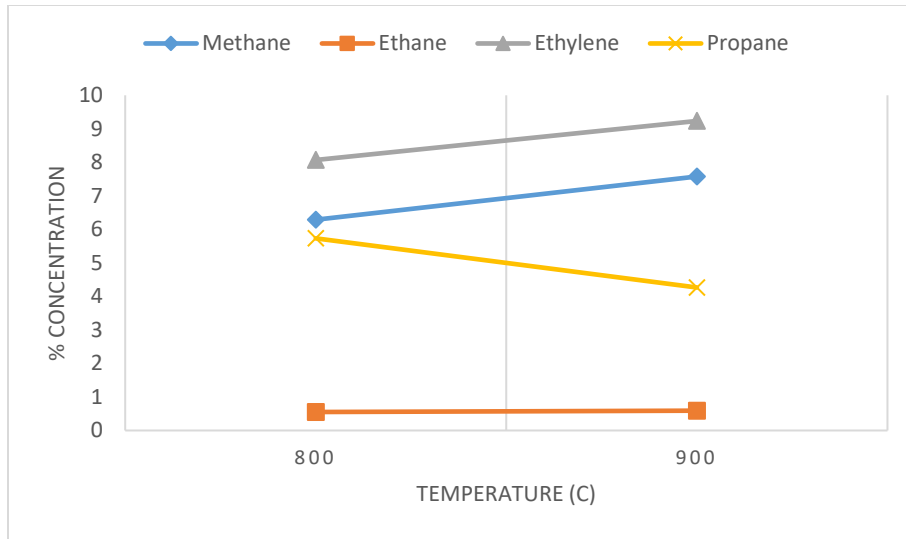

Figure 12: Mean ethylene concentration for 3mm tube, flow rate - 75sccm, ∅ - 6

The examination of error bars Figure 13 makes one doubtful of the trends observed in the above data sets. More data points are needed at 900 °C to reduce the overall uncertainty. However, the results until now make a strong case for the higher reaction and higher ethylene concentrations occurring at higher temperature.
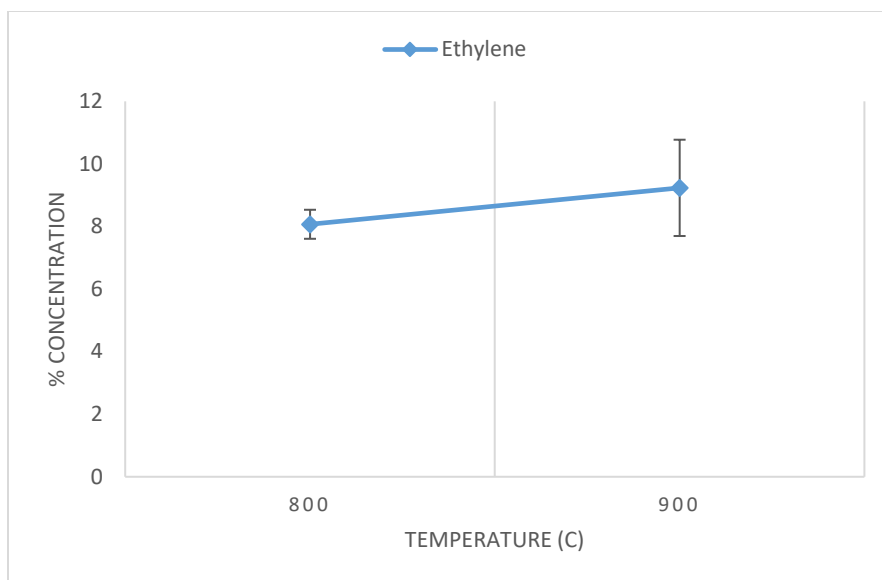
Figure 13: Mean ethylene concentration with error bar for 3mm tube, flow rate - 75sccm, Ø - 6

4.3 Analyzing the Impact of Flow Rate on Ethylene Production:

We shall now analyze the impact of changing the total flowrate. Figure 6 in section 4.1 of reactor diameter presents an uncertain picture of the effect of altering flow rate. Increasing flow rate seemed to be desirable in the case of the 1 mm tube whereas for the 3 mm reactor an increase in the flow rate lowered the ethylene concentration. Thus, probing into the consequences of changing flow rate is critical.

We experimented with different flow rates at 900 °C for both reactors with the equivalence ratio of 6 kept constant. We chose the intervals of 10, 25, 50, 75 and 100 sccm for the 3 mm reactor and proportionate flow rate was calculated as per the section 3.3 for the 1 mm reactor. At least two data sets were taken for each of the flow rate interval for the 3 mm tube. Efforts were made to obtain similar data for the 1 mm reactor. However, at an equivalent flow rate of 50 sccm which is 5.55 for 1mm tube and below, we could not obtain

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satisfactory results. No reaction takes place at lower flow rates as the results indicate high propane concentrations. As a result, we only have 75 and 100 sccm to compare for the smaller reactor. The study conducted for the 1 mm tube is not adding much to the information we have already obtained. Following is a comprehensive study of all the flow rates which help us take a position on the varying flow rates.

We have already seen that for the small diameter tube, flow rate increase proves advantageous to the propane partial oxidation reaction. Figure 14 expresses the same result with addition of the outcome for the other gases. The increase in ethylene and methane is not significant as the flow rate increased, and a similar trend follows with the fall in propane concentration. Again, we see a similar result of overall propane concentration are at one third of Methane and Ethylene. The gap between the line of ethylene and methane and the slope of both the lines remains constant. Overall, the concentration of ethylene is as high as 10% in both cases, suggesting this combination of variables is suitable for maximizing the ethylene yield.
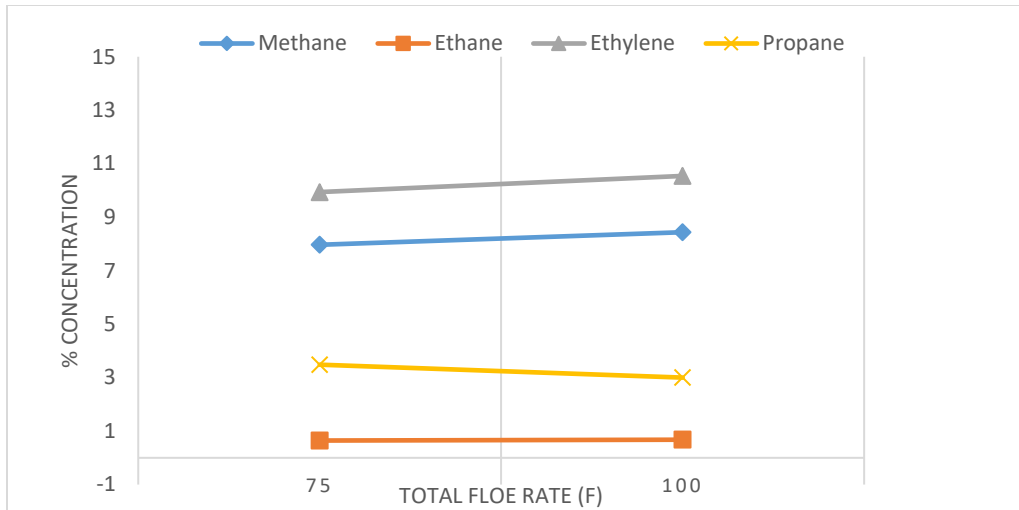
Figure 14: Mean ethylene concentration for 1mm tube, temperature – 900 °C , ∅ - 6

Figure 15 displays the result of experiment on the 3 mm tube with all the flow rates. The scatter has a standard deviation of 1 for the ethylene data points. The maximum concentration of ethylene recorded was around 11% at a flow rate of 75 sccm and the second highest was at 25 and 50 sccm at about 9% concentration.
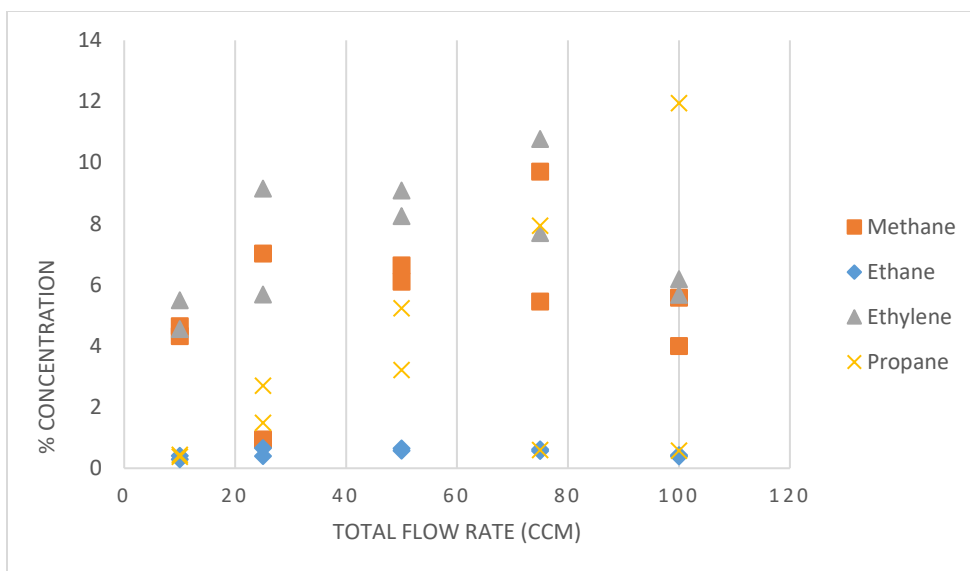
Figure 15: Scatter plot of species concentrations for 3mm tube, temperature – 900 ºC, Ø - 6

The statistical mean of these data points are plotted in Figure 16 to better visualize the output of this experiment. First, we can see the higher ethylene concentrations compared to other species. However, the discrepancy that we suspected in section 4.1 elaborates itself here. The amount of ethylene rises steadily with the increasing flow rate. The same thing happens to the methane concentration with the exception at 25 sccm. The amount of propane also increases rather steadily as well. However, at 75 sccm the ethylene concentration appears to peak as well as methane. At 100 sccm ethylene concentration drops by one third and so does methane while the propane concentration on the other hand increases sharply from 75 to 100 sccm. Overall, the average propane concentration also exceeds that of ethylene and methane at a total flow rate of 100 sccm, which hardly came across in the previous results. There is also a noticeable decrease in ethane, an otherwise negligible species, at the same flowrate.

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Thus, we can say, the increasing flow rate does result in better outcome until a certain point. Past a specific limit higher velocity of the flow results in lesser reaction time giving no significant output, at least for the bigger reactors.

Another viewpoint describes that even though the Ethylene percentage is increasing from 10 to 75 CCM at constant rate, the Propane line roughly takes the slope though lesser in absolute value. This implies the efficiency of the reaction in terms of Ethylene per unit Propane is approximately similar at all flow rates till we have reached the peak. Therefore, in terms of the desired output the flow rate does not hold much of difference until a certain point. Varying flow rate below the point of peak reaction has no effect whatsoever.
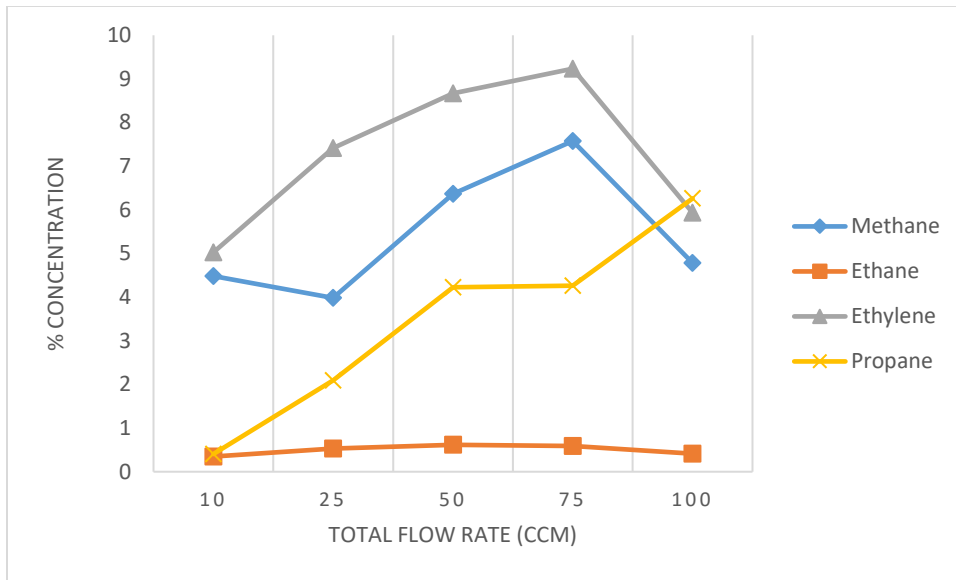

Figure 16: Mean ethylene concentration for 3mm tube, temperature – 900 ºC, Ø - 6

To validate these results further, standard error bars of Ethylene were calculated and plotted in Figure 17. Standard errors signify the faith in data. At a couple of points the

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error is large which also is the indication of a smaller data set of two. However, if we ignore the points of 25 and 75 CCM for an instance, we can see a clear difference in Ethylene concentration at 10,50 and 100CCM where the error bars do not overlap the other. That means the graph does increase up to a certain point and then takes a downward slope validating the Figure 16. In addition, point 75 and 100 CCM error bars also do not cross each other further bolstering the validity of the conclusions.
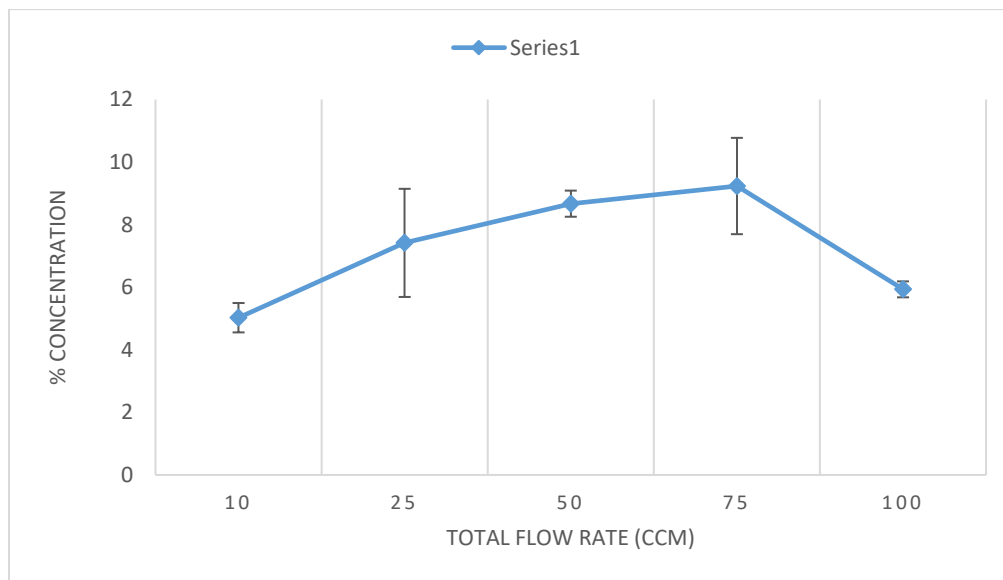

Figure 17: Mean ethylene concentration with error bar, temperature – 900 °C , ∅ - 6

4.4 Analyzing the Impact of Equivalence Ratio on Ethylene Production:

Lastly, we shall look at the significance of equivalence ratios. The quality of mixture should influence the outcome very much as quality of combustion is directly dependent on the quality of mixture. In the first section, the clearest and undoubtful position was of the equivalence ratio. Rich mixture does support the partial combustion which is desirable here.

This study we did at a temperature of 800ºC, and we found the peak Ethylene generation at 75 sccm in the previous section so the same flow rate was chosen. Equivalence ratio of 1 is the stoichiometric ratio and above 1 are richer mixtures. Once more the data is collected on both the reactors. And yet again, 1mm tube shows insignificant results at lower equivalence ratio of 1 and 2. Multiple data points were only taken on 3mm tube. Four data entrees were recorded for each equivalence ratio on the bigger reactor.

Figure 18 explains results for the smaller reactor. Indeed, 800ºC is insufficient to light up any combustion let alone partial inside the smaller reaction chamber. Mixture gets richer and so the increase in propane concentrations is a clear indication of absence of any kind of notable reaction inside the tube. All the other gases do not exceed 1 to 2 percent share at any point. It can be concluded, smaller the tube higher the temperature needed to satisfactorily achieve partial combustion at flow rates of such magnitude.
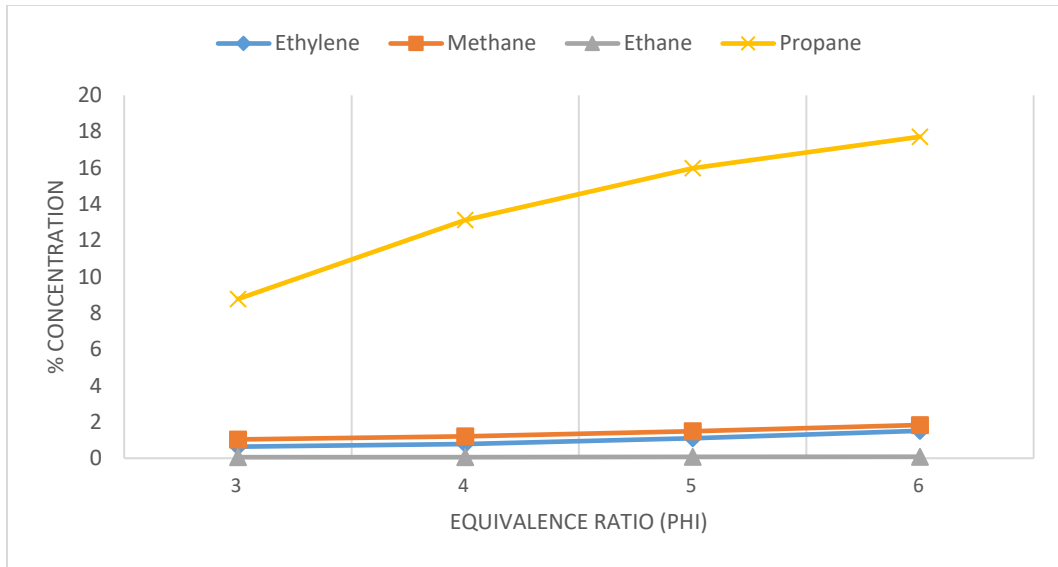
Figure 18: Mean ethylene concentration for the 1mm tube at temperature - 800 ℃, flow rate - 75sccm

We shall further consider the observations taken on the 3mm reactor. A scatter graph of all the data sets is plotted in Figure 19. 800℃ is enough to produce results in bigger reactor at all equivalence ratio is the information that we get straight away. This scatter plot has an average standard deviation of 1.3 for all ethylene data points. Scatter shows steady increase in ethylene performance with the equivalence ratio rise. Maximum Ethylene concentration of 10.53% appears at ∅ of 5. On the other hand, the lowest Ethylene value comes at stoichiometric ratio. Overall, the scatter gives an idea of better ethylene performance at richer mixture but also tends to emphasize a false peak at equivalence ratio of 5.
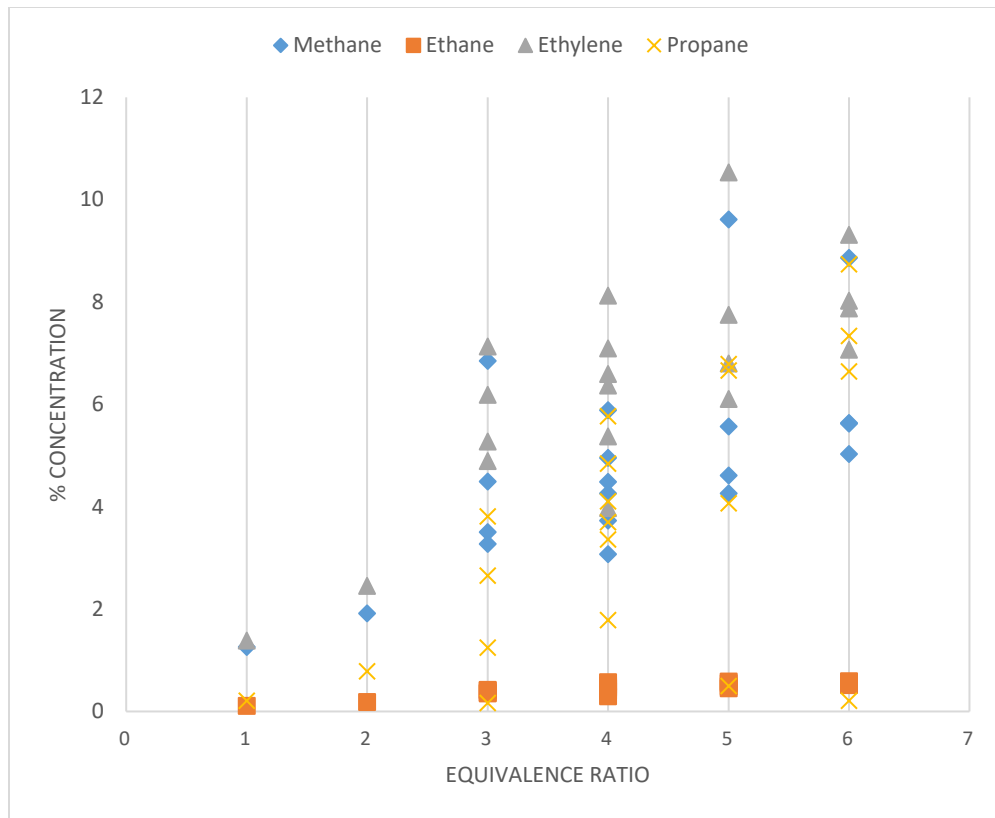
Figure 19: Scatter plot of species concentrations for 3mm tube, temperature - 800 °C, flow rate - 75 sccm

To get a clearer idea we plotted the statistical mean of the data set in Figure 20. Plot describes steady increase in Ethylene percentage from 1 to 6 equivalence ratio. There looks to be a sharp ascent in the Ethylene portion from 2 to 3 equivalence ratio and then steady but slow increase thereafter. Methane is equal in proportion with Ethylene at stoic ratio but then it maintains a constant share which is lesser as compared to ethylene. There is no evidence of a drop in any values in the chart and the rich mixture seems to be helping without exception. Remarkably like the study of flow rates, the difference between the

average value of Ethylene and Propane does appear to be similar at all the equivalence ratios which denotes inconsequential nature of varying equivalence ratio. The Ethylene output per unit propane feed will remain the same for richer equivalence ratios and it does not add any value to making mixture richer to achieve better results at least for the bigger reactor and at this flow rate and temperature.
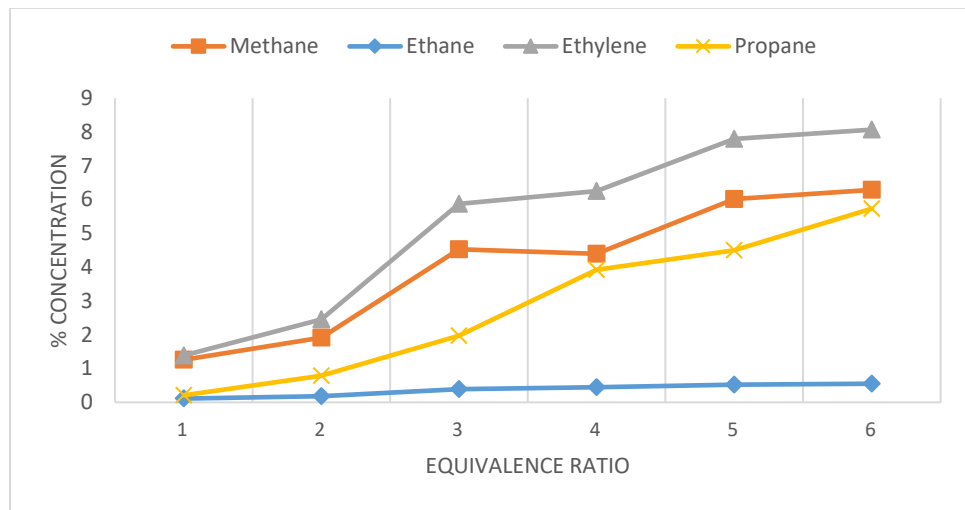

Figure 20: Mean ethylene concentration for 3mm tube, temperature – 800 $^{\circ}$C, flow rate - 75 sccm

In this section as well, we tried to incorporate a study of error bars for Ethylene in Figure 21 to validate results. We have 4 data points for each of equivalence ratios from 3 to 6. In this graph, just like the previous error bars graph, if we ignore the adjacent data points and consider the alternate ones, error bars do not overlap each other and thus produces a clean data of increasing Ethylene percentages from 3 to 6 equivalence ratio. The smaller absolute error at 3 also highlights the sudden rise of Ethylene from 2 to 3 equivalence ratio.
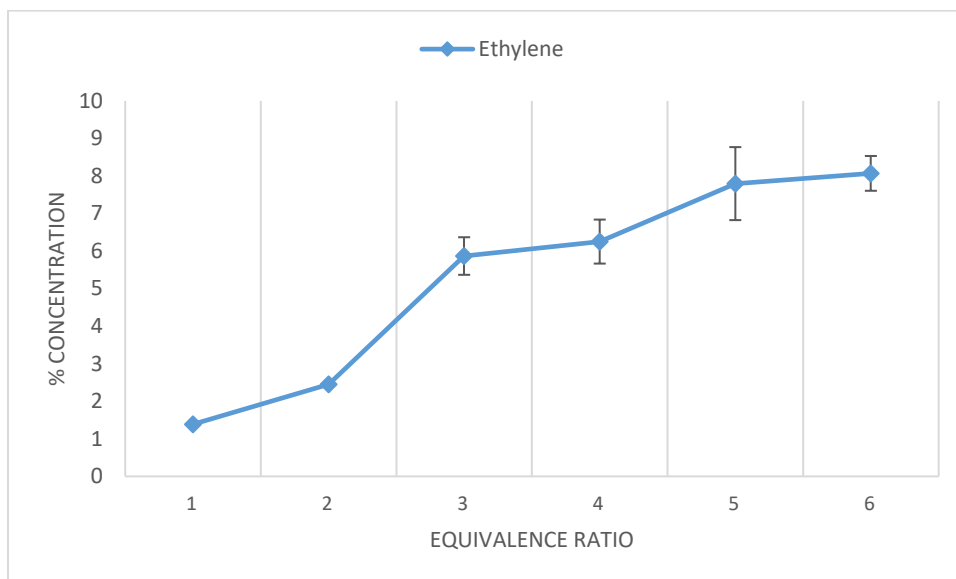
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Figure 21: Ethylene mean concentration with error bars for 3 mm tube, temperature – 800 $^{\circ}$C, flow rate - 75 sccm

CHAPTER 5

CONCLUSION

Ethylene demands are ever increasing and so are its costs as well. Given the disadvantages of conventional method of steam cracking and incessant demand, modern technologies of ethylene generation are continuously being proposed and evaluated. This study aims to assess a novel method of achieving maximum yield of ethylene by simpler means. Micro-scale partial oxidation can be considered as one of the approaches of producing ethylene.

It is known that formation of ethylene in the micro scale partial oxidation is impacted by reactor diameter, wall temperature, flow rate and equivalence ratio. Separate analysis of all the four variables is carried out in this study. The variables are not completely independent of each other and hence a comprehensive look on the results is necessary before arriving at any conclusion. The diameter of the reactor seems to be directly affecting the ethylene yield if related to the equivalence ratio, however, change in flow rate alters the results. Also, change in temperature needs to be considered before choosing the right diameter for maximum results. At lower wall temperature of 800 $^{\circ}$C larger tube is desired, smaller tube gives unsatisfactory performance whereas at higher temperature of 900 $^{\circ}$C there is not much difference in performance of both the tubes. In case of flow rates, a peak point was noticed with study of 3 mm tubes suggesting increasing flow rate gives an edge up to a certain point. Beyond the peak point increased velocities seem to restrict the oxidation process. Also, an important trend to notice is until the peak point the reaction efficiency in terms of ethylene per unit propane is approximately similar at all points indicating varying flow rate doesn't add much to the overall performance.

Study of equivalence ratio reveals partially similar trend where no traces of peak point was found but, the efficiency of the reaction doesn't seem to change much with equivalence ratio.

It should be noted that the sample size of the experiment is exceedingly small. Due to lack of data points, there might be some discrepancies in the results. Owing to the time limitations and time-consuming nature of the experiment for reiterations vast study could not be produced. Although micro-scale partial combustion is a long way behind the conventional ethylene producing methodologies, the results instill promise for further investigation of the proposed methodology. Further efforts can be taken using different fuels, even higher equivalence ratios and varying flow rates and tube diameters to better evaluate the procedure.

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