DEVELOPMENT OF POROUS MEDIUM COMBUSTION FOR MICRO-POWER GENERATION USING LIQUEFIED PETROLEUM GAS (LPG) FUEL

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by

MOHAMAD FADZLI BIN MOHD SUKARDI

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MOHAMAD FADZLI BIN MOHD SUKARDI

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LIST OF SYMBOLS

Symbol	Description	Unit
slpm	Standard liter per minute	L/min
wt %	Weight percentage	%
vol (%)	Volume percentage	%
^{o}C	Degree celcius	-
η	Combustion efficiency	%
η^{*}	Corrected combustion efficiency	%
S_L	Stake loss	%
I_L	Loss in incomplete combustion	%

LIST OF ABBREVIATIONS

LPG	Liquefied Petroleum Gas
USM	Universiti Sains Malaysia
AFR	Air-to-Fuel-Ratio
ER	Equivalence ratio

PEMBANGUNAN PEMBAKARAN MEDIUM BERLIANG UNTUK PENJANAAN KUASA MIKRO DENGAN MENGGUNAKAN BAHAN API GAS PETROLEUM CECAIR

ABSTRAK

Prestasi busa alumina berliang sebagai medium berliang dan pembakaran pemangkin mikro menggunakan Ni/Al_2O_3 busa pemangkin menggunakan LPG sebagai bahan api telah diselidik dalam kajian ini. Ni / Al_2O_3 busa pemangkin telah dibangunkan melalui kaedah penjerapan jisim basah. Prestasi yang dikaji adalah lokasi api yang dihasilkan, komposisi gas serombong, dan efisiensi proses pembakaran pada kondisi pembakaran sedikit (perkadaran nisbah bahan api/udara sebanyak 1.9 dan nisbah udara kepada bahan api lebih tinggi daripada 1) dan dikekalkan sepanjang ekperimen. Proses pembakaran bermula pada suhu ambien telah menghasilkan komposisi SO_2 dan NOx yang rendah disebabkan jumlah udara yang dihasilkan untuk keempat-empat gas (CO, CO_2, SO_2, and NO_x) adalah sangat rendah untuk kesemua ujikaji. Efisiensi pembakaran meningkat sebagaimana penurunan keliangan busa alumina di mana keliangan 22 % memberikan efisiensi pembakaran yang paling tinggi sebanyak 35.55 % tanpa menggunakan nikel sebagai pemangkin jika dibandingkan tanpa menggunakan busa alumina sebagai medium berliang, 3.55 %. Dengan mendepositkan bahan aktif, Ni pada busa alumina, keputusan yang sama telah dihasilkan di mana keliangan 22 % busa alumina memberikan efisiensi pembakaran yang tertinggi untuk 0.1 M Ni/Al_2O_3, 0.25 M Ni/Al_2O_3, 0.5 M Ni/Al_2O_3, dan 1.0 M Ni/Al_2O_3 pemangkin masing-masing sebanyak 39.54 %, 47. 40 %, 56.73 %, dan 71.39 %.

DEVELOPMENT OF POROUS MEDIUM COMBUSTION FOR MICRO-POWER GENERATION USING LIQUEFIED PETROLEUM GAS (LPG) FUEL

ABSTRACT

In this study, the performance of porous alumina foam as a porous medium and catalytic micro combustion using Ni/Al_2O_3 catalyst foam using LPG as fuel were investigated. The Ni/Al_2O_3 catalyst foam was developed through a wet impregnation method. The performances that were being studied is the flame location produced, flue gas composition, and the efficiency of combustion process at lean combustion condition (ER of LPG/air equal to 1.9 and AFR higher than 1) and keep constant throughout the whole experiment. The combustion process started at ambient temperature produced low composition of SO_2 and NO_x as the total air produced of four gases (CO, CO_2, SO_2, and NO_x) is low for all samples. The combustion efficiency increase as the decrease in porosity of alumina foam where 22 % of porosity gives the highest combustion efficiency which about 35.55 % without using nickel as catalyst compare to without using alumina foam as porous medium, 3.55 %. By the deposition of active material, Ni on the alumina foam, the same result were obtained where 22 % porosity of alumina foam gives the highest combustion efficiency which about 39.54 %, 47. 40 %, 56.73 %, and 71.39 % for the 0.1 M Ni/Al_2O_3, 0.25 M Ni/Al_2O_3, 0.5 M Ni/Al_2O_3, and 1.0 M Ni/Al_2O_3 catalyst, respectively.

CHAPTER ONE

INTRODUCTION

1.1 Research background

In recent times, energy requirement of portable devices are exponentially increasing while the capacity of the current battery technology is not progressing accordingly (Pla et al., 2015). Due to various challenges involved in stabilizing flame at small scale, micro-combustion has attracted the attention of researchers (Yadav et al., 2015). Most of devices such as cellular phones, notebook computers, digital camera and many other electronic device applications required a compact, long lifetime, and instantly rechargeable power supplies capable of providing power from several miliwatts to hundred watts (Maruta, 2011). Unfortunately, the most efficient lithium-ion electrochemical batteries have very low power densities (0.2 kW h/kg) compared to hydrocarbon fuel but require several hours of charging and their life is limited to finite and limited rechargeable cycles (Yadav et al., 2015). The impact from this drawback is low demand from consumer that need a high performance and also a long lasting usage as well.

Micro power generator provide electricity for portable electronic devices. They convert chemical energy into electricity directly, thus have longer operation period (Wang et al., 2010). Even though the emission of gases such as carbon dioxide and carbon monoxide that come from an incomplete combustion would be the main concern to the world, the production is less significant if compared to human body release (Dunn-Rankin et al., 2005). In 1996, the first micro power generator is suggested in Massachusetts Institute of Technology (Wang et al., 2010).

In recent years, many innovative micro-combustors for propulsion, power generation, chemical sensing, and heating have been designed or under development (Maruta, 2011). However, it was found the use of micro-scale combustor has given several problems. For example, high quenching distance, radical quenching, and uniform temperature distribution, heat loss from high surface to volume ratio, and blow out (Wang et al., 2010). Improvement and fabrication on micro combustor is required. Swiss-roll combustor is the one improvement that could increase the enthalpy of the reactants, thus stabilize flame (Lloyd and Weinberg, 1974). Besides, catalytic reaction is another method that can help to stabilize the performance of micro combustion (Wang et al., 2010).

1.2 Problem statement

Micro/meso-scale combustion had shown that the used of catalyst can improve the performance and stability of combustion in terms of flame condition and heat distribution (Wang et al., 2010). Most of the study came across with challenges of the combustor such as quenching issues due to the large surface-to volume ratio of small scale devices, and also thermal and chemical stability management (Maruta, 2011). According to Murat et al. (2014), there are several advantages by using catalytic combustion compared to other methods because of its capability in reducing the impact of thermal and radical quenching, easy start-up, robust to heat loss, low pollution gas emission, and operation at very lean air-to-fuel ratio condition.

There are few factors that can contribute directly or indirectly effect towards the efficiency of combustion such as preparation method, size of catalyst, interaction of catalyst with support, and dipping time of catalyst. Nonetheless, this research only focusing to the two main parameter that are to study the effect different porosity of alumina foam that acts as porous medium combustion as well as the effect of different concentration of catalyst loading that may lead changes to the efficiency of the combustion at micro combustor.

1.3 Research objectives

The main objectives of this study are:

i) To develop the porous medium combustion for micro-power generation by using different porosity of alumina foam.

ii) To develop the porous medium combustion embedded with nickel, Ni catalyst.

iii) To investigate the performance of micro combustion using Ni catalyst embedded on alumina foam.

1.4 Scope of study

In this work, the catalytic micro-scale power generation system will be developed by nickel, Ni as active materials. These active materials will be embedded onto the different type porosity of alumina foam that acts as a support catalyst. Different concentration of nickel nitrate hexahydrate solution will be used to compare the effect towards the micro-scale combustor. The Ni will be loaded onto the alumina foam by using wet impregnation method through nickel nitrate hexahydrate solution, $Ni(NO_3)_2\cdot 6H_2O$. In order to carry out the analysis, the performance of the developed catalysts were tested using micro-scale combustor for the combustion of fuel from liquefied petroleum gas (LPG) with industrial compressed air.

1.4 Organization of thesis

This report consists of five main chapters and each chapter contributes to the sequence of this study. The following are the contents for each chapter in this study:

Chapter 1 introduces a general overview of the study, problem statement, research objectives and organization of thesis.

Chapter 2 discusses the literature review of this study. In this chapter also provides the brief description of the research and previous researchers study in this field that related to this topic. Besides, the definition of the micro-porous medium of alumina, micro/meso scale combustion, nickel group element and safety precaution are included as well.

Chapter 3 covers the experiment materials and the details of methodology. It discusses on the description of equipment and materials and chemicals used, and also the methodology of active material deposition. The characterization of the develop catalyst using SEM also included in this chapter.

Chapter 4 refers to the experimental results and discussions of the data obtained. Further elaboration on the effect of different type of porosity and concentration of catalyst loading towards the location of the flame produced, flue gas composition and efficiency of the combustion also will be discussed.

Chapter 5 concludes all the findings obtained in this study. Recommendations are also included as well.

CHAPTER TWO

LITERATURE REVIEW

2.1 Porous medium combustion

In this recent years, the need of technology towards sustainability is very significant and important for the next generations to meet their own needs. By controlling the flame temperatures can reduce the NO_x emission, it is believe that the use of porous medium in combustion be able to control the flame temperatures. The problems of poor heat transfer properties of the gas mixture that cause the flame temperature to exhibit local peaks in free flame can be improved by inserting solid materials in the combustion region. Eventually, the heat transfer characteristics can be improved in terms of high thermal conductivities and thermal radiation output.

According to Keramiotis et al. (2012), combustor with porous medium can fulfils the requirements of a certain challenges that need to be encountered such as demand for more efficient, less polluting, and less energy consuming combustion technologies. By using porous medium combustion, it is eventually can lower the pollutant emissions, high power density, high turn down ratio, enhanced combustion stability, and the potential to operate in ultra-lean combustion regimes.

In general, porous medium combustion is an emerging technology particularly attractive in comparison with free flame technology (Avdic et al., 2010). The development of porous medium combustion still in the stage of practical application even though the principle of operation has been introduced for decades. According to Avdic et al. (2010), the porous medium combustion can give the excellent performance in terms of stability of combustion, reduction of pollutant emissions, wide power modulation ratios, multi-fuel capabilities and high heat production per unit burner cross-section. Besides, the porous medium combustion gives more advantages than disadvantages compared to conventional systems which can reduce the usage of fuel. Figure 2.1 shows the schematic diagram of porous medium combustion proposed by Avdic et al. (2010).

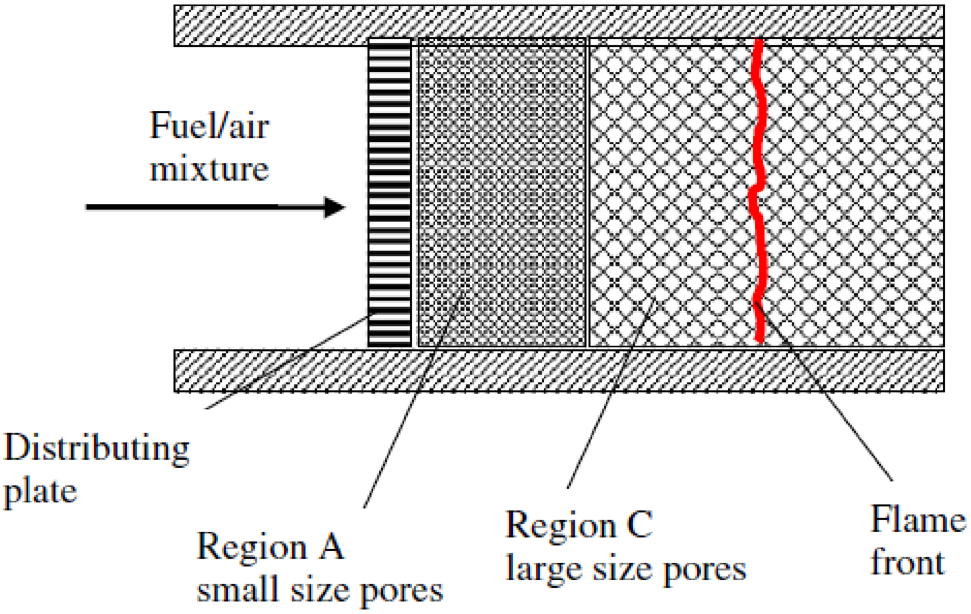

Figure 2.1 Schematic diagram of porous medium combustion

2.2 Combustion process

Combustion is a rapid oxidation of any combustible material with presence of oxygen which eventually release amount of energy from the reaction. A form of combustion in which large amounts of heat and light energy are released is called rapid combustion. The general chemical reaction for hydrocarbon fuel is as below:

$$\underset{\text{(Hydrocarbon)}}{C_xH_y} + \underset{\text{(Oxygen)}}{O_2} \rightarrow \underset{\text{(Carbon dioxide)}}{CO_2} + \underset{\text{(Water)}}{H_2O} + \text{Energy}$$

Normally, the combustion will only achieve complete combustion when there is no free oxygen or unburned fuel remain at the last and it is said to be stoichiometric. Then, carbon dioxide gas would release as a by-product also with water and energy production. However, there will be a case where there is not enough oxygen supply or it is called as incomplete combustion. Carbon monoxide gas would release instead of carbon dioxide that are harmful towards environment which cause a serious issue, global warming.

In the presence of excess air supply sometimes can reduce the efficiency of combustion because more heat losses as hot gas. Eventually, this phenomena can decrease the danger of explosion from waste flue gas but will result in unstable burner condition due to lean fuel to air mixture ratio (Dunn-Rankin, 2007).

2.3 Micro-scale combustor

In a few decade ago, a small-scale of heat source such an electrical heater use electricity to operate. Although electricity is easy to use, it is produced by the heat generated in the combustion of fossil fuels, and the thermal efficiency of electric power generation can be as low as 36.6% (Katsuyoshi et al., 2009). From this result, it can be concluded that the use of electricity that produce electricity can generate a large amount of carbon dioxide emissions than if the heat were directly produced by combustion. Therefore, a micro-scale combustor can be a solution to achieve an energy saving to replace such an electrical heating devices.

As stated by Maruta (2011), thermal and chemical stability management become a challenge to establish stable combustion in micro and meso-scale devices even though it is a device that becomes an alternative source to the problem conversion of energy into usable form. At this present, the research is still in progress to get the excellent performance of micro scale combustor due to its drawback. Although the current power source of portable device such as hand phone, laptop and other electronic devices is battery but it has limited energy densities (Yadav et al., 2015). The impact from this drawback is low demand from consumer that need a high performance and also a long lasting usage as well.

Due to the arbitrary choices of the reference length scale, the definition of micro-scale combustion is being confused with meso-scale combustion (Ju and Maruta, 2011). Generally, there are three types of different length scale have been used in the definition of micro-scale combustion (Ju and Maruta, 2011). One of the type is physical dimension of the combustor. According to Ju and Maruta (2011), the combustor is said as micro-scale if the physical length scale is below than 1 mm. Otherwise, the combustion is called meso-scale combustion if the physical length is larger than 1 mm but in the order of 1 cm. The development of micro-engines are widely used this kind of definition.

The second definition that was used is the quenching diameter; a reference length scale of flame. From Ju and Maruta (2011) article, the micro-scale combustion was defined if the combustor size is smaller than the quenching diameter. Otherwise, it is called meso-scale combustion as the combustor size is larger than the quenching diameter. However, it is difficult quantitatively define the boundary of micro and meso combustion since the quenching diameter is a function of mixture composition and wall properties as stated by Ju and Maruta (2011). The third definition is to use the relative length scale of the entire device to that of conventional large scale device for similar purposes. Table 2.1 shows the summary definition of micro and meso-scale combustion using different length scale. While Table 2.2 shows some important length and time scales in micro-scale combustion.

Table 2. 1 Definition of micro-scale combustion using different length scale (Ju and Maruta, 2011).

Definition (based on)	**Combustion regime**	**Length scale**	**Example**	**Application**
Physical length	Micro-scale	1-1000 μm	Micro-reactor	Thruster
Flame quenching diameter	Micro-scale	Quenching diameter (non-equilibrium)	Fuel Cells Nano-particle reactor	Energy conversion
Device scale	Micro-scale	Smaller than conventional engine size	Micro-thrusters Micro gas turbine	Micro-satellites Micro-air planes

Table 2. 2 Typical length and time scales in micro-scale combustion (Ju and Maruta, 2011).

Length scale	**Time scales**
Combustor scales	Flow residence time
Combustor structure scale	Characteristic combustion time
Flame thickness	Diffusion time scale of gas-phase
Quenching diameter	Diffusion time scale of solid phase
Mass diffusion length	Time scale of heat loss
Thermal diffusion length	Time scale of acoustic wave
Mean free path	Ignition time scale

There are several studies have been made in various combustor size and geometry of the device. Yang et al. (2003) stated that a backward-facing step is effective in enhancing the fuel-air mixing and prolonging the residence time as the research to investigate the performance of the cylindrical mirco-combustor with different configuration. Li et al. (2009) has similar point which the backward-facing step, the position of the peak wall temperature can be localized within a narrow zone over a wide range of flow conditions. As a result, it was found the higher wall temperature, same flow velocity and fuel-air equivalent ratio when reduce the wall thickness and decreasing the step height.

Bai et al. (2013) study the theoretical analyses on flame propagation in microreactors with emphasis oboth radical and thermal quenching mechanism. As a results, the radical quenching effect becomes stronger at lower cross-over temperature and/or higher wall temperature. Besides, the increasing wall temperature are significantly extended both of the kinetic and/or thermal quenching limits. Recently, Yuta et al. (2014) stated that there is no significant effect of radical quenching on the flame location. The effect of radical quenching on carbon monoxide concentration is not significant for equivalent ratio more than 1 at pressure of 5 atm but observing minor effect at lower pressure, 0.1 atm and 0.05 atm. Table 2.3 show the summary of experimental studies on micro-combustor with simple geometries.

Table 2. 3 Experimental studies on micro-combustor with simple geometries.

Author	**Fuel-oxidizer**	**Combustor geometry**	**Combustor size**
Yang et al.	H_2/air	Cylindrical tubes	3 mm
Li et al.	CH_4/air	Cylindrical tubes and parallel plate	1–2 mm
Maruta et al.	C_3H_8/air	Cylindrical tubes	2 mm
Zamashchikov	C_3H_8/air CH_4/air	Cylindrical tubes	2.7 mm
Yuta et al.	CH_4/air	Quartz tube	1.5-2 mm

2.4 Catalytic micro-combustor

There have been literatures about the catalytic micro combustors. Combustion without ignition or spark can be achieved through catalytic combustor that basically allow lower activation energy need. According to Murat et al. (2014), there are several advantages by using catalytic combustion compared to other methods because of its capability in reducing the impact of thermal and radical quenching, easy start-up, robust to heat loss, low pollution gas emission, and operation at very lean air-to-fuel ratio condition.

In some research made by Massachusettss Institute Technology (MIT), the first micro power generators is suggested by producing a prototype of a gas turbine generator less than 1 cm^3 (Wang et al., 2010). Nonetheless, there are several issues that need to overcome. Later, catalytic micro combustor was proposed to help stabilize micro combustion.

Kamijo et al. (2009) were developed and tested a micro-scale catalytic combustor using high-precision ceramic tape-casting technology for high-temperature application like thermophotovoltaic (TPV) power generation. It is stated that the wall temperature as high as 850 ^{o}C and extremely high heat generation density of 2-5 x 10^8 W/m^3 have been achieved by using palladium (Pd) catalyst/nanoporous alumina support. As a result, the wall temperature gradient was found significantly reduced with the proposed catalyst arrangement.

2.5 Nickel as catalyst

Catalysis is a chemical phenomenon that increases the rate of a chemical reaction by spending only a tiny amount of additional substance, called a catalyst. The feature of catalyst that make it special is that they are not being consumed in the reaction and can be used more than one time. In another word, the reaction only involved the catalyst physically not chemically. In this study, nickel based catalyst was chose as an active material. Mechanistic findings suggest that cheap and easily available nickel species can be much more chemically reactive compared to expensive palladium and platinum species. Moreover, the increasing price of Pd, Pt, and other noble metals even further stimulates search for inexpensive and easily available catalysts (Ananikov, 2015). This provides a remarkable opportunity to develop new nickel catalysts. However, nickel not only is an inexpensive replacement for noble metals but also enables new reactions and novel catalytic frameworks. Table 2.4 shows brief comparison of nickel, palladium and platinum-catalyzed reactions in organic synthesis.

Table 2. 4 Brief comparison of nickel, palladium and platinum-catalyzed reactions in organic synthesis (Ananikov, 2015)

Catalyst	**Activity**	**Application in organic synthesis**
Ni	High	Good area of application Potential of several reactions to be explored
Pd	Moderate	Outstanding area of application Leading catalyst for organic transformations
Pt	Low active	Good area of application Excellent models for mechanistic studie

2.6 Safety precaution

Safety is always a priority before commencing experimental work. It plays an important role in all fields. There might be a risk of serious injury during working with several chemicals or materials in a lab. Any potentially hazardous materials and risks associated with the experimental procedures are first identified and proper safety precautions are then proposed to avoid accidents and minimise the risks. Material safety data sheet must be read thoroughly especially nickel before handling with any chemicals or materials so that anything bad effect can be known early and take action on that. All the preparation of chemicals must be done in a fume cupboard to avoid any contaminant air towards users and environment. Besides, personal protective equipment (PPE) such as gloves, mask and goggles must be wore all time before conducting the experiment.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Introduction

In this chapter, the experimental materials, equipment and methods have been described in details for the surface cleaning on different porosity of alumina foam that act as support, Ni deposition on alumina foam by wet impregnation method. Besides, the performance test of the developed catalyst on the micro-scale combustor have been discussed in this chapter that were conducted at School of Mechanical Engineering, USM.

3.2 Overall experiment

The overall of this research mainly consist of four steps as shown in Figure 3.1. First thing first is to clean the surface of alumina foam that has been contaminated. Basically, the purpose of this process is to remove any foreign substances that are deposited on the surface of alumina foam. The reason is to ensure no external reaction that may interrupt on the support for the next process. Next, the active material solution which is nickel (II) nitrate hexahydrate solution, $Ni(NO_3)_2 \cdot 6H_2O$ will be prepared and being used to deposit the Ni onto the treated support. Last but not least, the catalysts were then being tested its performance for combustion process at School of Mechanics Engineering, USM. The flow chart of overall experiment in this study is shown in Figure 3.1.

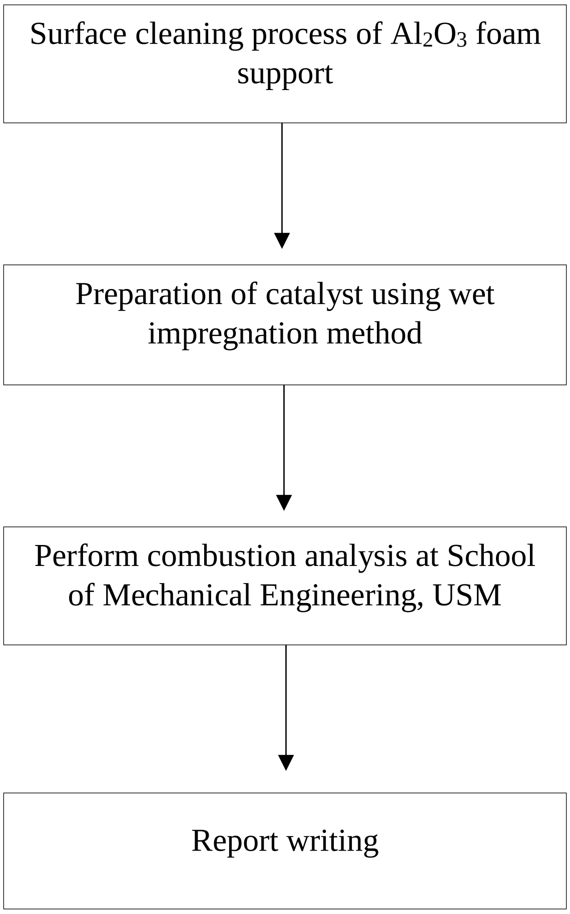

Figure 3.1 Flow chart of overall process involved in this research

3.3 Experimental materials and equipment

All of the chemicals and equipment used in this research were listed in Table 3.1 and Table 3.2, respectively.

Table 3.1 List of chemicals and materials used in this experiment

Chemicals/ Materials	**Chemical Formula**	**Usage**	**Specification / Brand**
Nickel Nitrate Hexahydrate	$Ni(NO_3)_2 \cdot 6H_2O$	Precursor for impregnation method	Supplier: Fluka
Alumina foam	Al_2O_3	Support catalyst	Porosity: 22 %, 84 %, 86 %, 91 %
Acetone	C_3H_6O	Use for surface cleaning of alumina foam	Supplier: Fluka
Liquefied petroleum gas, LPG	C_3H_8/C_4H_{10}	Fuel source	Composition: 40 % C_3H_8 60 % C_4H_{10}

Table 3.2 List of equipment used in this experiment

Equipment	**Model**	**Usage**
Oven	Memmert 600	Drying process of impregnated catalyst
Furnace	Carbolite (CWF 1200)	Calcination process of impregnated catalyst
Analytical balance	Shimadzu, AC 220	To weight the chemical
Mass flow controller for air	Sierra® Smart-Trak 50 Series	To control inlet flow rate of air
Mass flow controller for LPG	Sierra® SmartTrak2	To control inlet flow rate of LPG
Gas analyzer	Kane quintox	To analyze the amount of gases produced in ppm

3.4 Method of experiment

3.4.1 Surface cleaning process

Raw alumina catalyst foam must undergo surface cleaning process first before proceeding to another process. The main objective of this process is to remove any foreign substances that are deposited on the surface of alumina foam. The reason is to ensure no external reaction that may interrupt on the support for the next process. In this research, there are four types of different porosity of alumina foam (22 %, 84 %, 86 %, and 91 %) that were used to test which one give the best performance for combustion process. Table 3.3 shows the procedure that were involved in this process.

Table 3. 3 Procedure of surface cleaning process

Process Treatment	**Procedure**
Surface cleaning	1. About 50 ml acetone is measured and poured into a beaker. 2. The alumina foam (porosity: 22 %) are dipped into the acetone solution for 10 seconds. 3. The dipping process is repeated for 5 cycles. 4. The alumina foam are dried in a room temperature for about 10 minutes. 5. The alumina foam are the dried at 100 ^oC in an oven for 2 hours. 6. Then, the alumina foam are calcined at 500 ^oC in furnace for 5 hours. 7. The procedures are repeated for 84 %, 86 %, and 91 % of porosity.

3.4.2 Catalyst preparation using wet impregnation method

Based on work done by previous research, wet impregnation method is being chosen and used for the deposition of Ni onto alumina foam which acts as catalyst support following the method proposed by Liu et al. (2014). The parameters that were studied in this research with only two-factor-at-one-time are the porosity of alumina foam (22 %, 84 %, 86 %, and 91 %) and concentration of nickel (II) nitrate hexahydrate solution (0.1 M, 0.25 M, 0.5 M, and 1.0 M) by fixed the dipping time (24 hours) in the solution. The summary of the procedures for the catalyst are stated in detail as shown in Table 3.4.

Table 3. 4 Procedure for preparation of Ni/Al_2O_3 catalyst

Parameter	**Procedure**
Concentration of nickel (II) nitrate hexahydrate	1. The solid support is heated in an oven at 120 ^oC for 12 hours to remove moisture inside the pellets. 2. About 30 ml of 0.1 M $Ni(NO_3)_2{\cdot}6H_2O$ solution is prepared and poured into a beaker. 3. Then, the dry alumina foam with different porosity (22 %, 84 %, 86 %, and 91 %) are immersed in the 0.1 M $Ni(NO_3)_2{\cdot}6H_2O$ solution at room temperature for impregnation process and left for 1 day. 4. The catalyst samples are dried in an oven at 100 ^oC for 2 hours. 5. Lastly, the samples are calcined at 500 ^oC for 2 hours with temperature ramp of 5 ^oC min^{-1}. 6. The procedures are repeated for 30 ml of 0.25 M, 0.5 M ,and 1.0 M $Ni(NO_3)_2{\cdot}6H_2O$ solution.

3.5 Performance test for the developed catalyst

The performance of combustion was conducted at School of Mechanic Engineering, USM. The effect of catalyst on flame location and combustion efficiency that are the two factors that were investigated in this combustion analysis. Based on research by Murat et al. (2014), the experimental set up consists of two digital mass flow controllers, LPG cylinder, a compressed industrial air cylinder, a mixer, a connection tube, and a personal computer. The flow rate of LPG was controlled using Sierra® Smart-Trak 100 Series mass flow controller (Sierra Instruments, USA), whereas the flow rate of air is controlled using Sierra® Smart-Trak 50 Series mass flow controller (Sierra Instruments, USA). Figure 3.2 shows the actual experimental test set up for catalytic micro-scale combustor.

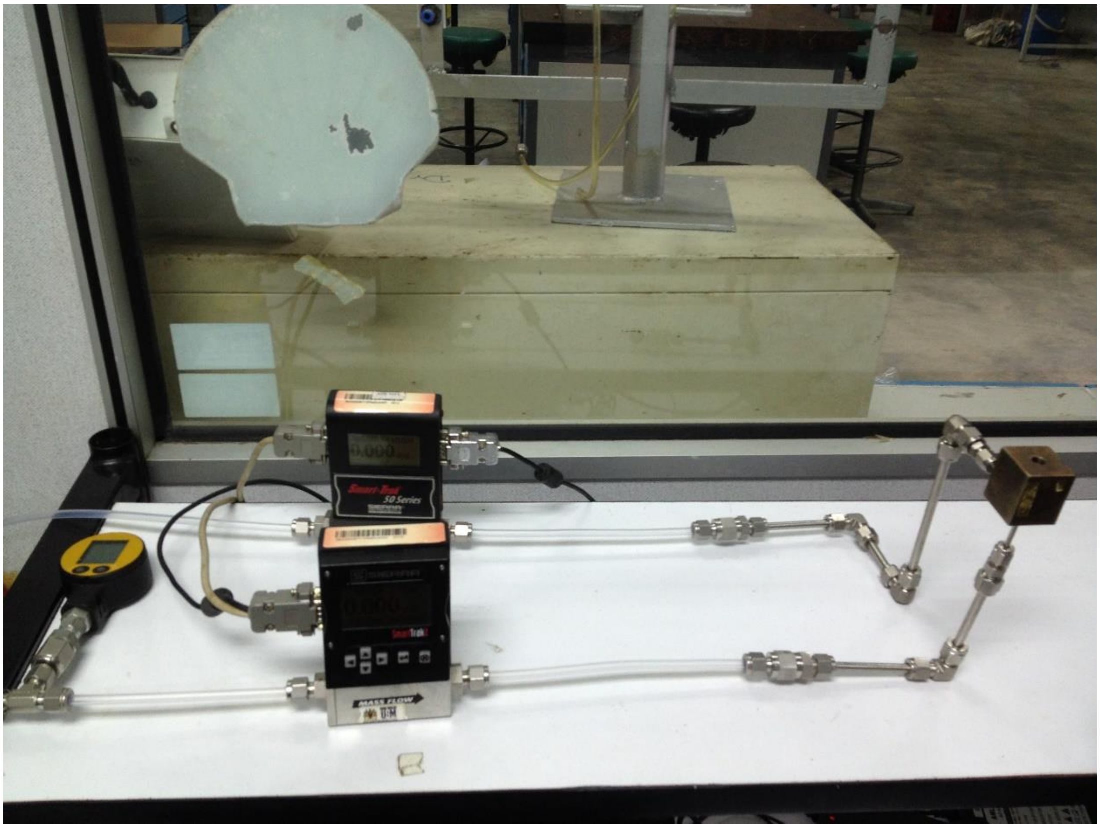

Figure 3. 2 Actual experimental test set up for catalytic micro-scale combustor

For combustion process, if the actual air-to-fuel ratio is less than the stoichiometry ($AFR_{actual} < AFR_{stoichiometry}$) it was said to be a rich combustion as the fuel used was in excess compared to air. Meanwhile, the combustion was said to be lean when the actual air-to-fuel ratio is greater than the stoichiometry ($AFR_{actual} > AFR_{stoichiometry}$) as the air used was in excess compared to fuel consumption. The flow rate of air as well as LPG were adjusted in order to establish the desired stable flame. Initially, the flow rates for both air and LPG were set to the stoichiometry value (Air flow rate: 0.100 slpm ; LPG flow rate: 2.81 slpm). Then, the equivalence ratio (ER) was increased to 1.9 as the value more than 1 that can consume a high amount of air but less in fuel. This condition was taken as it is can save much more fuel. For the optimum condition, the flow rates for both air and LPG were set and kept constant throughout the experiment (Air flow rate: 0.100 slpm ; LPG flow rate: 1.479 slpm). The air-to-fuel ratio calculation (AFR) and equivalence ratio (ER) were shown as in Appendix A. Figure 3.3 shows the mass controller of the LPG and air being used in this work.

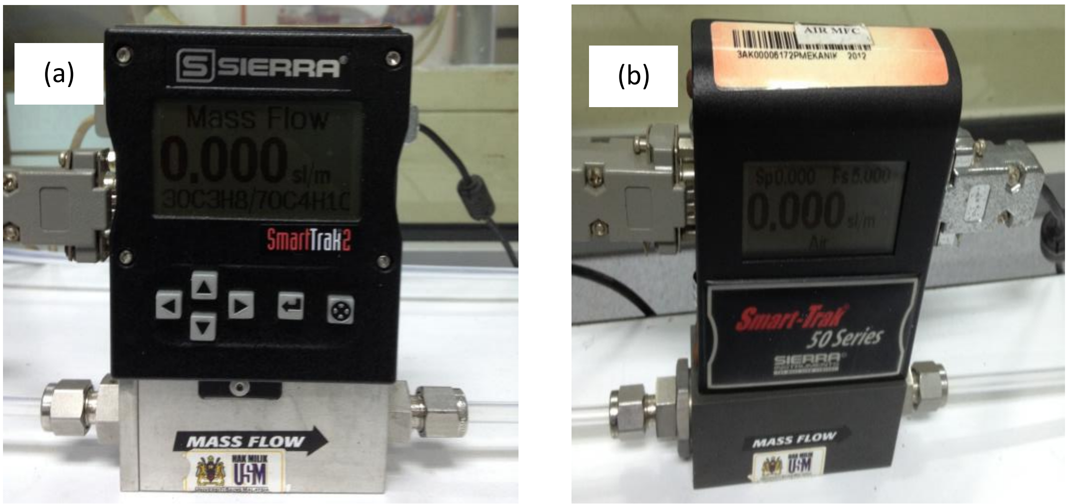

Figure 3.3 (a) Sierra® SmartTrak2 Mass Flow Controller and (b) Sierra® Smart-Trak 50 Series Mass Flow Controller

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter represents the experimental results and discussions on the development of the micro-porous media using nickel based catalyst for micro-scale power generation system. A comparison has been made between the four different types porosity of alumina foam and also after deposited of nickel onto the surface of alumina foam. The performance of four different type of porosity and the developed catalysts were tested on the micro-scale combustor that used LPG as a fuel at School of Mechanical Engineering, USM. In this chapter, the flame location, flue gas composition and combustion efficiency were discussed to compare the performance for every samples that were developed.