DEVELOPMENT AND ANALYSIS OF POROUS MEDIUM GAS COMBUSTOR

by

MUHAD ROZI BIN MAT NAWI

Thesis submitted in fulfillment of the requirements
for the degree of
Master of Science

June 2008

ACKNOWLEDGEMENTS

In the name of Allah, the Beneficent, the Merciful

I dedicate this work to my parents, Mr. Mat Nawi Jusoh and Madam Mek Som Hj. Awang Noh who have always encouraged, motivated and given me the moral values to lead a peaceful life. I would like to express my sincere thanks to my supervisor, Assoc. Prof. Dr. Mohd Zulkifly Abdullah for his tremendous guidance, advice, support, assistance and encouragement throughout my postgraduate candidature period. Also, special thanks to my co-supervisor, Assoc. Prof. Dr. Mohamad Zailani Abu Bakar and Assoc. Prof. Dr. Ridzuan Zakaria for their guidance, help and advice to handle the research works.

Apart from them, I would also like to express my appreciation to Assoc. Prof. Dr. Ishak Hj. Abd. Azid for his tremendous help and guidance on academic and professional developments with impromptu discussions or exchange of ideas. Special thanks also must be given to all academic and technical staff especially Mr. Khomaruddin and Mr. Shahril for their help and supportive ideas on my research work. I would like to forward gratitude to my fellow colleagues, Mr. Azmi, Mr. Khalil, Mr. M.A. Mujeebu, Mr. Hamid, Mr. Kamal, Mr. Rahim, Mr. Fairosidi, Mr. Sharupudin, Mr. Rosmaini, Mr. Ezral, Mr. Shahrizan, Mr. Khairul Anuar, Mr. Razlee, Ms. Hamidah, Madam Nurul Huda, Ms. Faradiana, Madam Rohayati, Ms. Umi Kalthom, Ms. Yushazaziah and Madam Mardiana and also my friends, Mr. Nik Zainal, Mr. Sabri, Mr. Afrol Rizam and Mr. Harun for their moral supports and help during my research works.

I would also like to express my gratitude to my siblings, Ms. Che Maznah, Mr. Mohd Asri, Mr. Mohd Azam, Mr. Mohd Zainal and Mr. Muhamad Saharuddin and my sisters in-law, Madam Wan Anna Wahidah and Dr. Fadzira and also other family members for their continuous support in my life. Their support allowed me to concentrate fully in my studies without hesitation. Special gratitude is forwarded to my beloved wife, Madam Azliza Ismail for her patience, encouraged, moral support and help since our marriage time.

I am gratitude to the Ministry of Science, Technology and Environment, Malaysia (MOSTI) for supporting me the financials of research and life, under the IRPA grant. I would also like to forward special thanks to Graduate Studies Institute (IPS) for awarding me the Graduate Assistance (Teaching) Scheme to support my life cost during study. Last but not least, my sincere thanks, compliments and regards to anyone who had helped and supported me in one way or another.

TABLE OF CONTENTS

LIST OF TABLES **Page**

LIST OF FIGURES

Page

LIST OF SYMBOLS

C_p	specific heat capacity (J/kg.K)
D	diameter (m)
d_m	equivalent porous cavity diameter (m)
D_p	particle diameter (m)
d_s	sphere diameter (mm)
E	emissivity
H_p	porous medium height (m)
K	permeability
k	thermal conductivity (W/mK)
Pe	Peclet number
Q	flow rate (m^3/s)
Q_{rad}	radiant heat flux (W/m^2)
R	radius of chamber (m)
r	radius of solid sphere (m)
S_L	laminar flame velocity (m/s)
T	temperature (K)
t	time (s)
V_f	volume of fluid (m^3)
V_s	volume of solid (m^3)
V_T	total volume (m^3)

Greek symbols

α	thermal expansion coefficient (1/K)
σ	Stefan-Boltzmann constant ($W/m^2.K^4$)
ε	porosity
Φ	equivalence ratio
ρ	density (kg/m^3)
μ	viscosity (kg/ms)

ABBREVIATION

CFD	computational fluid dynamics
COHb	carboxyhaemoglobin
ID	internal diameter
LPG	liquefied petroleum gas
PFTC	pilot-flame-temperature-controller
PM	porous medium
ppm	parts per million

PEMBANGUNAN DAN ANALISIS PEMBAKAR GAS BAHANTARA BERLIANG

ABSTRAK

Walaupun pembakaran memberikan banyak kebaikan kepada manusia, ianya juga mempunyai kelemahan yang mana menghasilkan pencemaran seperti nitrogen oxida (NO_x) dan karbon monoksida (CO). Dengan menggunakan bahantara berliang dalam pembakaran membuktikan pengurangan pemancaran NO_x dan CO dapat dicapai melalui sifat termanya dan fizikalnya. Bagaimanapun, sistem pembakaran ini yang menggunakan bahantara berliang dalam pembakaran pracampur adalah sistem yang sulit, berisiko tinggi dan bahantara yang digunakan adalah terlalu kompleks untuk dibuat. Oleh itu, penyelidikan ini cuba untuk meminimumkan kelemahan-kelemahan tersebut dengan membina satu sistem pembakaran gas petroleum cecair (LPG) dan udara bukan pracampur yang digabungkan dengan bahantara berliang. Satu pembakar berbentuk silinder yang dapat mengawal nisbah LPG dan udara dibangunkan dengan dilengkapi oleh satu sistem keselamatan api padam. Bahantara berliang adalah dibentuk berlapis dalam bungkusan dengan tiga saiz diameter sfera yang berbeza digunakan iaitu 20 mm, 30 mm dan 50 mm. Penyelidikan ini telah dijalankan secara berangka dan eksperimen. Dalam pembelajaran berangka, analisis tiga dimensi pembakaran bukan pracampur pada keadaan mantap telah dijalankan dengan menggunakan kod pengkomputeran dinamik bendalir (CFD) komersil iaitu Fluent. Sementara itu, eksperimen telah dijalankan untuk analisis pada keadaan mantap dan fana. Penyiasatan ini adalah tertumpu pada penyebaran NO_x dan CO dan juga profil dan kontur suhu.

Daripada analisis perbandingan pembakar tanpa bahantara berliang dan pembakar mengandungi bahantara berliang, didapati penyebaran NO_x dan CO dapat dikurangkan masing-masing kira-kira 59% dan 21% dengan kehadiran bahantara berliang. Bahantara berliang juga dapat menyebarkan haba pembakaran ke kawasan yang luas dalam kebuk pembakaran dan meningkatkan suhu dalam kawasan bahantara berliang. Dalam penyelidikan ini juga, didapati nisbah kesamaan yang sesuai untuk operasi pembakar adalah 0.83. Secara umum, rupa bentuk bahantara berliang yang digunakan menghasilkan fenomena maklum balas tenaga radiasi dan aliran patah balik spesis yang mana mempengaruhi penyebaran NO_x dan CO dan profil suhu. Perbandingan aliran NO_x dan profil suhu antara simulasi dan eksperimen menunjukkan persetujuan yang baik.

DEVELOPMENT AND ANALYSIS OF POROUS MEDIUM GAS COMBUSTOR

ABSTRACT

Although combustion offers many benefits to the human, it also has a downside which is producing pollutants such as nitrogen oxides (NO_x) and carbon monoxide (CO). The use of porous medium in combustion has proved that the reduction of NO_x and CO emissions can be achieved through its thermal and physical properties. However, these combustion systems which use porous medium in premixed combustion are complicated system, high risk and the porous medium used is too complex to be manufactured. Therefore, the present study tries to minimize such limitations by developing a system of non-premixed combustion of liquefied petroleum gas (LPG) and air incorporating with porous medium. A controllable LPG and air ratio cylinder combustor was developed with a blow-off safety system provided. The porous medium was formed in packed bed with three different sphere diameter sizes used, i.e., 20 mm, 30 mm and 50 mm. The study has been carried out numerically and experimentally. In the numerical study, a steady state three dimensional analysis of non-premixed combustion using a commercial computational fluid dynamics (CFD) code, i.e., Fluent has been performed. On the other hand, the experiment has been made for the analysis at steady state and transient conditions. The investigation was focused on the NO_x and CO emissions and temperature contours and profiles. From the comparison analysis of combustor without porous medium and with porous medium, it is found that the NO_x and CO emissions can be reduced approximately 59% and 21% respectively with the presence of porous medium. The porous medium can also distribute heat of combustion into large area in

combustion chamber and enhance the temperature at its region. From the study also, it is found that the suitable equivalence ratio for the operation of combustor is 0.83. Generally, the porous medium (PM) configurations used have created the phenomenon of radiative energy feed-back and species backflow which influence the NO_x and CO emissions and temperature profiles. Comparison of NO_x trends and temperature profiles results between simulation and experiment showed a good agreement.

CHAPTER 1
INTRODUCTION

1.0 Overview

In this chapter, brief information about the principles, benefits and problems in combustion is presented. This part discusses the combustion problems concerning environmental issue which encourage the present research. This part is followed by an approach of reducing NO_x and CO emissions using porous medium. The effects of thermal properties and the physical form of porous medium to the minimization of NO_x and CO emissions formation during combustion will be described in this section. Then, the problem definitions from the previous studies are presented. Lastly, the research objectives, the scope of present works and thesis outlines are presented.

1.1 Combustion: Principles, Benefits and Problems

Combustion is the conversion of a substance called a fuel into chemical compounds known as products of combustion by combination with an oxidizer. Basically, the combustion process is classified into two types of processes, i.e., premixed combustion and non-premixed combustion. In premixed combustion, the fuel and oxidizer is mixed first before the burning process occurs while the mixing and burning processes occur simultaneously in the non-premixed combustion. The combustion process is an exothermic chemical reaction, i.e., a reaction that releases energy as it occurs. Thus, combustion may be represented symbolically by:

$$\text{Fuel} + \text{Oxidizer} \rightarrow \text{Products of combustion} + \text{Energy}$$

The most common fuel sources are hydrocarbons and related organic molecules. These are molecules that are made up primarily from hydrogen and carbon atoms. Methane (natural gas), gasoline, kerosene, propane, butane, methyl alcohol and ethyl alcohol are all examples of hydrocarbons and related compounds. The hydrogen and carbon atoms in these molecules are the actual fuel in the combustion process. Either the chemical energy released is transferred to the surroundings as it is produced, or it remains in the combustion products in the form of elevated internal energy, or some combination of both.

Historically, combustion is the oldest technology of mankind and it has played an important role to the human history for more than million of years: from prehistoric times when fire was used for cooking food and keeping wild animals at bay, to modern times in which combustion is used in many application areas such as industrial processes, power generation and space heating in buildings. At present, about 90% of our worldwide energy support (e.g., in traffic, electrical power generation, heating) is provided by combustion (Warnatz et al., 2001). However, beside the benefits combustion offers, it also has a downside which is producing pollutants such as nitrogen oxides (NO_x) and carbon monoxide (CO).

NO_x is a collective name for nitric oxide, NO and nitrogen dioxides, NO_2. During combustion, the vast majority of nitrogen oxides are emitted as NO. Because of NO is converted to NO_2 in the atmosphere, therefore the emissions of both species are frequently lumped together with the designation NO_x. Once released into the atmosphere, NO_x plays an important role in the formation of photochemical smog and acid rain (Beer, 2000). Exposure to high levels of nitrogen oxides can damage the respiratory airways. Even when someone is breathing at low levels of nitrogen oxides, it may also cause cough, shortness of breath, tiredness and nausea. The global emission of NO_x since 1900 has increased by a factor of ten, and from 1950s with a factor of three (Bowman, 1992). According to the Department of Environment (DOE) Malaysia (2005), the recommended Malaysian air quality guideline at ambient for nitrogen dioxides is 0.17 ppm in averaging time of 1 hour. A significant amount (~70%) of this increase can be attributed to combustion sources (Muzio, 1997), while the rest of the NO_x emission comes from natural sources. During combustion, NO_x is formed when any fuel is burned in air because of the high temperature oxidation of N_2. To reduce the NO_x generation rate in a high temperature combustion, several methods can be implemented such as the use of high excess air ratio to reduce peak flame temperature, staged combustion air injection, staged auxiliary fuel injection and the injection of selective non-catalyst such as ammonia (NH_3) or urea ($CO(NH_2)_2$) into the furnace. But, it is noticed that the most direct method of controlling NO_x emissions is to control the flame temperature itself.

Meanwhile, the effects of carbon monoxide (CO) exposure are reflected in the oxygen-carrying capacity of the blood. In normal functioning, haemoglobin molecules in the red blood cells carry oxygen, which is exchanged for carbon dioxide in the capillaries connecting arteries and veins. When a haemoglobin molecule acquires a CO molecule, it is called carboxyhaemoglobin (abbreviated COHb). The presence of COHb decreases the overall capacity of the blood to carry oxygen to the cells. Symptoms of CO poisoning depend on the amount of haemoglobin combined with CO. The effects of CO exposure are summarized in Figure 1.1.

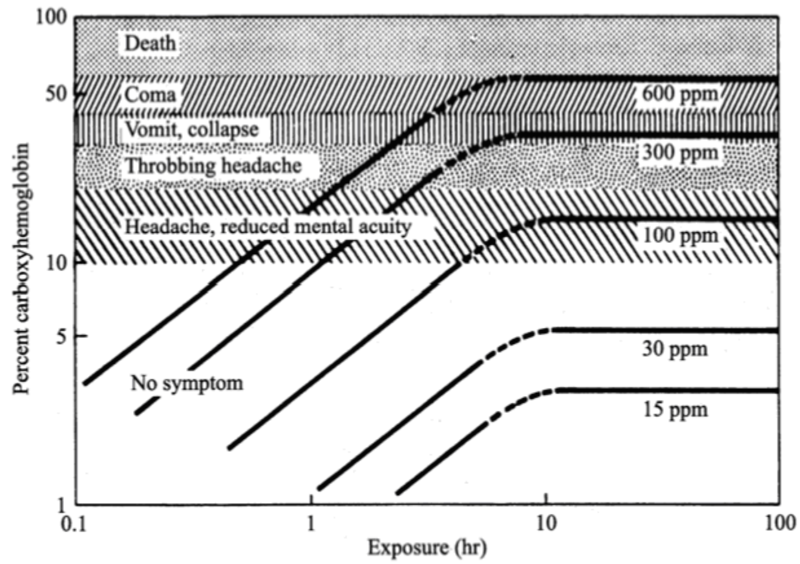

Figure 1.1: Effects of CO exposure on humans (Avdic, 2004)

During combustion, carbon monoxide (CO) is formed when the incomplete combustion occurs due to either insufficient of air or the problem of mixing process during combustion. The high incomplete combustion also may occur because of cold surfaces, at which flames are locally disappeared and the residence time of flue gases is not sufficiently long to approach conditions for complete combustion. In Malaysia, the recommended air quality guideline at ambient for carbon monoxide (CO) is 30 ppm in averaging time of 1 hour (DOE Malaysia, 2005).

1.2 Use of Porous Medium for the Reduction of NO_x and CO Emissions

Since the NO_x emission can be reduced by controlling the flame temperatures, the use of porous medium in combustion is believed to be able to control the flame temperatures. In free flame (combustion without porous medium), the flame temperatures exhibit local peaks because of poor heat transfer properties of the gas mixtures. These attributes are improved by inserting solid materials in the combustion region, utilizing the heat transfer characteristics in terms of their higher thermal conductivities and higher thermal radiation output. Therefore, heat can be extracted faster from those areas where high temperatures occur. This will ensure a reduction in local thermal NO production as a major of NO_x source. Furthermore, the physical form and structure of the porous material also affects the radiative heat transport by virtue of its optical thickness, conductive heat transport and convective heat transport by the porosity and the resulting flow pattern. Therefore, porous medium provides the essential features for efficient combustion with low NO_x emission. On the other hand, the CO emission can be minimized if the combustion process occurred is almost completed. This can also be realized by using porous medium. A high temperature porous medium provides a regenerative combustion and contribution to complete reaction because of energy feed-back by thermal radiation (Yoshizawa et al., 1988). Besides that, the convolute path within porous medium has played an important role of the much turbulence creation to the flow of fuel and air. Thus, the mixing process is improved which contributes to the completeness of combustion. These ensure the reduction of CO emission is possible. The reduction of CO may also be possible due to the residence time of flue gases is longer since the flow upstream of flue gases is slowed down by the convolute path of porous medium.

The use of porous medium in combustion also gives an advantage which is the ability to maintain stable combustion during any minor fluctuations of the flame temperature or even to restart the combustion immediately by simply restoring the flow of the fuel and oxidant after flame extinction caused by momentary interruption of the fuel, or oxidant flow or others. The reason for this advantage is that the specific heat of most porous material is sufficient to maintain its temperature above the ignition temperature for some time after the flame has been extinguished.

In the past, many works of using porous medium in combustion have been investigated and the successful results were achieved. However, mostly the works are regarding to the premixed combustion system with so many limitations.

1.3 Problem Definitions

As noticed, the premixed combustion system is quite complicated due to the system needs a proper mixer for the fuel and air. To be used as a home appliance, the system is quite high risk due to the high flammability of air-fuel mixture which can burn and explode instantaneously when the mixture is leaked at sufficient ignition temperature. From the past studies, most systems of porous medium premixed combustion are characterized as the ignition and reactions of gaseous mixture is occurred inside porous medium. This characteristic needs critical two different pore sizes and configurations of porous medium adjacent each other to support the mixture flow and flame quench processes and the flame propagation process. Therefore, the complex porous medium which is high precision of pore sizes and exact configurations are needed to obtain a successful operation. In order to minimize such limitations of the porous medium premixed combustion system, a system of non-premixed combustion incorporates with porous medium has been developed which can operate properly.

1.4 Research Objectives

For this project entitled "Development and Analysis of Porous Medium Gas Combustor", there are five objectives to be achieved:

- To develop a system of non-premixed gas combustion with the use of porous medium in combustion chamber.
- To do a comparison analysis of the combustion characteristics (NO_x, CO and temperature profiles) between combustor with porous medium and without porous medium (free flame).
- To analyze the effects of excess air on combustion characteristics (NO_x and temperature contour) of combustor with porous medium.
- To analyze the effects of different sphere sizes and different number of porous medium (PM) layers on combustion characteristics (NO_x, CO and temperature profiles) of combustor with porous medium.
- To do simulation studies on the combustion characteristics (NO_x and temperature profiles and contours) using Fluent software.

1.5 Scope of Works

In this research, a system of gas combustor which operates by non-premixed combustion is developed. During operation, the gas combustor uses LPG as a fuel and the air supplied by an air compressor as an oxidizer. In this study, the spherical aluminum oxides (Al_2O_3) are used as a porous medium. The sphere shape of Al_2O_3 or alumina ball is formed in packed bed in combustion chamber. Three different sphere diameter sizes are used in the present work, i.e., 20 mm, 30 mm and 50 mm. This study has been conducted by simulation using Fluent software and experiment. Three parameters are also considered in the present study, i.e., different equivalence ratios, different sphere sizes of PM and different layers number of PM. The results from simulation and experiment are compared with each other in order to measure the level of agreement between both results. The analysis of the results is concentrated on the emissions of NO_x and CO and the profile and contour of temperatures.

1.6 Thesis Outlines

The thesis is organized in such a way that it provides a continuous and smooth flow of information to the reader, regarding the development and analysis of porous medium gas combustor. There are total of six major chapters which are subdivided into suitable sections. The major six chapters in this thesis are introduction, literature review, computational fluid dynamics modeling, experimental description, results and discussion and finally conclusion. Chapter 1 gives brief information about the principles, benefits and problems of combustion and the problem solution by using porous medium. The scopes and objectives of the project are also presented in this chapter. In Chapter 2, the literatures regarding the previous studies of gaseous combustion, porous medium as heat transfer enhancement and the experimental and numerical investigations of the use of porous medium in combustion are reviewed. This chapter deals with the past and current trends of the porous medium combustion study. The numerical study by computational fluid dynamics (CFD) modeling using Fluent software is presented in Chapter 3. The modeling description which includes the CFD methodology of PM gas combustion and the simulation procedures are described in this chapter. In Chapter 4, the experimental description is presented, regarding the experimental set-up and the experimental procedures. In the experimental set-up, the air and fuel supply system, the details about gas combustor and porous medium used, the temperature measurement and gas emissions analyzer used are described. Results from Chapter 3 and Chapter 4 are presented and discussed in Chapter 5. Finally, the thesis will end with conclusions in Chapter 6.

CHAPTER 2
LITERATURE REVIEW

2.0 Overview

The improvement of combustion technology has been studied by many researchers from the past decades up to now. Their studies have been carried out through experimental and numerical works. This chapter is aimed at providing some of related information regarding the research carried out pertaining to the improvement of combustion technology with the important roles played by porous medium, from different researchers across the globe.

This literature begins by reviewing some of the previous studies of gaseous fuel combustion. It follows by reviewing the studies of heat transfer enhancement by using porous medium. Then, the usage of porous medium in different studies of combustion system has been presented. Lastly, this literature will be summarized to highlight the limitation of existing combustion technology pertaining to current work.

2.1 Gaseous Fuel Combustion: A Review of Previous Studies

In the past, the combustion research was directed to fluid dynamics that included global heat release by chemical reaction. This heat release was often described simply with the help of thermodynamics, which assumes infinitely fast chemical reaction. This approach was useful to some extent for designing stationary combustion processes, but it is not sufficient for treating transient processes like ignition and quenching or treatment of pollutant formation. Reducing pollutant formation such as nitrogen oxides (NO_x) and carbon monoxide (CO) during combustion of fossil fuels is, and will continue to be a central topic in future. This continuous demand is raised due to severe environmental requirements and international agreements on reduction of pollutant emissions.

In gaseous fuel combustion field, some researchers have tried to minimize the pollution formation in many different ways such as fuel and air staged combustion (Spliethoff et al., 1996; Pickenacker et. al, 2000), reburning fuel (Kicherer et al., 1994; Spliethoff et al., 1996), porous medium combustion (Brenner et al., 2000; Liu and Hsieh, 2004), swirl burner (Nemoda et al., 2005), turbulent reacting flow in nonpremixed combustion (Celik et al., 1996; Coats and Richardson, 2000; Coats et al., 2000) and catalytic combustion (Grace, 1990; Foka et al., 1994).

From the reviewed works of combustion improvement techniques, it is found that porous medium combustion is one of the latest combustion researches particularly in combustion of gaseous fuel. In porous medium combustion, the main idea is to make use the heat transfer enhancement in the combustion/flame region. By filling the suitable porous material, heat produced during chemical reaction at high temperature region can be removed at a fast rate through its heat transfer mechanisms of conduction, convection and radiation. Therefore, the past studies of heat transfer enhancement by porous medium are an important topic that should be reviewed.

2.2 Porous Medium as Heat Transfer Enhancement

Study of the porous baffles used to enhance heat transfer in a rectangular channel was carried out by Ko and Anand (2003). They measured the average heat transfer coefficients in uniformly heated rectangular channel with wall mounted foam metal baffles. The porous baffles were mounted alternatively on top and bottom of the walls. The data obtained were compared with the data for the straight channel with no porous baffles. From that experiment, Ko and Anand (2003) discovered that the usage of porous baffles can enhance the heat transfer as high as 300% compared to heat transfer in straight channel with no porous baffles.

Schroder et al. (2005) studied the heat transfer between particles and gas in packed beds. In their study, nitrogen gas was flown through packed beds of porous slate particles and of wooden cubes. They obtained the heat transfer data by measuring the particle and gas temperature. They arranged the test particles in order to ensure the heat conduction was excluded. From the temperature measurements of particles and hot gas, the convective heat transfer coefficient between the flowing fluid and the solid particles can be calculated. They found by the increasing of gas flow, it leads to larger values of the heat transport coefficient which implies that the increase of gas flow inside porous medium will increase the heat transfer.

The effect of a random porosity model on heat transfer performance of porous media has been investigated numerically by Fu and Huang (1999). In their study, the physical model was a porous block mounted on a heated region with a laminar slot impinging jet on flow and thermal fields. Their results indicated that the relationship between the local Nusselt number and the near wall local porosity is a negative correlation. Consequently, in order to enhance the thermal performance of the porous medium, the porosity near the solid plate should be smaller to make the conductive heat transfer to be dominant.

Porous medium researchers including Vadasz (2001) and Narasimhan et al. (2001) have studied in depth on the convective heat transfer in porous medium numerically. Vadasz (2001) investigated the different heat transfer regimes in porous layer convection heated from below and the phenomenon of hysteresis in the transition from steady convection to chaos and backwards. From the analytical and computational results, they found that the transition from steady convection to chaos via a solitary limit cycle happened at a sub-critical value of the Rayleigh number. Meanwhile, Narasimhan et al. (2001) studied to predict the global pressure-drop and heat transfer coefficient of a fluid, with temperature-dependent viscosity, convecting through a heated porous medium channel. From their study, they introduced a new theory which incorporated the form-drag effect of the porous medium. According to them, this theory is important for studying the effects of variations in a constitutive property. It is also vital for the design engineer to anticipate the thermo-hydraulic behavior of similar systems enhanced with porous medium and running fluids with temperature depending viscosity.

Yaghoubi and Zahmatkesh (2006) studied numerically the thermal performance of electrical heater by using porous materials and compared with the conventional ones. In their study, the solid heating element used in conventional heater was replaced by a porous heating element. In the numerical solution, they solved the coupled differential equations for both solid and gas phase simultaneously by a control-volume based procedure along with the corresponding boundary conditions, using SIMPLE algorithm. From their study, they found that for equal air flow rates, equal heater masses, and the same energy generations rates, the heating element in the porous heater attained the lower temperature compared to the conventional heater, which implies that the high-heat-flux removal is obtained by porous material.

2.3 Use of Porous Medium in Combustion System: Experimental Investigation

Since porous medium has been shown to enhance the heat transfer, it has also been used in liquid and gaseous fuel combustion to improve the combustion process. Babkin et al. (1991) were the first to do the experimental study of the porous medium usage in combustion. In their study, the combustion flame was directed to go through the porous medium in order to study the level of porosity that flame can pass through. From their study, they proposed a modified Peclet number, Pe to determine the ability of flame to propagate inside porous medium. The modified Peclet number is shown as follows:

$$Pe \geq 65$$

where

$$Pe = \frac{S_L d_m C_p \rho}{k} \tag{2.1}$$

with S_L is the laminar flame velocity, d_m the equivalent porous cavity diameter, C_p the specific heat capacity, ρ the density and k the thermal conductivity of the gas mixture. If Pe < 65, the flame structures will extinguish (quenching), since heat is transferred to the porous medium at a higher rate than it is produced.

In 1999, Kesting et al. used porous medium (silicon carbide crystalline form) in their radiation burner for methane and pure oxygen instead of ambient air as oxidant. Since pure oxygen and methane were used, the resulted combustion temperature will exceed the temperature resistance of all known materials. So, by using porous medium, they found that the temperatures of the radiation burner can be kept below the known material limits (<1800˚C), although pure oxy-fuel combustion produced a very high temperatures (>2800˚C) when they filled porous medium in high temperature zone.

The combination of small pores (Pe<65) and large pores (Pe≥65) of porous medium in methane/air combustion system was studied by Brenner et al. (2000) and Pickenacker et al. (2000). In this study, the methane/air mixture is fed into the combustion system through the small pores region and flame ignition occurred in large pores region. Brenner et al. (2000) have investigated numerically and experimentally the combustion occurred inside porous medium. They filled a zirconium oxide foam in the small pores zone and ceramic foam and static mixer-like alumina fiber structure in the large pores zone, while Pickenacker et al. (2000) have filled alumina perforated plate in the small pores zone and alumina fiber structure in the large pore zone in their staged combustion system. From their studies, they found that the small pores of porous medium which flame was quenched; the unburned mixture is only preheated by the heat fed back from the large pores region (combustion zone). The preheated of the unburned mixture is important to achieve the maximum amount of fuel burning during combustion process. Also, as expected the combustion occurred inside the large pores of porous medium.

Later on, Liu and Hsieh (2004) have embedded several cooling tubes in the post flame region which are surrounded by small porosity of porous medium (packed ceramic beads) in order to study the use of cooling tubes to absorb the combustion heat. Small porosity was used due to its heat transfer rate to the cooling tubes is higher than the large porosity. According to them, the heated working fluid in cooling tubes could be utilized in various applications such as water or air heaters, boilers and fluidic chemical heaters. In their study, they used a liquefied petroleum gas (LPG) as a fuel. Their research finding was the working medium flowing in the cooling tubes had absorbed a large portion of the combustion heat. Therefore, it changed the heat balance in the burner and introduced so-called "metastable combustion"; i.e., only one stable flame speed can be achieved at a particular equivalence ratio to maintain stable combustion within the porous bed. As reported by Liu and Hsieh (2004), their study has produced the emissions of NO_x and CO below 10 ppm.

Kamal and Mohamad (2005) have studied the radiation output from nonpremixed combustion by using porous medium (silicon carbide foam). In their study, the nonpremixed flame was flown upward through the porous medium. The nonpremixed flame was obtained by a vane-rotary burner, in which the swirling fuel flow was confined by an air duct. They found that with the presence of porous medium, the burner radiation flux can be promoted by the effective heat transfer between the completely burned gases and the porous medium. By optimizing the gap distance between the swirling flow and the base of porous medium, the radiation flux can be enhanced to 5.7 times compare to the combustion without porous medium. Beside that, the location of the porous medium relative to the flame zone can influence the completeness of the combustion process. It consequently reduced the pollution emission and increased the radiation performance. This is because the existence of a solid medium decelerates the mixing between the fuel and air, if they enter the porous medium before reaching their stoichiometric proportions. Also, the porous medium can enhance the turbulence flow inside combustion chamber, thus mixing of air and fuel was improved. In their study, the emission of NO_x was below 10 ppm. Meanwhile, CO and UHC concentrations reduction were obtained at stronger swirling flow.

Marbach and Agrawal (2005) studied experimentally the effects of two different locations of porous medium (silicon carbide coated, carbon-carbon composite foam) to the combustion characteristics. In the first experiment, the location of porous medium was below the combustion zone in consequence of combustion occurred at porous medium surface (so-called surface combustion). Meanwhile, the porous medium was placed in combustion zone for the second experiment in consequence of combustion occurred inside porous medium (so-called interior combustion). They found that the amount of heat transferred for each experiment is different although the heat transfer mechanism is similar for both experiments. In surface combustion, heat is transferred from the reaction zone to the porous medium at and slightly below the porous medium surface. However, interior combustion allows heat transfer to the porous medium both at the reaction zone and downstream by interfacial convection between the products and the porous structure. It is believed that the result of this additional convective heat transfer is the potential for increased preheating of reactants and consequently controls the flame stability and temperature. The emissions of NO_x and CO from their study were in the range of 5-30 ppm and 10-25 ppm respectively.

Study of liquid fuel combustion by using porous medium was started by Kaplan and Hall (1995). In their study, they analyzed the combustion characteristics for three different porous ceramics used: magnesia-stabilized zirconia, silicon carbide and yttrium-stabilized zirconia. Heptane fuel was impinged upward to the porous medium by pressure atomizer (spray nozzle). From their study, they realized that porous medium used has provided the fuel with a convoluted path through a homogeneously radiant field that is without cold boundaries, ensuring droplet vaporization and contributing to complete reaction. On the observations of three ceramic materials, Kaplan and Hall (1995) have found that yttrium-stabilized zirconia and silicon carbide ceramics have good resistance to thermal recycling but they also have limitations. The yttrium-stabilized zirconia supports complete combustion only for prevaporized fuels and the silicon carbide melts at high combustion temperature (>1600˚C). Meanwhile, the magnesia-stabilized zirconia has poor resistance to thermal cycling. In term of emissions, both CO and NO_x were measured low for the range of stable equivalence ratios CO varied from 3 to 7 ppm and NO_x varied from 15 to 20 ppm.

Jugjai et al. (2002) also investigated the combustion of liquid fuels using a porous medium (stainless steel wire net) but without the need of using pressure atomizer. In the combustion chamber, they supplied kerosene fuel dropwise into the porous medium and burnt on the porous medium lower side where the swirling combustion air was supplied and mixed with the fuel vapor. From their observation, the kerosene fuel can be evaporated by the presence of thermal radiation from the downstream combustion zone and the interaction with porous medium. They also confirmed complete evaporation with effective vapor preheating of the liquid kerosene within the porous medium is possible due to a strong energy feedback mechanism by thermal radiation from the flame and combustion chamber surface.

Jugjai et al. (2002) have installed a porous emitter (stainless steel wire net) at the downstream side of the combustion chamber. From their findings, the porous emitter were significantly improved the downstream temperatures compared with the combustion chamber without porous emitter. This may be attributed to an efficient energy feedback by thermal radiation emitted from the porous emitter towards the combustion gases inside the combustion chamber. Thus, it minimized the convective heat loses from the combustion chamber, while enhancing fuel evaporation and fuel vapor preheating inside the porous medium. Beside that, they also found the porous emitter can reduce more CO and NO_x emissions compared to the system without installing porous emitter. Also, the combustion regime was changed by the existence of flue gas recirculation in the combustor resulting from the increase in back pressure.

Since porous emitter can improve the evaporation and combustion process from the earlier study (Jugjai et al., 2002), Jugjai and Polmart (2003) have extended the study to thoroughly investigated the effect of different porous emitter (aluminum oxides packed bed instead of stainless steel wire net) heights and the gap distance between the porous medium to the combustion characteristics. Their research findings was that with the higher of the bed heights, the higher and the more uniform the combustion temperatures become, thus enhancing the combustion process. However, the temperatures within porous medium were almost unchanged as height increases. This means no further improvement in evaporation process within the porous medium. Also, the installation of the packed bed emitter with higher bed heights can cause higher back pressure, thus leading to poor ventilation of the gas from the combustion chamber. It can be expected that once the bed height is above a limited value, the temperature are dropped until reaction ceases and the whole combustion process is stopped. In term of gap effect, the porous emitter has major affects the fuel vapor preheating rather than evaporation and combustion characteristics when the gap distance is big. From their study, they observed the relative low NO_x emission for the whole operating range. Meanwhile, CO emission was found to be strongly dependent on the bed length of the packed bed emitter used.

2.4 Use of Porous Medium in Combustion System: Numerical Investigation

Barra et al. (2003) performed a numerical study of the effects of material properties on flame stabilization in two sections porous medium. They examined the effects of solid conductivity, volumetric heat transfer coefficient, radiative extinction coefficient. Their study was a one-dimensional time-dependent model including the effects of solid conduction, solid-to-solid radiation, convection between the solid and the gas, full chemistry and dispersion effects. From their study, they concluded that the material properties of the solid matrix significantly affect the stable operating range. For the two section porous medium, the upstream section should have low conductivity, a low volumetric heat transfer coefficient, and a high radiative extinction coefficient. The downstream section serves to recirculate heat and should have high conductivity, a high volumetric heat transfer coefficient, and an intermediate radiative extinction coefficient.

The same numerical methods as Barra et al. (2003) was used by Barra and Ellzey (2004) to investigate the heat recirculation and heat transfer of combustion in porous medium. In this study, heat was recirculated through solid conduction and solid-to-solid radiation from the matrix downstream of the flame to the matrix upstream of the flame. Solid-to-gas convection upstream of the flame preheats the incoming reactants, resulting in enhanced flame speeds and local temperatures above the adiabatic flame temperature. From their study, they found that when the equivalence ratio was increased, the heat recirculation efficiency was decreased. Also, both solid conduction and radiation play important roles in the heat transfer process.

Two-dimensional study of combustion and heat transfer in two different geometries of porous medium was carried out by Hackert et al. (1999). The first geometry was a honeycomb, in which a ceramic is penetrated by many small, straight and non-connecting passages. The second geometry consists of many small parallel plates aligned with the flow direction. In their numerical solution, they neglected body forces, Soret and Dufour effects and gas radiation. From the study, it was indicated that the second geometry has produced higher burning rate compared to the first geometry. But, both two geometries showed that the transverse heat losses from the uninsulated porous medium were shown to reduce the peak burning rate and cause flame curvature on a porous medium scale.

The two-dimensional numerical predictions of temperature profiles and pollutants formation of combustion in porous medium integrated with heat exchanger was carried out by Malico et al. (2000). In this study, a multistep kinetics mechanism (77 reactions and 26 species) was employed. They also considered non-equilibrium between the solid and the gas phase and radiation using discrete ordinates method. From the study, they found that by increasing the solid conductivity and the convective heat transfer coefficient, it caused the peak temperature to decrease, the flame front to move upstream and the NO emission to decrease. Beside that, the increase of the extinction coefficient did not have big influence either in the temperature profiles or in the NO emission. Meanwhile if no absorption exists, the flame front moves downstream and the peak temperature increased. Consequently, the NO emissions increased. The perturbations in these parameters had little influence on the CO emission.

Diamantis et al. (2002) have computationally studied the two distinct modes of premixed combustion in porous medium; surface and submerged combustion. The computational model was one-dimensional, steady, and included the effects of solid and gas conduction, convection between the solid and the gas, radiation, species diffusion, and full chemistry using GRI 2.11. From the study, they found that the flame speed (and hence thermal load) was significantly higher in submerged flames and hence low volumetric heat transfer coefficient than in a free flame at the same equivalence ratio. Meanwhile, surface flames were stabilized with burning velocities much lower than those of the respective free flame due to heat loss to the surroundings. Therefore, it revealed that enhancement of flame speeds were caused by preheating of the reactants.

Hayashi et al. (2004) performed a numerical study of reacting flow in a two-layer porous medium. Premixed fuel and air were fed into the perforated plate (aluminum oxides) and reaction occurred inside the foam (silicon carbide). In their study, they considered three-dimensional, steady, laminar, local thermal non-equilibrium between the solid and gas phase and Newtonian flow in inert porous medium. From the study, it was found that strong dissipation of the jets from the perforated plate contributed the flame stabilization inside the foam. Also, for several operating conditions point to the potential for damage of the perforated plate, owing to the high radiative and conductive fluxes, and to the necessity of using smaller pore diameters to avoid flashback.

The effects of hydrogen addition on methane combustion in porous medium were studied numerically by Tseng (2002). A steady one-dimensional laminar flow model was used in their work. Also, this work included the nongray radiation transport for the solid phase. Gas radiation from the fuel/air combustion mixture was considered to be negligible due to insignificant compared with solid radiation. GRI-Mech 2.11 is used for the detailed chemical kinetic model. From the study, they found that the flame speed of combustion in porous medium was increased when added the hydrogen to the fuel. Beside that, the increasing of the hydrogen fraction in the fuel further reduced the flame thickness. Also, the study showed the CO emission was slightly increased and the NO_x emission was decreased as the hydrogen fraction in the fuel was raised.

2.5 Summary

Review of the previous improvement studies for gaseous fuel combustion has indicated that porous medium combustion is one of the latest researches which is being carried out by combustion researchers. Therefore, this type of research is definitely worth for further study. Recent researches on heat transfer enhancement by porous medium have proved that, it can enhance the overall heat transfer as high as 300%

compared to the medium without porous material. Such high heat transfer is needed in flame region during combustion process to minimize the formation of NO_x emission by removing heat from the high temperature zone to the surrounding in the combustion chamber as pointed out in literature. In addition, NO_x emission is also reduced due to the change in the combustion regime with the existence of flue gas recirculation in the combustor resulting from the increase in back-pressure played by porous medium as reported by Jugjai et al. (2002). Besides that, porous medium can enhance the turbulent flow inside combustion chamber by its physical configuration, thus mixing of air and fuel is improved. As a result, the combustion characteristic is improved and consequently the CO emission is reduced.

In the literatures, most researchers have developed the system of premixed combustion inside porous medium where the flame ignition occurred inside the porous medium. Some researchers have also used both the small pore and large pore of porous medium in their combustion system to study the characteristic of the flame towards the size of pore. It is found that a variety of porous medium commonly features used are aluminum oxides, silicon carbide and solid zirconia in the forms of packed bed, foam, matrix and crystalline. Almost all of the available literatures show that by using porous medium, the combustion products, i.e., NO_x and CO emissions were found to be relatively low for the whole operating range.

From the literatures, it is indicated that the combustion systems developed by using porous medium are too complex and quite high risk. In the systems developed, the ignition and combustion occur inside the porous medium. Such technique needs a very