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THE EFFECT OF GEOMETRY CONFIGURATION ON FLAME STABILIZATION IN MICRO COMBUSTOR

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THE EFFECT OF GEOMETRY CONFIGURATION ON FLAME STABILIZATION IN MICRO COMBUSTOR

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DECLARATION

I declare that this thesis entitled "The Effect of Geometry Configuration on Flame Stabilization in Micro Combustor" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : ....

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Date : 21/9/2020

APPROVAL

I hereby declare that I have checked this thesis and in my opinion this thesis is adequate in terms of scope and quality for the award of Master of Mechanical Engineering (Energy Engineering).

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DEDICATION

"To my beloved family"

ABSTRACT

The prime motivation to the renewed interest in meso and micro-scale power generation is the limited energy resources and the strong demand of long-lasting power sources for electronics devices. The thermal energy from the micro combustors can be converted into electrical energy. However, the main obstacle that limits the use of micro combustor is difficulty in stabilizing flame. This difficulty is mainly related to the substantial heat losses due to large surface area to volume ratio. Hence, purposed of this research focuses mainly on determining the factors that affect the flame stabilization in micro-scale combustors with stainless steel wire mesh. The factors focusing on the geometry configuration of the combustor which are the inner diameter of the combustor and the number of stainless-steel wire mesh. A three-dimensional (3-D) numerical model was developed. Computational Fluid Dynamics (CFD) simulation were then performed using the numerical model. The results of the simulations are analyzed based on the flame stability in the micro combustor. The results show that a few of these factors have significant effect on the flame stability in micro scale combustors. The flame stability can be improved by increasing the inner diameter of the combustor. As for the number of stainless steel wire mesh, when the number of stainless steel wire mesh doubled, the burning velocity of the flame also increase resulting to the more stable flame with in the combustor. These findings are important for future improvement of the proposed micro-scale combustor with wire mesh.

KESAN KONFIGURASI GEOMETRI TERHADAP STABILASI NYALAAN API DI DALAM PEMBAKAR MIKRO

ABSTRAK

Motivasi utama penghasilan tenaga meso dan mikro adalah kerana sumber tenaga yang terhad dan permintaan tinggi bagi sumber daya tahan lama untuk peranti elektronik. Tenaga haba dari pembakar mikro boleh ditukar menjadi tenaga elektrik. Namun, halangan utama yang membatasi penggunaan mikro pembakar adalah kesukaran menstabilkan api di dalam pembakar mikro tersebut. Kesukaran ini berhubungkait dengan kehilangan haba yang tinggi semasa pembakaran kerana nisbah luas permukaan dan isipadu yang besar. Oleh itu, tujuan penyelidikan ini adalah untuk menentukan faktor-faktor yang mempengaruhi penstabilan nyalaan dalam pembakar skala mikro dengan jejari besi. Faktor yang dikaji hanya difokuskan pada konfigurasi geometri pembakar iaitu diameter dalaman pembakar dan bilangan jejari besi yang digunakan. Model berangka tiga dimensi (3-D) dirangka dan simulasi berangka dilakukan dengan menggunakan model 3-D terebut. Hasil simulasi dianalisis berdasarkan kestabilan nyalaan dalam pembakar mikro. Hasil kajian menunjukkan bahawa faktor-faktor ini memberi kesan posifif terhadap kestabilan nyalaan dalam pembakar skala mikro. Kestabilan nyalaan dapat ditingkatkan dengan meningkatkan diameter dalaman pembakar. Bagi bilangan jejari besi pula, apabila jumlah jejari besi ditingkatkan pada dua kali ganda, halaju pembakaran api meningkat dan menghasilakan api yang lebih stabil di dalam pembakar. Penemuan ini penting untuk penambahbaikkan pada masa hadapan bagi bidang pembakaran skala mikro dengan jejari besi.

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May He bless our life, give us the desires of our heart and grant us happiness and success in this dunya and in the akhirah.

Nur Umairah binti Md Nor

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3-D	-	Three-dimensional
CFD	-	Computational Fluid Dynamics
TPV	-	micro thermo-photovoltaic
d	-	Inner diameter of combustor
Da_h	-	Damkohler number
E_a	-	Activation energy
F_x	-	External force in x-direction
F_r	-	External force in r-direction
h	-	Convective heat transfer coefficient
k	-	Wall thermal conductivity
mm	-	Millimeter
q''	-	Heat flux
R	-	Gas constant
T	-	Temperature
T_{amb}	-	Ambient temperature
U	-	Flow velocity
u_x	-	Flow velocity in x-direction
μ	-	Fluid viscosity
ϕ	-	Equivalence ratio
ρ	-	Density

ε	-	External emissivity
σ	-	Stefan-Boltzmann constant
$\tau_{residence}$	-	Residence time
$\tau_{chemical}$	-	Chemical time scale

CHAPTER 1

INTRODUCTION

1.1 Research Background

The prime motivation to the renewed interest in meso and micro-scale power generation is the limited energy resources and the strong demand of long-lasting power sources for electronics devices. The thermal energy from the micro combustors can be converted into electrical energy. Micro power generation system has a potential to be a solution to provide an improved version of energy requirement for small-scale devices as another power source compared to conventional batteries. According to Veeraragavan and Cadou (2011), the strong demand for better alternatives to the current lithium ion batteries have resulted in increase of the research interest in micro power generation system. The coupling of electronic devices such as mobile phones and laptops, with conventional lithium ion batteries might limit their potential superior performance as those devices requires high energy capacity, fast charging and light in weight. On this basis, micro power generation system is considered as one of the best alternative to the conventional batteries. One of the advantages of micro power generation system is the high-energy storage per unit mass and power generation per unit volume (Norton, Wetzel et al. 2004). Energy density of hydrocarbon fuels has approximately 100 times compared to lithium batteries. Theoretically, with only 10% of efficiency, the total useful energy harvested is still outnumbering the lithium ion batteries. The use of the hydrocarbons fuels as the combustion source substantially reduces the operational cost and improves the voltage stability (Li, Chou et al. 2009).

According to previous research, flame stabilization in such narrow channel combustors is difficult but achievable (Miesse, Masel et al. 2004). As time passes, some researcher came up with solutions and proved that it is possible to achieve combustion within micro scale channel (Choi, Kwon et al. 2008). The performance of micro scale combustion influenced by few factors such as convection, radiation, gas-phase and surface reactions, molecular transport, thermal and mass diffusion (Ju and Maruta 2011).

Nevertheless, the main obstacle that limits the use of micro combustor is difficulty in stabilizing flame and the system portability issue with the use of gaseous fuels. According to the research by Munir and Mikami (2015) and Yuliati (2018) on stability issue, utilizing flame holder is able to stabilize the flame inside the narrow combustion chamber. Flame stabilization also can be realized by recirculating the heat generated from the combustion of fuel mixture (Fan, Li et al. 2019). In macro scale combustors such as the internal combustion engine (ICE), part of the burned exhaust gas is recirculated and injected into the incoming reactants. As such the amount of oxides of nitrogen (NOX) can be significantly reduced (Turns 2000). For any combustion process to take place, the residence time should be larger than the combustion time (Zhang, Wu et al. 2020). However, in micro scale combustors, the length scale is tremendously reduced. Consequently, the flow becomes laminar due to the decrease of Reynolds number. This laminar flow causes the diffusion time to increase, which lowers the residence time. In such condition, combustion might cease to exist. It is important to analyze the factors affecting flame stabilization in meso and micro scale combustors in order to achieve high energy conversion. Those factors including thermal heat loss, wall flame thermal and chemical coupling, fuel-air mixing, flow field structure and flame temperature (Wang, Yang et al. 2011, Zuo, E et al. 2018).

The meso scale combustors with heat recirculation mechanism was first proposed by Weinberg et, al. (2002). The hot exhaust gas is used to pre-heat the reactant which consist of fuel air mixtures. As a result, the flame stabilization is enhanced. This mechanism of flame stabilization is known as excess enthalpy principle (Zhang, Wu et al. 2020). Basically, there are two types of preheating methods which are direct and indirect method (Pan, Zhang et al. 2017). Direct method is where the heat from the unburned gas region is mitigated to the burned gas region by means of heat conduction via the combustor wall. This type of method is commonly applied for single narrow channel combustor. As for indirect method, reversing hot exhaust gas is used to pre-heat the unburned reactants before being combusted in the combustion region. It is widely utilized in counter-current heat recirculation combustors (Zuo, E et al. 2017, Tang, Cai et al. 2018). Swiss-Roll (SR) combustor is one of most popular micro combustor that applied indirect preheating method. Yet, the complexity in terms of geometry and design parameters of SR combustor lead to the difficulty for the combustor to be analytically and experimentally investigated (Mane Deshmukh, Krishnamoorthy et al. 2018, Wang, Yuan et al. 2019).

As mentioned before, flame stabilization in such narrow channel combustors is difficult but achievable (Miesse et al., 2004). One of the methods to stabilize flame inside micro combustors is by utilizing flame holder (Munir and Mikami, 2015). Mikami et al. (2013) has proposed stainless steel wire mesh as the flame holder for cylindrical quartz tube micro combustors. It is reported that both liquid and gaseous fuel can be used as the fuel source for combustors with stainless steel wire mesh. However, the use of ceramic adhesive in their combustors induced hot spot which can potentially reduce the lifespan of the combustors.

Experimental works to investigate the effect of geometry configuration on flame stabilization in micro scale combustor with stainless steel wire mesh will be performed. In this research, a numerical three-dimensional (3-D) model of micro combustor with wire mesh is will be utilized. The continuity, momentum, energy and species equations are solved by using Fluent 6.3 to understand the heat transfer, fluid flow, chemical reactions and other related phenomena.

1.2 Problem Statement

Micro power generation system is considered as one of the best alternative to the conventional batteries. One of the most important components in micro power generation system is the micro combustor. The thermal energy from micro combustor can be converted into useful electrical energy to be utilized by electronics equipment. Flame stabilization in such narrow channel combustors is difficult but feasible even in a sub-millimeter combustor diameter (Miesse et al., 2004). There are few ways to improve flame stability such like by utilizing frame holders, catalyst and modification of combustor geometry (Munir and Mikami 2015). Apart from that, utilizing hydrogen gas as fuel source also can stabilize the flame but the portability and safety issues might become a great concern. Preheating methods is one of the effective technique to improve flame stabilization limit. Pre-heating methods can be done by increasing the number of wire-mesh inside the combustor. By preheating the incoming reactants prior to combustion leads to the elevation of flame burning velocity (Maruta 2011). Thus, a larger flame blowout limit occurred resulting to higher power conversion. In this project, the factors affecting the flame stabilization limits of micro scale combustors will be numerically investigated. This investigation focusing on the geometry configuration of the micro combustors which are inner diameter of micro combustor and the number of wire mesh stainless-steel use inside the combustor. The ultimate objective is to enhance the flame stability in such combustors for better performance, which can lead to better conversion efficiency for the use in micro power generation system.

1.3 Objectives of the research

The main objectives of this research are as follow:

a) To validate the effect of parameters focusing on inner diameter of the micro combustor with the results of previous study.

b) To analyse the effect of number of wire mesh on flame stabilization in micro combustor.

1.4 Scopes of Research

The numerical work of this project was conducted to examine the effect of geometry configuration in order to enhance the flame stabilization in micro-scale combustors. The first scope of the research was to construct numerical model for simulation purposes using the available commercial license. ANSYS Release 16.0 was utilized for the development of the numerical model. A three-dimensional (3-D) model was developed. A stainless-steel wire mesh is model in between the unburned and burned gas region. The role of the wire mesh is to act as the flame holder where the flame can be stabilized in certain positions.

Furthermore, numerical simulations were performed using the numerical model. The continuity, momentum, energy and species equation are solved by using Fluent 6.3 software. The evaluation on various parameters that might affect flame stabilization in the micro-scale combustor were conducted using numerical simulations. Example of these factors are combustor inner diameter, the configuration of the wire mesh and external factors such as heat transfer coefficient. Finally, the analysis and discussion on the changes in the combustion characteristics such as flame stabilization and combustion efficiency will be presented in this thesis.

1.5 General Methodology

The methodology implemented on this research takes the following steps of works:

a) Literature review

Review the journals, articles, books or any website regarding the project.

b) Create the numerical model using commercial license

A three dimensional (3-D) numerical model of micro scale combustor with stainless steel wire mesh was developed. The stainless-steel wire mesh is placed between the unburned and burned gas region. The main function of the wire mesh is to act as the flame holder where the flame can be stabilized near the wire mesh.

c) Numerical simulations

Numerical works will be performed by utilizing the numerical model. Evaluation on various factors affecting the flame stabilization in the micro scale combustors with stainless steel wire mesh will be conducted.

d) Result analysis

The flame stabilization limit was established for each factors. Besides, the results in terms of gas temperature, outer wall temperature, combustion efficiency, wire mesh temperature and heat fluxes were analyzed and presented. The correlation between these results with the changes in flame stabilization phenomenon is established.

1.6 Research Organization

The structure of this study consists of five chapters. Chapter one provides a research background, problem statement, objectives, scopes and general methodology. A brief summary of micro power generation is given. The main component of micro power generation which is micro combustor is also explained. As for the second chapter, the highlights of the literature review from previous studies which addresses all the details of micro power generation system and factors affecting combustion characteristics in different types of combustors is presented. Chapter three focused on the discussion of the numerical setup applied in this study. The methodology details of the primary work to prepare the numerical setup were explained. Numerical simulations were performed to investigate the factors affecting the flame stabilization limits for micro scale combustors with stainless steel wire mesh. Examples of these factors are the combustor outer wall thickness, inner diameter of combustor, configuration of wire mesh, type of fuel used, material type used for combustors and other external factors such as heat transfer coefficient. Chapter four described the important results of obtained from the numerical simulations. Chapter five summarized all the research work results, where the most important findings and contribution of present work are mentioned. Besides, various recommendations for possible developments and future applications are also suggested in this chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter explains the bottom line of micro-power generation system based on previous experimental work. Further elaboration regarding micro combustors, which is the main component in micro power generation and the fundamental issues which is flame stabilization is presented.

2.2 Micro power generation system

The prime motivation to the renewed interest in meso and micro-scale power generation is the limited energy resources and the strong demand of long-lasting power sources for electronics devices (Vican, Gajdeczko et al. 2002, Vullers, van Schaijk et al. 2009, Töreyin, Topal et al. 2010). The thermal energy from the micro combustors can be converted into electrical energy to be utilized by electronics equipment. According to Fernandez-Pello (2002), micro power generates heat from combustion and motion through movement which then will be converted into electricity. Micro power generation described as a devices or a system that consumed a very small amount of electric generators between range of milli-watts to watts, typically integrated with microelectronic devices (Chou, Yang et al. 2011). Micro-combustion systems have the same feature as macro-scales, but on a miniature scale. There are two main