NUMERICAL SOLUTION ON THE EFFECTS OF BLUFF BODY WITH SLIT IN MICRO-CHANNEL COMBUSTOR

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Thesis submitted to the Centre of Graduate Studies, Universiti Pertahanan Nasional Malaysia**,** in fulfilment of the requirements for the Degree of Master of Science (Mechanical Engineering)

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ABSTRACT

Small-scale electronic devices required long hours operation and fast charging time. Potential technology to support requirement of small-scale electronic device is micro scale combustor. Production of heat in micro level from progression of exothermic chemical reaction between reactants is known as micro combustion and may be utilized to generate electricity for small-scale electronic devices. Unfortunately, micro scale combustion is prone to combustion instability. This research is to study micro scale combustion with slit. Therefore, objective of this study is to investigate the combustion characteristics, mechanism that stabilize the flame and combustor performance of the 2-D microchannel combustor with bluff body having various slit percentages gap using ANSYS Fluent 15.7. Effects of the bluff body with slit in the micro-channel combustor have been studied numerically. Two-dimensional computational domain with the height and length of the channel H = 1 mm and L = 16 mm is used respectively. The height of the bluff body is 0.5 mm and located at 2 mm from the inlet. The slit gap percentage varied in this study is 0% to 70%. The percentage of the slit size is the ratio between slit gap height and the bluff body height. The one-step reaction mechanism of CH_4/air mixture is utilized. Equivalence ratios of 0.8 to 1.0 with inlet velocities 1.0 m/s to 5.0 m/s were used. The results show that the combustion characteristic such as stable flame, wavy flame, blow-off and flame split into two parts is significantly influenced by the slit gap percentage. Flame is moving downstream and blow-off at the slit percentage of 10% to 25%. At the slit percentage of 30%, the flame zone moves towards the upstream result in stable flame. From the observation is suggested due to the secondary vortex exist behind the bluff body as slit gap increases and pull or push the flame to the upstream or downstream. The reaction zone is split into two parts at 60% and 70% slit gap percentage. It is due to the incoming fresh mixture of CH_4/air mixture flows through the slit and cut the flame zone. It is also found that by increasing inlet velocity beyond 2.0 m/s, the flame become unstable and lead to blow-off as increase in equivalence ratio up to 1.0. Lastly, the highest emitter efficiency is found for the case of 40% slit which is 25 W/m.

ABSTRAK

Alatan elektronik mudah alih memerlukan penggunaan untuk jangka masa lama dan masa pengecasan yang cepat. Teknologi yang berpotensi untuk memenuhi keperluan alat elektronik ini adalah ruang pembakaran mikro. Penghasilan haba di peringkat mikro dari proses tindak balas kimia eksotermik antara bahan bakar dikenali sebagai pembakaran mikro dan ia boleh digunakan untuk menjana elektrik bagi alat elektronik mudah alih. Malangnya, pembakaran mikro terdedah kepada ketidakstabilan pembakaran. Kajian ini bertujuan untuk mengkaji ruang pembakaran mikro bersama *bluff body* yang mempunyai belahan. Oleh itu, objektif kajian adalah untuk melaksanakan kajian terhadap karakter pembakaran, mekanisma yang menyebabkan api stabil dan keupayaan ruang pembakaran mikro dalam dua dimensi bersama *bluff body* yang mempunyai belahan di tengah dengan menggunakan ANSYS Fluent 15.7. Kesan-kesan dari *bluff body* yang mempunyai bukaan di tengah telah dikaji secara berangka. Ruang pembakaran secara 2 dimensi yang mempunyai ketinggian H = 1 mm dan panjang L = 16 mm telah digunakan. Ketinggian *bluff body* adalah sebanyak 0.5 mm yang ditempatkan 2 mm dari bahagian masuk ruang pembakaran. Peratusan bukaan *bluff body* yang digunakan adalah dari 0% sehingga 70%. Peratusan ini dikira berdasarkan nisbah ketinggian bukaan dibahagikan kepada ketinggian *bluff body* itu sendiri. Bagi reaksi kimia pula, mekanisma satu langkah reaksi dari campuran *methane* dan udara CH_4/*air* telah digunakan bagi keseluruhan kajian. Pemboleh ubah yang dimanipulasikan dalam kajian ini adalah nisbah keseimbangan campuran bahan bakar iaitu sebanyak 0.8 hingga 1.0 bersama kelajuan masuk bahan bakar tersebut iaitu 1.0 m/s hingga 5.0 m/s. Keputusan kajian mendapati sifat pembakaran seperti api yang stabil, api yang berombak, api yang tertolak keluar dan api terpisah kepada dua bahagian adalah hasil dari kesan peratusan bukaan pada *bluff body* tersebut. Didapati juga bagi bukaan 40%, keberkesanan pemancar adalah yang tertinggi. Selain itu, didapati setelah ditambah peratusan bukaan melebihi 10%, pembakaran akan bergerak kearah belakang ruang pembakaran dan terpadam. Apabila peratusan bukaan ditambah sebanyak 30%, pembakaran akan bergerak ke bahagian hadapan ruang pembakaran disebabkan kehadiran *vortex* kedua di belakang *bluff body* yang menarik pembakaran ke hadapan. Selain itu, pada bahagian tengah pembakaran telah terpecah kepada dua disebabkan kehadiran bahan bakar *methane* dan udara CH_4/*air* baharu yang telah menembusi pembakaran tersebut dan seterusnya memotong zon pembakaran menjadi dua bahagian. Didapati juga dengan peningkatan kelajuan masuk melebihi 2.0 m/s, api tersebut menjadi tidak stabil dan akhirnya mengakibatkan terpadam apabila nisbah bahan bakar ditingkatkan sehingga 1.0. Kesimpulannya, ruang pembakaran yang paling efisien adalah dicadangkan di dalam lingkungan 40% bagi belahan *bluff body* iaitu sebanyak 25 W/m.

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APPROVAL

The Examination Committee has met on **26th September 2018** to conduct the final examination of **Wan Mohd Amin bin Wan Shuib** on his degree thesis entitled '**Numerical Solution On The Effects Of Bluff Body With Slit In Micro-channel Combustor'**

The committee recommends that the student be awarded the Master of Science (Mechanical Engineering)

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This thesis was submitted to the Senate of Universiti Pertahanan Nasional Malaysia and has been accepted as fulfilment of the requirements for the degree of **Master of Science (Mechanical Engineering)**. The members of the Supervisory Committee were as follows:

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C	-	Carbon
CH_4	-	Methane
O_2	-	Oxygen
CO_2	-	Carbon Dioxide
H_2O	-	Water
H	-	Hydrogen
exp	-	Exponential
T	-	Temperature
r	-	Arrhenius reaction / Radial coordinate
ρ	-	Density
Y_i	-	Mass fraction of species i
D_i	-	Diffusion coefficient of species i
p	-	Static pressure
μ	-	Dynamic viscosity
Σ	-	Sum of
Re	-	Reynolds number
Ø	-	Equivalence ratio
F	-	Fuel
A	-	Air
stoic	-	Stoichiometric
H	-	Height of micro channel
L	-	Length of micro channel

H_{bluff}	-	Bluff body height
H_{slit}	-	Height of slit
ζ	-	Blockage ratio
η	-	Emitter efficiency
H_i	-	Diameter of inner combustor
t	-	Wall thickness of combustor
ε	-	Surface emissivity
σ	-	Stefan-Boltzmann constant
T_{w_0}	-	Temperature of micro combustor walls
X_i	-	Position from inlet of combustor
H_c	-	Heating value of CH_4
$\dot{m}_{CH4}$	-	Mass flow rate of CH_4
Q_N	-	Heat loss by the convection
Q_R	-	Heat loss by the radiation
Q_{loss}	-	Total heat loss
h_{out}	-	Heat transfer coefficient of the natural convection
T_∞	-	Ambient temperature
α	-	Emissivity of the solid surface
s_c	-	Flame consumption speed
s_d	-	Flame displacement speed
s_a	-	Flame absolute speed
θ_f	-	Isolevel
$\vec{w}$	-	Velocity of burnt gas move to remain on the surface

$\vec{n}$	-	Velocity of burnt gas to fresh reactants
$\vec{u}$	-	Flow speed
ϴ	-	Reduced temperature
u_1	-	Flow velocity ahead of the flame
s_L^0	-	Speed of a laminar planar unstretched freely propagating in one-dimensional flame
y	-	Axial coordinate
$\vec{J_i}$	-	Species *i* diffusion flux
S_h	-	Chemical reaction heat formation
R_i	-	Species *i* net production rate by chemical reaction
$D_{i,m}$ or	-	Species *i* mass diffusivity in the mixture
$\bar{\bar{\tau}}$	-	stress tens
Y_i	-	Species *i* mass fraction
$D_{T,i}$	-	thermal diffusion coefficient
k	-	Thermal conductivity
c_i	-	Species *i* molar concentration
$\widehat{\omega}_i$	-	Species *i* rate of change in the molar concentration
$k_f(T)$	-	Specific reaction rate constant
E_a	-	Activation energy
A	-	Pre-exponential factor
n_i	-	Reaction rate order with reference to the *i* th species
u	-	Radial velocity
v	-	Axial velocity

CHAPTER 1

INTRODUCTION

1.1 Introduction

Electronics system and mechanical system required a power to be operated. Power is the usage of energy over the time. Energy neither can be created nor destroyed. Energy comes in multiple forms including radiation, chemical, gravitational potential, electrical potential, latent heat, kinetic and others. Study on energy is a never-ending story along with its resources. The United States Energy Information Administration (US EIA) had published the latest amendment of its International Energy Outlook 2017 (IEO2017), which is a research for world energy markets and reported that fuel sources are the main usage for energy consumption and have been increased year by year. Fast growing energy source is expected by renewable and nuclear power but the world is still dependent on fossil fuels as its primary principle energy source well into the future. Figure 1.1 illustrated the world energy consumption by energy source (1990-2040).

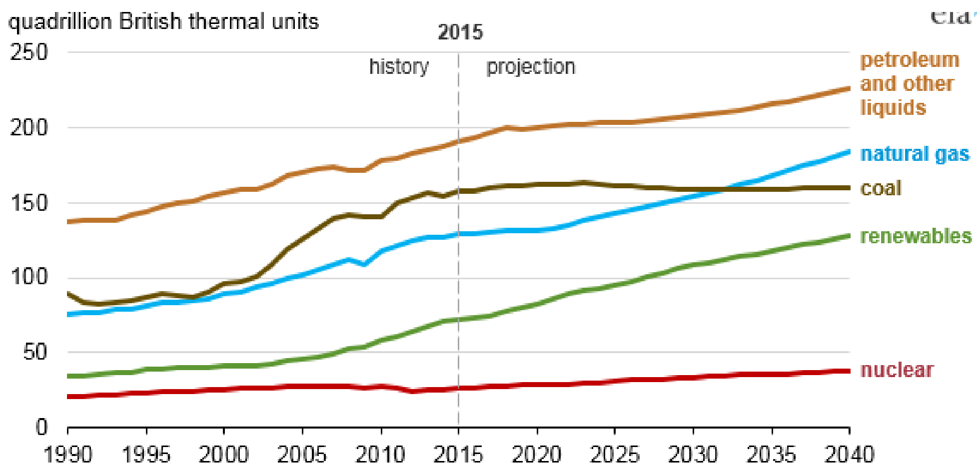

Figure 1.1 World energy consumption by energy source (1990-2040) (Kleven, 2017)

This study is one of the efforts to improve the energy supply for electronics or particularly on Microelectromechanical System (MEMS) technology. Contribution for this study can be divided into several points, which are enhancement safety for aviation, supporting green campaign for environmental safety, enhancement in energy density for MEMS, and prolonged serviceability of electronics component.

Top management for high-risk work at any company is always emphasizing safety and health at work. By having reliable machine or system as medium to execute the mission or task, safety and risk management is easy to manage. Although most of the machines in aviation industry use electrical power from electric power station, aircraft engine or generator, they still require secondary power or back up power at least to operate the mandatory component. For example, in the case of an aircraft that totally loses its power, pilots are able to avoid collision with the other aircrafts and landed safely when communication and navigation devices are still functioning. This back up power can be energized by batteries or alternatively micro combustor in

MEMS technology. Microscale combustion is the production of heat in micro level from progression of exothermic chemical reaction between reactants in which combustor geometry less than 1 mm (Bui, 2013). This research is to elucidate the stability and efficiency of micro combustor so that it can be used for a longer period of operation.

Other than that, nature is paramount to be concerned for the sake of people interact with nature consistently and these interactions can influence health variation and quality of life (Healthy People Team, 2018). Chemical waste contributes to pollution and pollution contributes to diseases. Batteries are made from chemical substance. For instance, lithium, zinc, alkaline, and silver. These chemical may jeopardize the stability of nature especially water and land. The widespread use of batteries has created many environmental concerns, such as toxic metal pollution, and also contributes to electronic waste. Americans purchase nearly three billion batteries annually (Sharman, 2014). Batteries may also explode due to misuse or malfunction, or short circuit and the other factor is corrosion due to many batteries chemicals are corrosive, poisonous, or the chemicals released could be dangerous (Sharman, 2014). As for the effects of water pollution due to batteries waste, several diseases may occur such as Cholera, Malaria, and Typhoid. Besides that, aquatic life may also be destroyed. Thus, micro combustion energy generated system may contribute for environmental safety and at the same time keeps our world green.

In addition, micro combustion has other incomparable advantages. Hydrocarbon fuels make a relatively low environmental footprint in utilization while disposal of used battery can cause serious environmental issues (Fernandez-Pello, 2002, Kaisare and Vlachos, 2012). Moreover, unlike batteries suffering from vital drawbacks of long recharging but short operating time, micro combustion based devices take advantage of instant rechargeability just by replacing the fuel cartridge (Ju and Maruta, 2011, Kaisare and Vlachos, 2012). In combination with these benefits, other strong points for micro combustion process are constant voltage during operation, no memory effect, better chemical stability, and longer lifetime that make it quite attractive and promising for providing power in various small-scale applications (Chia and Feng, 2007).

1.2 Problem Statement

The main problem in small-scale electronic devices such as smartphones, unmanned aerial vehicles (UAV), and MEMS is the capability to sustain long operation hours. Conventional batteries and even the latest technology of common alkaline batteries (lithium-ion) can only provide an energy storage of 0.6 MJ/kg whereby sustainability is about three to six hours for non-stop operation (Fernandez-Pello, 2002). Thus, requirement for new method of energy-generated system is highly demanded. Currently, every user demands for the most reliable system to ease their workload. With that concern, electronic devices such as smartphones are required to be operated in longer hours to avoid communication break down or any unwanted incident. Epstein and Senturia (1997) proposed new method of power generated system for small electronics devices by creating micro combustor to supply heat energy to be converted to electrical power. Every new finding has its own challenges; major issue in micro combustor is how to stabilize the combustion in small volume area. Several methods have been proposed to overcome the issue in micro combustor such as adjusting the geometry of the combustor, making cavities, wire insertion and adding bluff body at the inlet of combustor. To the author's knowledge, bluff body with a slit in micro combustor has minimal studies in micro combustion field. Thus, this topic builds an author's interest. One of the contributions of this study is the improvement the combustion stability on supplying heat towards achieving higher energy density for micro-scale system. In conjunction with higher energy density, the serviceability of electronic components or system can be prolonged.

The most valuable micro-scale system is MEMS Technology. MEMS grows rapidly as well as nanotechnology and makes the world competing for development for tiny scale devices out of the blue for the field, such as small-scale sensors, small unmanned aerial vehicles, printers, cars industries, smartphone industries, biomedical engineering, defense technology and aviation industries. On the other hand, the progression on developing small-scale energy source to empower those devices is still lacking specifically when mass to volume and energy density play an important role to determine the capability of certain devices (Fernandez-Pello, 2002, Chia and Feng, 2007, Ju and Maruta, 2011, Maruta, 2011, Kaisare and Vlachos, 2012). Presently, conventional batteries experience many difficulties due to low energy density and unable to solve the challenge as batteries always take considerably more mass fraction and volume fraction of the devices and thus contribute to logistical issue (Fernandez-Pello, 2002).

Utilization of micro combustor with high energy density of hydrocarbon as one of reactants is highly required to fulfill the needs of compress and high energy density power sources for power generating system. Figure 1.2 indicates that typical liquid hydrocarbons are capable of providing a high specific density at 25 MJ/kg while common alkaline batteries (lithium-ion) can only provide an energy storage of 0.6 MJ/kg (Fernandez-Pello, 2002). Therefore, in reality, the energy conversion efficiency from chemical to electrical energy should be scaled with power generating systems. It is predicted that the replacement of traditional batteries with this competitive small-scale combustion based power systems is possible.

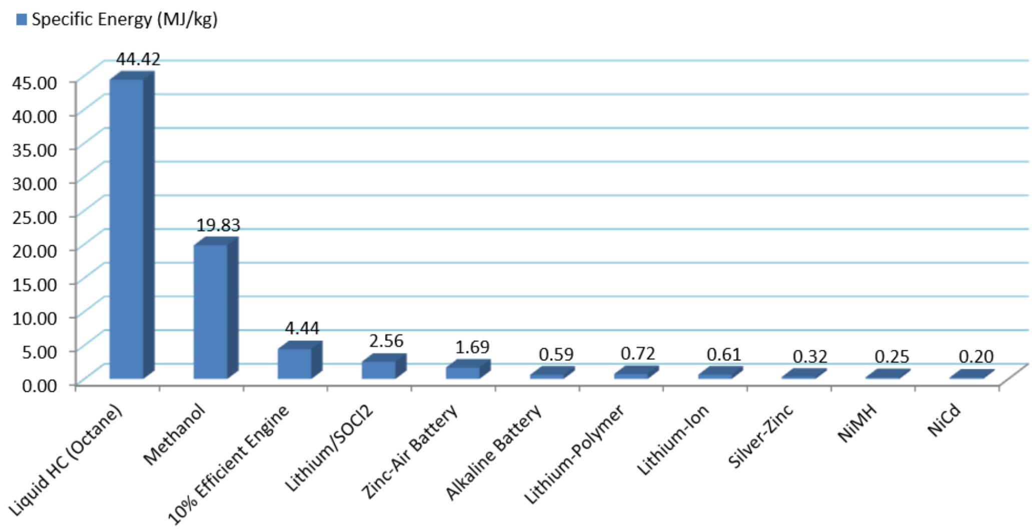

Figure 1.2 Specific energy for hydrocarbon fuels and traditional batteries (Fernandez-Pello et al., 2002)

However, there are essential obstacles for micro combustor, which are the stability of the flame internally due to short flow residence time at small-scale, and heat losses from the combustor walls that contributes to increasing surface-to-volume ratio (Kang et al., 2017). There are many methods to stabilize the flame inside micro combustor and one of it is by using bluff body inside micro combustor. Yan et al.

(2018) had studied combustion characteristics of methane/air in a micro combustor with a regular triangular pyramid bluff body and found that blow-off limit was extended 2.4 times more than micro combustor without bluff body. In addition, by increasing blockage ratio of the bluff body, the temperature behind bluff body increased. Liu et al. (2014) had investigated the blowout in slit bluff-body stabilized flames for macro scale and found out that blowout limit can be improved by optimal slit ratio. Thus, gap for new research was found that bluff body with a slit in micro combustor has never been studied previously. Therefore, the research problem is to investigate the effects of slit gap percentage of trapezoidal bluff-body on flame dynamics of methane/air combustion in a micro-channel.

In the nutshell, this study may contribute some useful information for the improvement of thermal efficiency and flame stability of micro combustion system. Consequently, it will contribute to work-life balance because the work can be done effectively, continuously and safely.