INVESTIGATION OF FLAME STABILIZATION IN COUNTER CURRENT MICRO COMBUSTORS

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A report submitted

in fulfilment of the requirements for the degree of

Bachelor of Mechanical Engineering (Automotive) with honours

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DECLARATION

I declare that this project report entitled "Investigation of Flame Stabilization in Counter Current Micro Combustors" is the result of my own work except as cited in the references.

Signature : …………………………….

Name : AKHMAL FIRDAUS BIN OSMAN

Date : ……………………………

APPROVAL

I hereby declare that I have read this project report and in my opinion this report is sufficient in terms of scope and quality for the award of the degree of Bachelor of Mechanical Engineering (Automotive) with honours.

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Name of Supervisor	: DR. FUDHAIL BIN ABDUL MUNIR
Date	: ……………………………

DEDICATION

This thesis is dedicated to Osman Bin Raban, Masita Binti Md. Ali, family and friends.

ABSTRACT

This project present an investigation of flame stabilization in counter current micro combustors. The stabilizing a flame inside a micro combustors poses a great challenge to researchers. This Final Year Project focuses mainly on the designing the numerical model for simulations to investigate effect of counter current flow on the flame stabilization in counter current micro combustor with stainless wire mesh. In the counter current combustors, a portion of the tube was heated exhaust gas coming from the burned gas region. Flame stabilization limits were then determined. The flame stabilization limits in this case is defined as the limits in which the flame stabilizers near to the wire mesh of the tube counter current combustors. Investigation of the numerical models with different combinations were performed to deduce the trend pattern of the gas temperature. From the result of the simulations, it can be deduced that higher wall temperature in the burned gas region contributes to better flame stabilization limits. The effective role of the wire mesh in distributing heat from the burned to the unburned gas region was demonstrated by using the developed 3-D numerical simulation. The result from the simulations are then utilized to propose a combustors that can be used for both gaseous and liquid fuels.

ABSTRAK

Projek ini membentangkan siasatan penstabilan api di kaunter pembakar mikro semasa. Penstabilkan api di dalam satu pembakar mikro menjadi cabaran besar kepada penyelidik. Projek Tahun Akhir ini memberi tumpuan terutamanya kepada mereka yang membentuk simulasi model yang memberi kesan penstabilan api di kaunter pembakar mikro semasa dengan jaringan dawai tahan karat. Di kaunter pembakaran semasa, sebahagian daripada tiub itu ekzos panas yang datang dari kawasan gas yang terbakar. Had penstabilan api kemudian ditentukan. Had penstabilan dalam kes ini ditakrifkan sebagai had di mana penstabil api berhampiran dengan jaringan wayar tiub menangani pembakaran semasa. Siasatan tiub model berangka dengan kobinasi yang berbeza telah dijalankan untuk menyimpulkan corak tred suhu. Dari hasil simulasi, ia boleh disimpulkan bahawa suhu dinding di rantau gas yang terbakar menyumbang kepada lebih baik penstabilan had api. Peranan yang berkesan jaringan dawai di dalam mengeluarkan haba dari dibakar ke rantau gas yang tidak terbakar ditunjukkan dengan menggunakan sumulasi 3-D model berangka. Keputusan daripada simulasi digunakan untuk mencadangkan bahawa pembakaran diantara kedua-dua bahan api bergas dan cecair boleh digunakan.

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LIST OF ABBEREVATIONS

MEMS	Micro Electro – Mechanical System
MIT	Massachusetts Institute of Technology
TPV	Thermo – Photovoltaic
SC	Single Channel
CC	Counter Current
SR	Swiss – Roll
RF	Reverse Flow
3-D	Three- Dimensional
E_a	Activation Energy
mm	Millimetre
W/mK	Watt per Metre Kelvin
Kg/ms	Kilogram per Metre Second
m^2/s	$Metre^2$ per Second
cm/s	Centimetre per Second
K	Kelvin
J/kmol	Joule per Kilomol

LIST OF SYMBOLS

V	=	Volume
P	=	Pressure
T	=	Temperature
$\dot{m}$	=	Mass Flow Rate
A	=	Area
Da_h	=	Damkohler Number
k	=	Thermal Conductivity
S_m	=	Source Term
q_{loss}	=	Heat Flux Loss
h_{conv}	=	Convective Heat Transfer
T_{wall}	=	Wall Temperature
T_{amb}	=	Ambient Temperature
ε	=	External Emissivity
σ	=	Boltzmann Constant
U	=	Flow Velocity
ϕ	=	Equivalence Ratio
$D_{i, m}$	=	Mass Diffusion Coefficient for Species, i
$D_{T, i}$	=	Thermal diffusion coefficient
X	=	Molar Fraction

MW_{mix}	=	Mixture Molecular Weight
S_L	=	Laminar Flame Speed
ρ	=	Density
R	=	Gas Constant
T_u	=	Temperature Unburned Gas
T_b	=	Temperature Burned Gas
$\tau_{residence}$	=	Residence Time
$\tau_{chemical}$	=	Chemical Time Scale

CHAPTER 1

INTRODUCTION

1.1 Background

Dwindling energy resources and strong demand for better power sources as compared to conventional batteries have sparked research interest in micro power generation (Fernandez, 2002). The invention of state of the art electronics devices requires more energy capacity, shorter charging period and lightweight, characteristics which batteries. A micro combustor is an alternative device to the conventional lithium-ion batteries. Miniaturized product development such as micro robots, notebook computers and other small scale gadget needed in developing small scale of combustion to generate power source. Therefore, in recent years, micro power generation systems have been seen as potential alternatives to batteries owing to obvious advantages that it possesses. One of the advantages is the high-energy storage per unit mass and power generation per unit volume. As shown in Figure 1.1, the energy density of hydrocarbon fuels is approximately 100 times larger than the lithium ion batteries. Even with only 10% of efficiency, the total energy harvested is still by far out numbering the conventional batteries. In addition, the use of the hydrocarbons fuel as the source substantially reduces the operational cost and improves the voltage stability (Li et al. 2009).

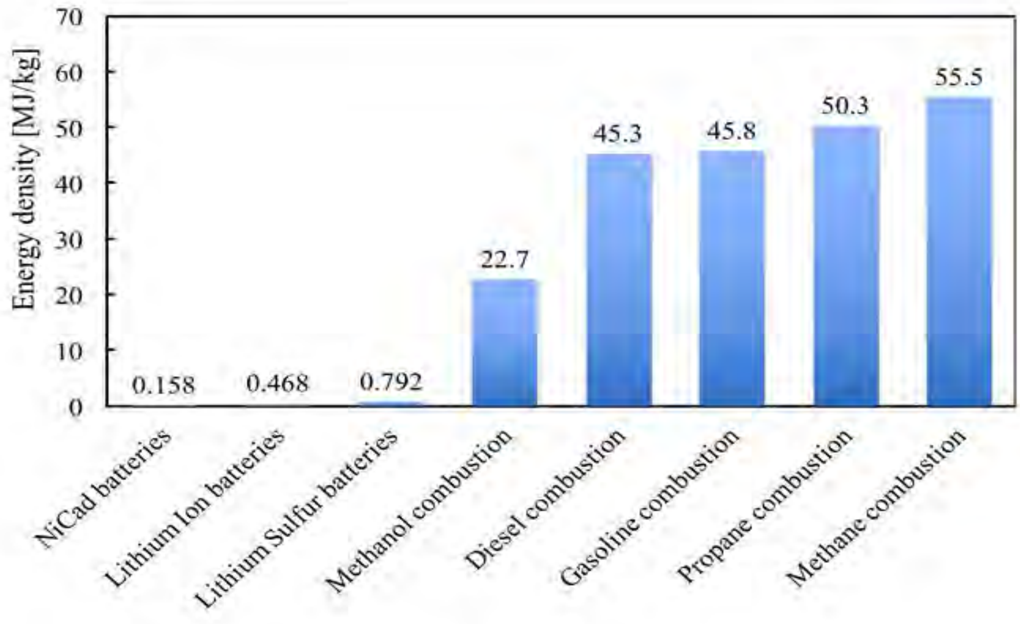

Figure 1.1: Energy Density of Conventional Batteries and Hydrocarbons Fuels (Kaisare and Vlachos, 2012)

The process of developing feasible micro power generators is indeed a formidable task since it involves complex flow, transport and thermodynamics phenomena (Lior, 2009). The invention of micro electro - mechanical system (MEMS) has become the trigger factor to the development of more practical micro power generation systems. In an MEMS system, the conventional liquid fuels like gasoline or diesel cannot be used due to the instability of the fuel properties (Dunn et al. 2005). Diesel or gasoline tends to degrade if they are kept for a long period of time. Therefore, liquefied gaseous hydrocarbons such as propane and butane which are suitable for long term storage is the most preferred fuel in MEMS (Dunn et al. 2005).

Meanwhile, significant efforts have been made to develop micro engines, which have the similar mechanism as in the conventional internal combustion engines. Research teams from Massachusetts Institute of Technology (MIT) have developed a silicone gas-turbine engine that utilizes hydrogen as the fuel source (Yuasa et al. 2005). The schematic of the gas turbine engine is shown in Figure 1.2.

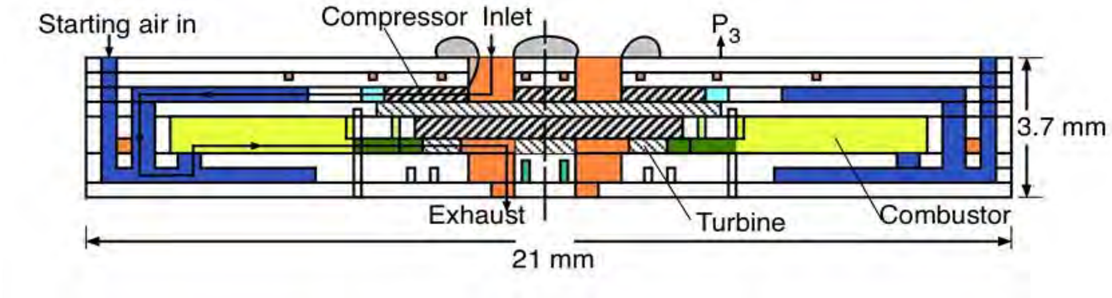

Figure 1.2: Schematic Diagram of the MIT Micro Gas Turbine (Yuasa et al. 2005).

A rotary meso-scale engine with 78 mm^3 has been successfully developed and tested by Kelvin et al (Fu et al. 2001). The engine uses hydrogen mixture as the fuel source as shown in Figure 1.3 (a). It has the capacity to generate 3 W of power (Fu et al. 2001). The same research group has also developed a rotary engine that is able to combust liquid methanol-nitro methane fuel. Nonetheless, the reduction of the scale has led to severe heat loss and friction sealing problem. Moreover, the complexity of the geometries makes them difficult to be fabricated (Zhou et al. 2009).

The alternative to micro engines is thermoelectric generators that can be considered as more technologically feasible. The development of micro thermo-photovoltaic or called (TPV) system has been on the rise over the past decades. Unlike the conventional internal combustion engines, the basic principle of micro TPV system is direct conversion of thermal energy into electricity without using any moving parts (Li et al. 2009). In addition, the elimination of these moving parts makes TPV system quieter and cleaner source for the electrical power than the conventional system. TPV systems are also considered as simple and easy to be fabricated.

(a) (b)

Figure 1.3: Meso – Scale Rotary Engines (Fu et al. 2001)

(a) MN30 Engine with Gaseous Fuel

(b) MN50 with Liquid Fuel

The most important component in a TPV system is of course the combustor. This system consists of a combustor and converter. The converter comprises a large number of flat annular washers and the alternate *n*-type and *p*-type thermoelectric materials are connected in series. Due to limitation of the thermoelectric materials, the allowable maximum flame temperature is around 1500 K.

There are four important sections in a TPV system which are the combustor, emitter, filter and the low band gap photovoltaic array (Chia and Feng, 2007). The process started when the emitter is heated up to a certain temperature, and it will emits photons. The emission of photons of which impinges on the photovoltaic cells causes free electrons to be generated. As a result, electricity is produced. The schematic of a TPV system is shown in Figure 1.4. Generally, a TPV device is applied in military applications where portable electronics for soldiers require minimal weight and charging time (Lee et al. 2013).

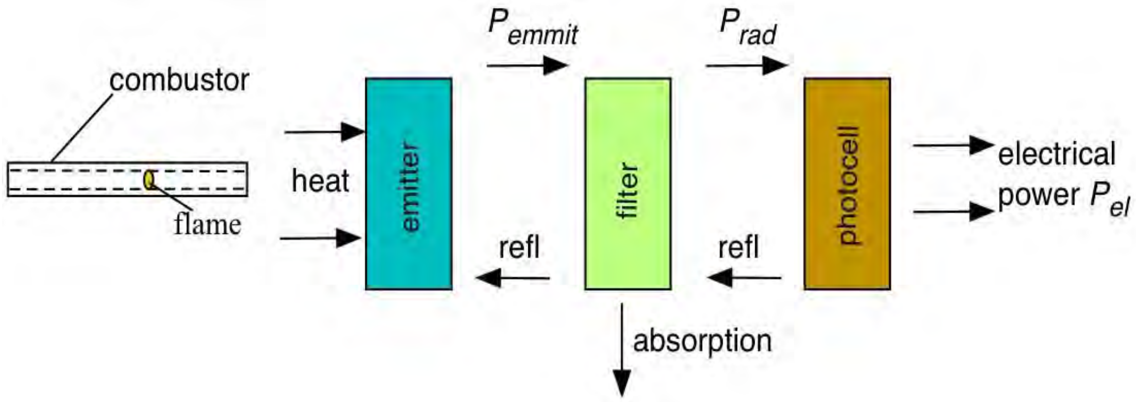

Figure 1.4: Schematic of a Micro-Thermos Photovoltaic Unit (Chia et al. 2007).

As seen in Figure 1.4, the heat energy produced from the combustor is converted into electrical energy. This heat energy can also be converted into various forms of useful energies as illustrated in Figure 1.5. It is practically important for the combustor to generate a high and uniform temperature along the wall (Yang et al. 2012). A cylindrical tube combustor is favourable since the coupling with different parts in the system, especially the emitter, can be easily performed (Lee and Kwon, 2008).

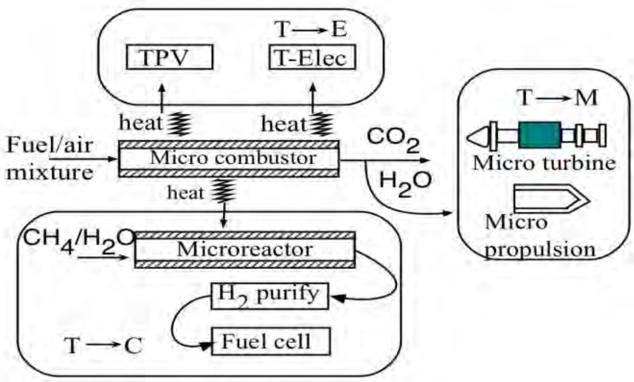

Figure 1.5: Utilization of Micro Combustor (Kaisare and Vlachos, 2012)

Combustion in micro combustor is a chemical reaction of exothermic between oxidant and chemical substance which in this study are using propane - air mixture shown in Figure 1.6. Air act as oxidant and propane is the chemical use in this study. In experiments, the result is the heat released in product of light which is flame or glowing form. To stabilize the flame is the major problem in this study, which is mainly due to high surface to volume ratio. The surface to volume to ratio is increase, heat loss to wall of combustor is also increasing.

Figure 1.6: Micro combustor (Micro Thruster) (Maruta, 2011).

1.2 BACKGROUND OF STUDY

The ability of a given fuel to be combusted in narrow channels is at first, assumed to be impossible. However, the recent progress in micro power generation has shown that combustion within a confined space, even in sub-millimetre scale is achievable. Despite this positive advancement, there are fundamental issues that need to be addressed and solved. There are many factors that influence micro scale combustion, which generally can be divided into physical process and chemical processes. The examples of these factors are convection, radiation, gas-phase and surface reactions, and molecular transport, thermal and mass diffusion (Ju and Maruta, 2011).

Generally, the difficulty to sustain combustion in micro-scale devices is related to the substantial heat losses due to large surface area to volume ratio and physical time available for the combustion to occur. For any combustion process to take place, the residence time should be larger than the combustion time (Benedetto et al. 2010). However, in micro-scale combustors, the length scale is tremendously reduced. This laminar flow causes the diffusion time to increase, which lowers the residence time. In such condition, combustion might cease to exist.

The behaviour of fluids in micro scale devices can be assumed as the same as in macro scale. However, a few micro combustion features are distinctively different from macro scale combustion. Defines the micro-scale combustion as a condition where combustion occurs in a space that has the characteristic length scales approaching to the quenching distance (Maruta et al. 2011). On the other hand, combustion that occurs in a space with the characteristic length larger than 1 mm, but features the same features as micro-scale combustion is defined as meso-scale combustion.

Strong thermal and chemical coupling between the flame and combustor structure is also exhibited in micro combustor. In such combustor, the flame quenching is greatly depending on the flame-wall thermal coupling (Guo, 1997). Therefore, it is essentially important to fully understand the underlying factors that contribute to the flame stabilization in micro combustors so that high-energy conversion can be achieved. Examples of these factors are thermal heat loss, excess enthalpy, wall-flame thermal and chemical coupling, fuel-air mixing, liquid vaporization, flow field, burning rate and flame temperature (Wang, 2011). Since the combustion of hydrocarbon fuels in micro scale devices is not as efficient as in larger conventional devices, it is also vital to address the issue of fractional production of unburned species and high amount of carbon monoxide (CO). Overall, it is vital for an efficient micro combustor to have features as follows (Lee, 2010):

1. Wide flame stability limits.
2. Versatility in terms of the combustion modes for different use of the application.
3. Considerably good of combustion efficiency.
4. Minimum the hazardous gas emission.
5. Simple in the geometry for easier coupling with energy conversation module.

A single channel combustor (SC) can also be considered as a heat recirculation combustor since the heat from the burned gas region is distributed to the unburned gas region via the combustor wall. For this case study are focus on the counter current micro combustor that to generate more energy.

1.3 PROBLEM STATEMENT

Combustion in micro-scale channels is possible. However, stabilizing flame in such narrow channel combustors is relatively difficult due to large heat losses and produce more heat that can be convert to electrical energy. Thus, a proper thermal management is required. Many approaches can be applied to enhance the produce of heat to convert to electrical energy. The use of flame holders, catalysts and modification of combustor geometry are the examples of these approaches. Depositing catalysts on micro combustors involves complex and costly process. The increase of reactants temperature prior to combustion leads to the elevation of flame burning velocity. In general, there are two types of pre-heating methods, namely direct and indirect method. A direct method is a condition where the pre-heating is performed by using high combustor wall thermal conductivity. On the other hand, using the heat from the exhaust gas to pre-heat the incoming reactants is the example of indirect pre-heating method. Swiss-roll combustor is one of the micro combustors that utilizes the heat from the exhaust gas to increase the reactants temperature. Nevertheless, the geometry of such a combustor is relatively complicated, which makes it difficult to be numerically and experimentally investigated. Hence, a combustor with counter current in design is preferred. It is desirable that both liquid and gaseous hydrocarbon fuels can be used in the proposed combustor. Apart from that, the emission of the micro combustor with the wire mesh can also be studies with the counter current mechanism.

1.4 OBJECTIVES

The main purpose of this case study is to propose a flame stabilization in counter current micro combustor that utilizes heat recirculation mechanism. Both liquid and gaseous fuels can be used. The following approaches are conducted:

1. To design a counter current combustor with wire mesh using ANSYS software.
2. To numerically investigate the counter current (CC) micro combustor at ambient air temperature on the flame stabilization.
3. To numerically examine the effect of wall thermal conductivity of combustor on the flame stabilization limits with one air flow. Numerical simulations are also utilized to provide the detailed insight and basic understanding of the problem.