UNIVERSITI TEKNIKAL MALAYSIA MELAKA

INVESTIGATION OF FACTORS AFFECTING FLAME STABILIZATION IN MESO-SCALE COMBUSTOR

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A thesis submitted
in fulfillment of the requirements for the degree of Master of Science
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DECLARATION

I declare that this thesis entitled “Investigating of Factors Affecting Flame Stabilization in Meso-Scale 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.

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APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Science in Mechanical Engineering.

Signature : ……………………………………………

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Date : 20 · 04. 2024 ……………………………………………

DEDICATION

''To my beloved family''

ABSTRACT

Dwindling energy resources and strong demand for better power sources have sparked research interest in micro power generation. The invention of state-of-the-art electronic devices requires characteristics of which conventional batteries lack. Meso and micro combustors can be considered as the most important component in micro power generation. However, stabilizing a flame inside a meso combustor poses a great challenge to researchers. This difficulty is mainly related to the substantial heat losses due to large surface area to volume ratio. This research focuses mainly on the determining factors that affect the flame stabilization in meso-scale tube cylindrical tube combustors with stainless steel wire mesh. Apart from that, the combustion characteristics are also analyzed to establish the correlation between these factors that have significant effect on combustion. A three-dimensional (3-D) simulation model of combustor with stainless steel wire mesh was developed to numerically investigate the vital factors that contribute to flame stabilization by using ANSYS-Fluent software. The effective role of wire mesh in distributing heat from the burned to the unburned gas region was also demonstrated by using the developed 3-D simulation model. For the baseline model, the inner diameter of base three-dimensional (3-D) model is set at 3.5 mm while the outer wall thickness is 0.7 mm. Meanwhile, the stainless-steel wire mesh is modeled and placed between the unburned and burned gas region. The total length of the model is set to 40.2 mm. Propane (C_3H_8)-air mixture with equivalence ratio of 1.0 is used as the fuel source. The investigative factors that have been examined are the combustor geometry configuration such as the inner diameter and outer wall thickness, the wire mesh function and type of fuels. The results show that as the outer wall thickness increases from 0.3 mm to 1.5 mm, the blowout limits increase from 0.4 m/s to 0.5 m/s. As the wall thickness is above 1.5 mm, the blowout limit remains unchanged. On the other hand, there is insignificant increases of the blowout limit, which is from 0.47 m/s to 0.49 m/s with the use of thicker wire mesh from 0.4 mm to 0.8 mm. Apart from that, the use of combustor tube material with high wall thermal conductivity *(k)* significantly increases the blowout limit. Nevertheless, higher values of *k* beyond 100 W/mK is no longer effective for flame stabilization. The utilization of double wire mesh increases the blowout limits of from 0.47 m/s to 0.51 m/s. It is also shown that the stainless-steel wire mesh has a dual role function. At low flow velocity, the wire mesh tends to act as a flame inhibitor where heat is being transferred to the ambient. However, at higher flow velocities, the wire mesh acts as a flame enhancer where it circulates the heat into the unburned region. All these findings are important for future improvement of the proposed meso-scale combustor with wire mesh.

PENYIASATAN FAKTOR-FAKTOR YANG MEMPENGARUHI KESTABILAN NYALAAN API DI DALAM PEMBAKAR BERSKALA MESO

ABSTRAK

Permintaan yang tinggi terhadap sumber tenaga yang lebih baik telah menyebabkan aktiviti penyelidikan dalam bidang penghasilan kuasa mikro bertambah secara mendadak. Ini ditambah pula dengan penciptaan alat-alat elektronik canggih yang memerlukan penggunaan sumber tenaga yang banyak. Alat-alat ini juga memerlukan tempoh masa untuk dicas yang lebih pendek serta punca kuasa yang lebih ringan daripada bateri konvensional. Justeru itu, pembakar mikro dilihat sebagai salah satu komponen yang paling penting dalam sistem penghasilan kuasa mikro. Walau bagaimanapun, untuk menstabilkan api di dalam pembakar mikro ini merupakan satu perkara yang sulit dan mencabar. Sebab utama kesukaran untuk menstabilkan api di dalam pembakar mikro adalah kadar kehilangan haba keluar ke persekitaran yang tinggi. Kadar pemindahan haba yang tinggi ini disebabkan oleh nisbah luas kepada isipadu yang besar. Penyelidikan yang dibentangkan dalam tesis ini adalah berfokus kepada menentukan faktor-faktor signifikan yang boleh mempengaruhi kestabilan nyalaan api di dalam pembakar mikro serta menganalisis kelakuan ciri-ciri pembakaran dan hubung kait di antara dapatan kajian. Sebuah model simulasi tiga dimensi (3-D) telah dibangunkan untuk tujuan itu menggunakan perisian ANSYS-Fluent. Selain daripada itu, fungsi jejaring besi di dalam pembakar juga telah ditunjukkan dengan simulasi menggunakan model berangka yang dibangunkan. Diameter dalaman untuk model tiga dimensi (3-D) pada asalnya ditetapkan pada 3.5 mm sementara diameter luaran adalah 0.7 mm manakala jejaring besi diletakkan di antara bahagian terbakar dan tidak terbakar. Jumlah panjang keseluruhan model adalah 40.2 mm. Campuran gas propane (C_3H_8) dan udara dengan nisbah setara bernilai 1.0 digunakan sebagai sumber bahan api. Faktor-faktor yang disiasat adalah konfigurasi geometri pembakar seperti diameter dalaman dan ketebalan dinding luaran, bilangan jejaring besi dan jenis bahan bakar. Hasil dapatan menunjukkan bahawa semakin tebal dinding luaran pembakar iaitu pertambahan daripada 0.3 mm kepada 1.5 mm, dapatan menunjukkan had api terpadam telah menaik daripada 0.4 m/s kepada 0.5 m/s. Walaubagaimanapun, dengan penambahan ketebalan dinding kepada 1.5 mm, didapati had api terpadam tidak berubah. Selain itu, had api terpadam hanya bertambah sedikit daripada 0.47 m/s kepada 0.49 m/s jika ketebalan jejaring besi meningkat daripada 0.4 mm kepada 0.8 mm. Hasil dapatan juga menunjukkan bahawa penggunaan bahan tiub pembakar yang mempunyai kadar keberaliran haba yang tinggi (k) dengan ketaranya dapat meningkatkan had api terpadam. Peningkatan nilai k melebihi 100 W/mK tidak lagi efektif terhadap had ini. Selain itu, penggunaan bilangan jejaring besi daripada satu kepada dua dapat meningkatkan had api terpadam daripada 0.47 m/s kepada 0.51 m/s. Jejaring besi yang diletakkan di dalam pembakar juga ditunjukkan mempunyai dua fungsi mengikut kadar halaju campuran. Pada halaju rendah, jejaring besi bertindak sebagai perencat api manakala pada kadar halaju tinggi, jejaring besi bertindak sebagai peningkat kestabilan api. Hasil dapatan ini amat penting dalam bidang penyelidikan penghasilan kuasa mikro memandangkan dapatan tersebut dapat digunakan untuk menambahbaik keboleharapan sistem tersebut.

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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
Q_{C1}	-	heat conducted via the inner wall of the burned gas region
Q_{C2}	-	heat conducted via the inner wall of the unburned gas region
Q_{RU}	-	heat recirculated to the unburned gas region
Q_{RM}	-	heat recirculated to the wire mesh
Q_{LB}	-	heat loss from the outer wall of the burned gas region to the ambient
Q_{LM}	-	heat loss from the outer wall of the wire mesh to the ambient
Q_{LU}	-	heat loss from the outer wall of the unburned gas region to the ambient

LIST OF PUBLICATIONS

Journal with Impact Factor

F.A. Munir, M.I. Muazzam, A. Gader, M. Mikami, H. Saputro, and L. Fitriana. 2018. Effects of wall thickness on flame stabilization limits for combustors with wire mesh. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences,* 49 (1), pp. 11-17. (Scopus Indexed)

Muazzam, M.I., Munir, F.A., Roseli, A., Yob, M.S., and Jumaidin, R. 2018. Numerical simulation of spark ignition engine with pre combustion chamber (PCC). *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences,* 52(2), pp. 198-204. (Scopus Indexed)

CHAPTER 1

INTRODUCTION

1.1 Research background

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 (Veeraragavan and Cadou, 2011). As such, micro power generation systems can be considered as the potential alternative to conventional batteries due to advantages that it has. 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). The energy density of hydrocarbon fuels has energy density of approximately 100 times more than the lithium-ion batteries. Theoretically, with only 10% of efficiency, the total useful energy harvested is still by far outnumbering the lithium-ion batteries. In addition, 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).

The ability of a given fuel to be combusted in meso and micro scale combustors is at first, assumed to be impossible (Miesse, Masel et al., 2004). However, the latest progress in micro power generation research has shown that combustion even within micro scale channel is now possible (Choi, Kwon et al., 2008). 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 and chemical processes. The examples of these factors are convection, radiation, gas-phase and surface reactions, molecular transport, thermal and mass diffusion (Ju and Maruta, 2011).

Flame stabilization in meso and micro scale combustors 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 (NO_x) 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 examine the factors affecting flame stabilization in meso and micro scale combustors in order to achieve high energy conversion. Examples of these factors are 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).

As mentioned before in the previous paragraph, one of the thermal managements that can be made in meso and micro combustors is by recirculating the heat from combustion to significantly reduce the heat loss and to enhance the flame stabilization limits. The meso scale combustors with heat recirculation mechanism was first proposed by Weinberg (Weinberg, Rowe 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 also known as excess enthalpy principle (Zhang, Wu et al., 2020).

Generally, there are two types of preheating methods (Pan, Zhang et al., 2017). The first type is defined as a direct method where the heat from the unburned gas region is mitigated to the burned gas region by means of heat conduction via the combustor wall. Generally, a single channel narrow channel combustor utilizes this kind of pre heating method (Wan, Fan et al., 2016). The second type of pre-heating method is by reversing the hot exhaust gas to pre-heat the unburned reactants before being combusted in the combustion region. The hot heat from the exhaust gas can significantly increase the unburned reactants temperature. This method is named as indirect preheating and mainly utilized in counter-current heat recirculation combustors (Zuo, E et al., 2017; Tang, Cai et al., 2018). The most popular micro combustor with this kind indirect preheating method is Swiss-roll (SR) combustor. However, Swiss roll combustor complexity in terms of geometry and design parameters has made them difficult to be analytically and experimentally investigated (Mane Deshmukh, Krishnamoorthy et al., 2018; Wang, Yuan et al., 2019).

The utilization of stainless steel wire mesh as a flame holder in quartz tube combustors was proposed by Mikami et al. (Mikami, Maeda et al., 2013) and his co-worker (Yuliati, Seo et al., 2012; Munir, Hatakeda et al., 2013). It was reported that flame can be stabilized without external heating. More interestingly, liquid fuel can also be used as the primary fuel source, which can potentially solve the problem of portability. Nevertheless, the use of ceramic adhesive in their combustors induced hot spot which can potentially reduce the lifespan of the combustors. Generally, it is vital for an efficient micro combustor to have features as follows (Lee, Cho et al., 2010);

a) Wide flame stability limits
b) Versatility in terms of combustion modes for different use of application
c) Considerably good combustion efficiency
d) Minimum hazardous gas emission
e) Simple in geometry for easier coupling with energy conversion module

This research study proposed to further investigate the factors affecting flame stabilization in meso scale combustor with stainless steel wire mesh. In this research, a numerical three-dimensional (3-D) model of micro combustor with wire mesh is being