COMBUSTION IN MICRO COMBUSTORS WITH REDUCED CHEMICAL KINETIC MECHANISM

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This report is submitted
in fulfilment of the requirement for the degree of
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DECLARATION

I declare that this project report entitled "Combustion In Micro Combustors With Reduced Chemical Kinetic Mechanism " is the result of my own work except as cited in the references

Signature : ....

Name : Luqman Hakim bin Zainudin

Date : 15 JUNE 2017

APPROVAL

I hereby declare that I have read this project report and in my opinion this report is sufficient in term of scope and quality for the award of degree of Bachelor of Mechanical Engineering (Plant & Maintenace).

Signature :. ....

Name of Supervisor: Dr. Fudhail bin Abdul Munir

Date : 15 JUNE 2017

DEDICATION

I would like to dedicate to

My father,

ZAINUDIN BIN AB AZIZ

My mother,

KAMSIAH BINTI TAN KOFLI

My supervisor,

DR. FUDHAIL BIN ADUL MUNIR

And

All my friend,

For their assistance & supportive efforts.

ABSTARCT

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 devices are critical in need of powerful energy resources. Nonetheless, stabilizing flame inside narrow channel combustor is the greatest challenge for the researchers. This research can be categorized as fundamental research where the flame stabilization in micro combustors is investigated. In this project, two dimensional (2-D) numerical simulations that focus on the effect of thickness on combustion of micro combustor with reduced chemical kinetics mechanism were performed. By using ANSYS-Fluent 17.1 as the Computational Fluid Dynamics (CFD) tool, the blowout limits for micro combustors with different size of thickness is determined. The thickness use for each micro combustor design are 0.3 mm, 0.5 mm, 1.0 mm and 1.2 mm, respectively. The chemical reaction employed is global one-step and two-step propane-air mixture. The blowout limits for the different thickness micro combustor had been determined. Thus, trend pattern of the effect of combustor thickness on the flame stabilization are also deduced. From the results, it can be concluded that the thickness of the micro combustors significantly affect the blowout limits. Meanwhile, two types combustion reaction mechanism for propane-air mixtures were employed to investigate the effect reaction mechanism on flame stabilization limits. It is suggested that the reaction mechanism for one-step and two-step combustion of propane-air mixture does not significantly affect the flame stabilization limits of the combustors.

ABSTRAK

. Peranti pembakar mikro adalah alternatif kepada bateri lithium-ion konvensional. Kemajuan produk bersaiz kecil seperti robot mikro, komputer riba dan peranti kecil adalah kritikal yang memerlukan sumber tenaga yang kuat. Namun begitu, menstabilkan api di dalam saluran pembakar sempit adalah cabaran terbesar bagi para penyelidik. Kajian ini boleh dikategorikan sebagai penyelidikan asas di mana penstabilan api dalam pembakar mikro disiasat. Dalam projek ini, dua dimensi (2-D) simulasi berangka yang memberi tumpuan kepada kesan ketebalan pada pembakaran pembakar mikro dengan mengurangkan mekanisme kinetik kimia telah dijalankan. Dengan menggunakan ANSYS-Fluent 17.1 sebagai alat dinamik bendalir sebagai pengiraan (CFD), had pembakaran terpadam untuk pembakar mikro dengan saiz yang berbeza ketebalan ditentukan. Penggunaan ketebalan bagi setiap reka bentuk pembakar mikro adalah 0.3 mm, 0.5 mm, 1.0 mm dan 1.2 mm, masing-masing. Tindak balas kimia yang digunakan adalah satu langkah dan dua langkah campuran propana udara global. Had semburan keluar untuk ketebalan yang berbeza pembakar mikro telah ditentukan. Oleh itu, trend corak kesan ketebalan pada penstabilan pembakar api juga disimpulkan. Daripada keputusan, ia boleh disimpulkan bahawa ketebalan pembakar mikro ketara memberi kesan kepada had semburan keluar. Sementara itu, dua jenis mekanisme tindak balas pembakaran untuk campuran propana-air telah digunakan untuk menyiasat kesan ke atas mekanisme tindak balas had penstabilan api. Adalah dicadangkan bahawa mekanisme tindak balas untuk satu langkah dan dua langkah pembakaran campuran propana-udara tidak ketara memberi kesan kepada had penstabilan api daripada pembakar.

ACKNOWLEDGEMENTS

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LIST OF ABBEREVATIONS

MEMS	Micro-Elctromechanical System
2-D	Two-Dimensional
CFD	Computational Fluid Dynamics

CHAPTER 1

1. INTRODUCTION

1.1 BACKGROUND OF STUDY

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 devices needed in developing small scale of combustion. Nonetheless, stabilizing flame inside narrow channel combustor is the greatest challenge to the researchers. This research is considered as a fundamental study. Due to supply power to these devices, higher energy density, higher heat and mass transfer coefficient are needed in developing these devices. Micro combustor are the medium of the study and to achieve the objective of the study is to stabilizing the flame inside the micro combustor with reduce chemical kinetic mechanism (Hua et al, 2005). Understanding of the flow dynamics, chemical kinetics and heat transfer mechanism within micro-combustors is essential for the development of combustion-based power MEMS devices. In this study, only numerical simulations using the commercial software are performed.

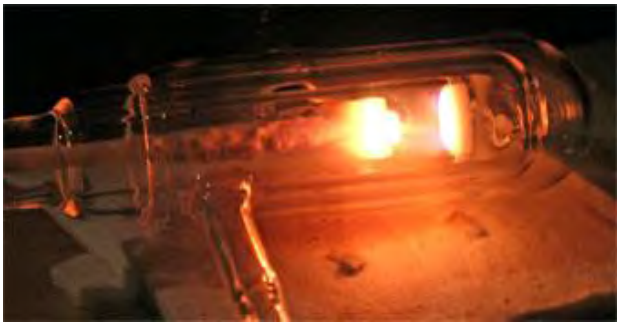

Figure 1-1 Micro combustor (micro thruster) (Fan et al, 2012)

Combustion in micro combustor is a chemical reaction of exothermic between oxidant and chemical substance which in this study are using propane-air mixture. 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.

Chemical kinetic mechanisms is determine in the reaction order and rate of equation of reactant. By using hydrocarbon propane as chemical reactant which is C_3H_8 combining with air [1]For these mechanism, it must satisfy two requirement which is the elementary steps must add up to give the overall balanced equation for the reaction and the rate law for the rate-determining step must agree with the experimentally determined rate law. Rate law equation is $r = k[A]^x[B]^y$, by applying these two requirement will stabilize the chemical reaction equation and needed to design the flow to simplified the chemical kinetics reaction modelling which retained the essential features of full system inside the tube channel of the micro combustor.

By using software of ANSYS-Fluent to solve the governing equations, the flow is shown inside the tube combustor channel. Determine the flow steady-state, the flame inside are need to stabilize. Parameter is set in this software are from the equation of reaction of propane-air mixture in this area of study. The figure shown below is the example of flow that simulation ANSYS-Fluent produce after simulation is running.

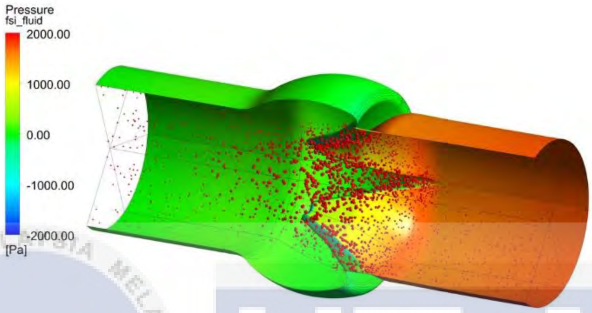

Figure 1-2 Simulation ANSYS-Fluent flow

In this research, the area of the study is limited to numerical simulations using ANSYS-Fluent with reduced chemical kinetic mechanisms of propane-air mixture. The aim of this study is to investigate the effect of combustion reaction mechanism on the flame stabilization in micro combustors with stainless steel wire mesh.

1.2 PROBLEM STATEMENT

Micro combustor is a small combustion devices. Stabilizing the flame inside such narrow channel combustors poses a great challenge to researchers. Despite such difficulties, flame stabilization in sub millimetres combustors is feasible. Numerical simulations using one step global reaction has greatly over predicted the flame temperature, which is not realistic. Hence, a reduced kinetic mechanism simulations are preferred for results with better accuracy. Apart from that, the emission of the micro combustor with C can also be studied with the reduced kinetic mechanism.

1.3 OBJECTIVE

1) To establish a two dimensional (2-D) numerical model of micro combustors with concentric rings.
2) To utilize a reduced kinetics mechanism to stimulate combustion in micro combustion in micro combustor with concentric rings.
3) To investigate the effect of thickness of the micro combustor using reduced kinetics mechanism

1.4 SCOPE

1) To utilize ANSYS-Fluent as CFD tools.
2) The reduced kinetics mechanism is limited to propane-air mixture only which is 1-step propane-air mixture and 2-step propane air mixture
3) To investigate the blowout limit of combustion phenomena in micro combustor with concentric rings.

CHAPTER 2

2. LITERATURE REVIEW

2.0 Overview

This chapter summarizes the previous related well-known work which in area of experimental and numerical that have been performed in micro power generation field. In this chapter, the related work that have been review is only using hydrocarbon fuel as experimental or medium source. The objective of the most study is to stabilize the flame in micro combustion. Several of research or journal have been proposed by using various method and mechanism to stabilize flame in narrow channel of micro combustor. It is also will explained the terminologies of micro combustion field area.

2.1 Flames Stabilization in Micro Combustor

Many paper proposed the method or mechanism use to form combustion in micro combustion, but it is challenging task to able to form stabilize flame in narrow tube channel of micro combustor. Fudhail et al. stated that it is essential to fully understand the underlying factors that affect the combustion stability in meso and micro-scale combustors (Fudhail et al, 2015). Fudhail et al. in their other paper also said that flame stabilization in such narrow channel combustors is a considerably challenging task and requires a proper thermal management due to larger heat loss ratio (Fudhail et al, 2015).

In general, flame can be stabilize within the certain limit that called flammability limits. The definition of flammability limit is range of mixture strength of which particular flame propagate within these limit (Turn S.R, 2000). Majority of micro combustor field of study use hydrocarbon fuel air mixture as the medium of the study. Each of these fuel-air mixture have their own propagate speed. The flame started to propagate when it is been ignited to the fresh unburned mixture area with their own velocity approximately near to the propagation speed theoretically. To get stationary flame or stable flame, it is need to adjust the mean flow velocity of the unburned mixture. In the real life, it is difficult to able stabilize the flame due to complexity interaction between flame and the wall of micro combustor. Feng et al. say in their paper that at the gas-wall interfaced, a highly intensified heat loss from the combustor wall and radial destruction occur (Feng et al, 2010).

Many method have been proposed to stabilize the flame in micro combustors. One of them is to overcome flame quenching. It is needed to utilize the heat recirculation mechanism can significantly enhance the flame stabilization limits (Fan et al, 2012). From combustion product, there is an excess enthalpy is utilized to pre-heat the fuel and air mixtures. There is various example of micro combustion model in figure 2.1. Categorize the flow of heat in micro combustor is laminar, the mixing process between fuel and air are relatively slow. Caused of that, the mixing process is performed by the molecular diffusion and chaotic advection (Stroock et al, 2002). To enhance the blending procedure that can conceivably upgrade fire adjustment, a blender can be presented (Hessel et al, 2005). The mixer can be introduced.

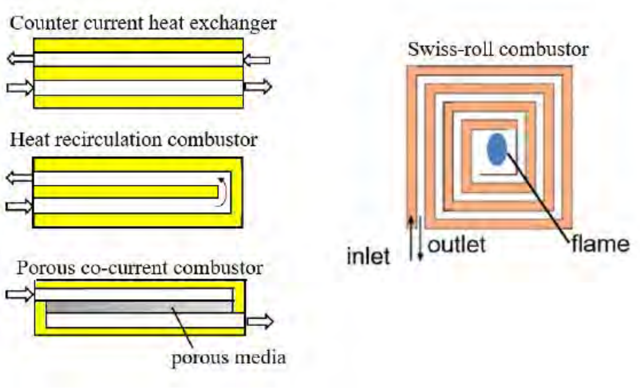

Figure 2-1 Various geometry of heat recirculation micro combustor (Kaisare et al, 2012)

Other than that, Lei et al. proposed that an annular tube of micro combustors with recirculation of exhaust heat is one of the method to get stabilize flame in micro combustor narrow tube channel (Lei et al, 2016). It is to understanding the mechanism of sustaining combustion within quenching distance of fuel. Another work that use to performed micro combustor flame stabilization from experimental method is analyse the difference in flame stabilization, temperature distribution at external wall and flammable channel-height (Tang et al., 2015) As the result, the difference between equivalent ratios of mix hydrogen/air has much wider and stable flammable range.

The alternative method that to improve stabilization of flame in micro combustor tube is the utilization of the catalyst. The use of catalyst enhances the flame stabilization limits inside the micro combustor by boosting the mass transfer (Maruta et al, 2002). Lower flame temperature are generate by the combustion of reactant in catalytic combustor than non-catalytic combustors. This low ignition temperature prompts to the decrease of warm anxiety related issues (Maruta et al, 2002). There is three major components in catalytic material which are catalyst, support and substrate. There are many techniques to deposit catalyst in micro burner. From Kikas et al. , they recommended that by using catalytic wires in micro combustors the likely the most effortless approach to deposit the catalyst into micro burner (Kikas et al, 2003). From figure 2.2 shows that the thin film is coated with catalyst. There also disadvantages using catalyst. Such as in paper Li et al., there is very complex interaction of combustion between heterogeneous and homogenous combustion (Li et al, 2012). As consequences is it is difficult to perform an experiment since there are too many variables needed to be controlled.

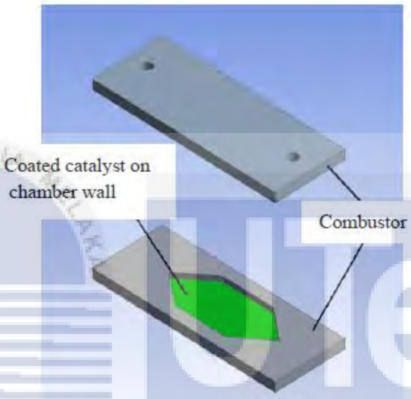

Figure 2-2 Schematics of micro-catalytic combustor with thin-film coated

2.2 Flame Quenching

Phenomenon of incomplete combustion due to the flame quenching is the task challenged in order to designing a reliable micro combustor (Hua et al, 2005). The definition of the flame quenching is a condition of flame extinguish upon entering small channel. The two types of mechanism of flame quenching it is thermal quenching and radial quenching. For thermal quenching, it is occurs when the heat is generated by the combustion process is not sustainable not feasible because of the heat misfortunes to the surrounding. Fernandez-Pello in his paper, in micro scale combustors, the heat losses in not only due to radiation, it is to a great extent contributed by the convection and conduction of heat (Fernandez-Pello, 2002). Radial quenching happens when radicals from the fire are diffused to the dividers, coming about to radical species exhaustion (Kim et al, 2006). The recombination of radical prompts to the loss of active combustion of bearers that in the long run outcomes to a to a flame quenching.

Quenching distance it is the critical distance of a channel in which the flame extinguish. For determine this distance, the two type of flame quenching mechanism which is thermal quenching and radial quenching plays an important role. It is depend on the reaction rate, temperature, species and radial concentration. For designing fire-resistance devices, the quenching distance is essential part that should have been consider. To achieve a better and safe design for micro combustor tube, the flame must not flashback to the upstream of the circular tube when the reactant is disconnected and the diameter of the tube is larger than the quenching distance.

Many studies investigate the effect of flame quenching. For example, in figure 2.3 Miesse et al. performed an experimental work that show the possibility of combustion of gaseous hydrocarbon fuels in their designed micro scale combustor (Miesse et al, 2004). On the other journal, Saiki et al. posted that the effect of thermal and radical quenching on flame propagation is dominant in meso and micro-scale combustion (Saiki et al, 2013). Selection of proper operating conditions and optimization of combustor design are required in order to reduce or eliminate the flame quenching problem (Shirsat et al, 2011).

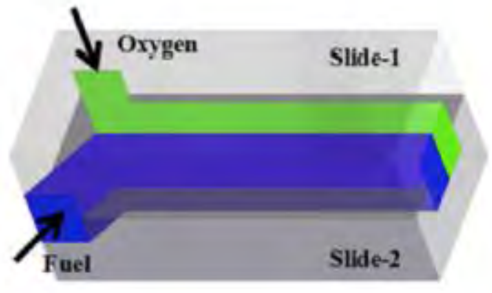

Figure 2-3 Schematic diagram of designing combustor (Miesse et al, 2004)

2.3 Numerical simulations of combustion in narrow channel combustors

Numerical Simulation is one of the method to study the behaviour of flame in micro combustor. By using numerical simulation can reduce the development cost of micro combustor research. By performing numerical validations, any recently outlined smaller scale combustors can be altogether examined and enhanced (Kurdyumov et al, 2009).

Computational Fluid Dynamic (CFD) has been used to numerically explore the fire trademark in micro-combustors with hydrocarbon fuels (Lee and Kwon, 2007). Raimondeau et al. in his study demonstrated the combustion of methane-air in two-dimensional tubular micro combustor (Raimondeau et al, 2002). A detailed multi-component carriage and gas chemistry was utilized in the numerical model. The consequences show that the effect of reactants pre-heating and insulation allows the flame to propagate even in micro channel combustors. The main parameter that determine the flame propagation in micro combustor are initial heat losses and wall radial quenching.

Norton and Vlachos in his study using two-dimensional elliptic computational fluid dynamics model of a microburner to solve the effect of microburner wall conductivity, external heat losses, burner dimensions, and operating conditions on combustion characteristics and the steady-state, self-sustained flame stability of propane/air mixtures (Norton and Vlachos, 2004). As the result, in stability of flame in the system, it is determine that wall thermal conductivity is the major effect of the flame stability in microburner. The other study that been proposed by Norton and Vlachos is combustion characteristics and flame stability at the microscale with a Computational Fluid Dynamic (CFD) study of premixed methane and air mixtures. The design of microburner are shown in figure 2.4 (Norton and Vlachos, 2003). Combustion chemistry with one-step irreversible reaction mechanism was employed. The result of their study is that propane-air microflame mixture are more stable then methane-air microflame mixture. The propane fuel lower ignition temperature cause of the flame stability improvement.

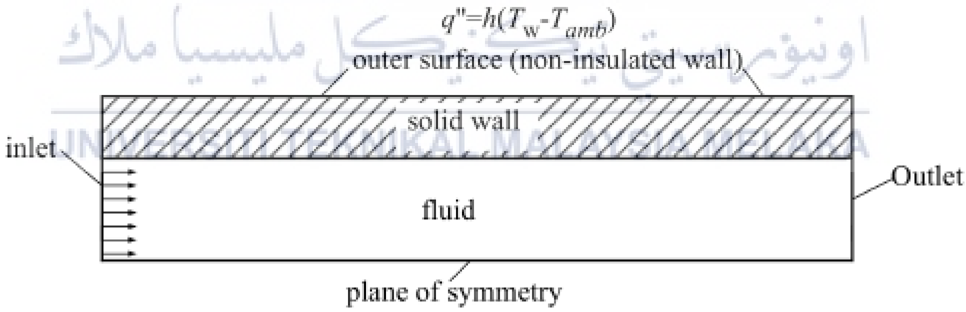

Figure 2-4 Computational domain employed in (Norton and Vlachos, 2006)

Other related study that study the effect of transport properties and chemical kinetics on the flame propagation in meso-scale straight quartz tube is Ju et al. In that journal, Ju et al propose one-dimensional (1-D) model applied numerical code. By using propane (C_3H_8) presented and GRI was used to numerically model the flame (Ju et al, 2005). As the result, two remarkable flame regime which is fast and slow burning regime occur as the stature of channel is reduction.

Federici and Vlachos, propose computational fluid dynamics (CFD) of propane-air microflame stability single-pass heat recirculation microburner (Federici and Vlachos, 2008). Their focus is on related to a single channel (no recirculation) with respect to critical heat loss coefficient, power loss, and critical inlet velocity. Their find out are the effect on reactor length and outer wall thickness contribute that heat recirculation profoundly affects blowout due to preheating of the cold incoming gases but as a minimal effect on extinction.

Other related work for two-dimensional (2-D) numerical simulation it is from journal Li et al (Li et al. 2009). Li et al. presented their finding of two-dimensional (2-D) cylindrical tube and parallel plate using 25 reversible reaction mechanism of methane –air combustion. The reaction process involved is partial oxidation represented in detailed mechanism. The results show that if the flame temperature is recognize the proper material selection can be performed.

Mostly study of micro combustor are using hydrogen fuel. Numerical simulation are likewise led to anticipate the premixed fire temperature and fire elements of miniaturized scale burning with hydrogen fuel (Jejurkar et al, 2011). Hua et al. demonstrated that the effects of various heat transfer conditions on hydrogen fuel. In their work, 19-reversible reaction was been utilized to concentrate the flame stability with or without wall presence of wall conduction (Hua et al, 2005). In their result, heat losses can be reduce if wall thermal conductivity is lower. Therefore, flame stability is achieve.

By using numerical simulation of FLUENT software, it able to calculate even more complex numerical simulation and complex structure. For example, complex simulation of micro combustion with catalyst have been performed by Stefanidis and Vlachos and Yan et al. in their paper (Stefanidis and Vlachos, 2009) (Yan et al, 2014). Study of hetero and homogeneous combustion of micro combustor is the main objective of numerical simulation. Flame stability maps were also additionally settled concerning the needy parameters (Karagiannidis et al, 2007).

Table 2.1 shows numerical simulation models that related work to meso and micro combustor by previous researcher. By using FLUENT software to solve hydrocarbon fuel were utilized and governing equation.

Table 2.1 Summary of previous numerical simulation of hydrocarbon fuel

Researcher	Combustor Geometry	Fuel Type	Reaction Mechanism	Objective of research
Raimondeau et al, 2002	Cylindrical tubes (2-D), steady-state	CH_4 +air	Detailed gas phase reactions	To investigate the effect of pre-heated gas mixture
Norton and Vlachos, 2004	Parallel plates (2D), steady-state	C_3H_8+air	One-step global reaction	To determine flame stability factors
Norton and Vlachos, 2003	Parallel plates (2D), steady-state	CH_4 +air	One-step global reaction	To determine flame stability factors
Lee and Kwon, 2007	Cylindrical micro tube (2D), transient state	CH_4 +air	Reduced mechanism with 25 steps	To investigate flame structure at elevated temperature and pressure
Federici and Vlachos, 2008	Parallel plates (2D) steady-state	C_3H_8+air	One-step global reaction	To investigate the flame stability with heat recirculation combustor
Choi et al, 2009	3D micro cyclone combustor, steady state	CH_4 +air	2 step global reaction	To determine flame stability of the designed combustor
Li et al, 2009	Cylindrical tube (2-D),steady-state	CH_4 +air	Reduced kinetic mechanism (25 steps)	To investigate flame temperature with different combustor geometry

2.4 Chemical Kinetics Mechanism

Chemical Kinetics is a topic of physical chemistry. It is covers on the rate of reaction, and analysis of experimental data which review all the quantitative kinetic information about any given reaction. Combustion equation have their own mechanism which react at their own rate of reaction. Focusing on combustion in micro combustor, not many related work focusing on how to reduce chemical kinetics mechanism of combustion in micro combustor.

One of popular research works of combustion that focus on chemical kinetics mechanism is Rajasekhar and Lea (Rajasekhar and Lea, 2009). On their propose experiment, the compare of four-step reduce mechanism and starting mechanism for methane diffusion flame. By using 65 elementary reaction and 18 species, and they predicted of each chemistry model have essentially same blowout velocity. As the result, the flame leading edge shown pointedly different structure was predicted alike.

Another famous work related to reduce chemical kinetics mechanism on paper of Chen et al. (Chen et al, n.d.). By using 10 species and 19-step for methane oxidization. It was derived from GRI-Mech3.0 using directed relation graph with error propagation (DRGEP) method. As the result, the reduced mechanisms work well over a wide range of equivalent ratio.

Bibrzycki and Poinsot proposed experiment of two reduced mechanism tested for a conventional air methane combustion (Bibrzycki and Poinsot, n.d.). Their find out is a large disagreement between detailed chemistry calculations and result obtained for J-L and 2S-CM2 global schemes, for the oxy-fuel combustion, was found freely propagating 1D laminar premixed flame. The simulation of methane combustion in the oxidizer composed of N_2/O_2 or of CO_2/O_2 contain no argon. By using;

$$k_j = A_j T^{\beta_j} \exp(\frac{-E_j}{RT}) \quad (1)$$

The simulation was performed to obtain the result of 4-step scheme for CH_4/air.

CHAPTER 3

3. METHODOLOGY

3.1 Overview of Methodology

In this study the numerical simulations were performed by using ANSYS-Fluent 17.1 software only. ANSYS-Fluent software is a software that have capabilities for user to able to understanding model flow, turbulence, heat transfer, and reaction for industrial application and in context of this area study is combustion model flow, heat transfer and reaction.

Figure 3-1 Logo of ANSYS-Fluent

As the overview of the for the flow of this research study on the title Combustion of Micro Combustor with Reduced Chemical Kinetics Mechanism is shown at figure 3.2. This research started by literature review on other related work. Next, there is needed to set up chemical mechanism equation and parameter which is start from design of the micro combustor until the parameter been set up. After that, the numerical simulation is performed and data analysis were conducted.

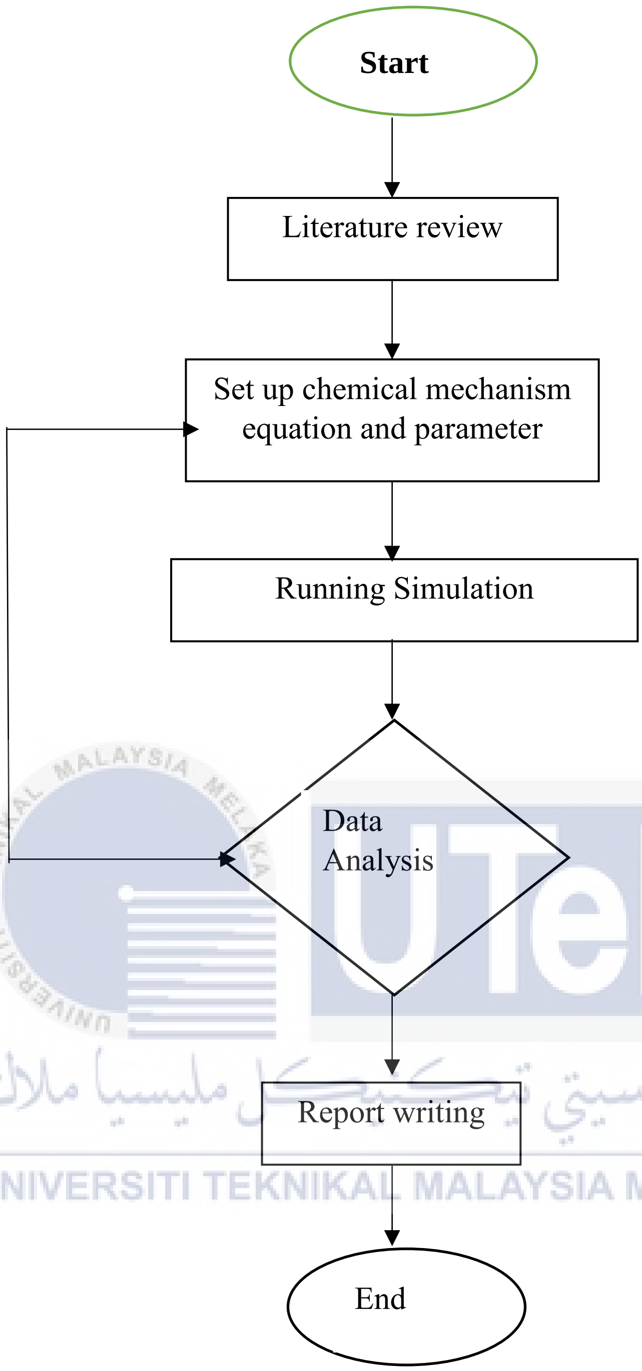

Figure 3-2 Flow chart of flow on the research

This numerical simulation of combustion of micro combustion with reduced chemical kinetics mechanism area. The next part shows how both chemical which propane-air mixture and 2-step propane-air mixture been setup their boundary condition for numerical simulation. To be able to do this numerical simulation, several step have been taken by using ANSYS-Fluent software which are:-

1) Designing model of micro combustor
2) Meshing graphical of micro combustor
3) Finding Mass Fraction of $CH_4$and $O_2$by Φ
4) Computational domain

3.2 Designing Model of Micro Combustor

For the first step, it is required to design a micro combustor. Micro combustor designed must be simple for easier to study the flow of the micro combustor. For this design of micro combustor, the concentric rings has been design at the tube of micro combustor. The design of this micro combustors is been design by using ANSYS software. Figure 3.3 below is shows the model of the micro combustor use in this study.

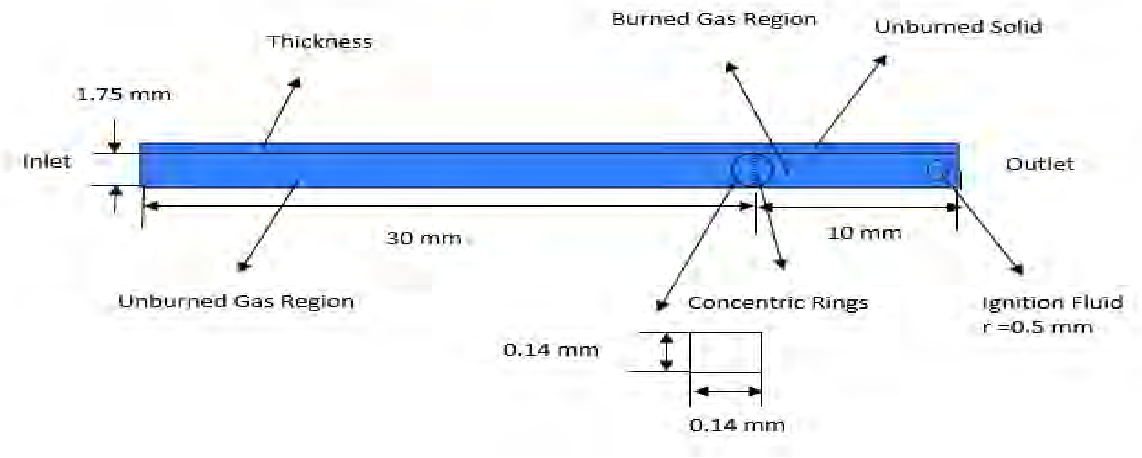

Figure 3-3 Model of micro combustor for two dimensional numerical model

For this two dimensional micro combustor design are used for both numerical simulation which is 1-step propane-air mixture and 2-step propane-air mixture. The only parameter change is only the thickness of micro combustors which are 0.3 mm, 0.5 mm, 1.0 mm and 1.2 mm. This is because in this research only study on effect of thickness for stabilization of flame in micro combustor at concentric rings. Every numerical simulation of both chemical mechanism are undergoes all four thickness that been setup.

3.3 Meshing Graphical of Micro Combustor Model

After the design has been completed, the next step is to design meshing for designed micro combustor. From figure 3.4 shown the example of meshing of the micro combustor used for numerical simulation for both chemical mechanism which is 1-step propane-air mixture and 2-step propane-air mixture. As in figure below, the mesh are more focus at thickness part of the micro combustion model which is smaller sizing of the meshing nodes.

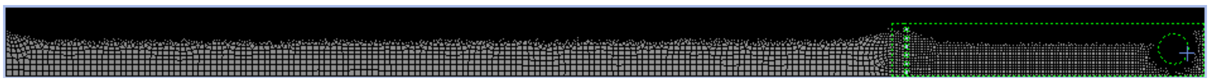

Figure 3-4 Meshing geometry of micro combustor of two dimensional numerical model

The meshing sizing design for this relevance centre are coarse. For sizing function for this design is been setup to curvature. Active assembly are been setup for initial size seed. For smoothing medium of this model design of micro combustor are set to defaults. Under smoothing medium, span angle centre are set to fine and automatic mesh based is on to defaults with minimum edge length is 0.14 mm. From table 3.1 below show the statistics mesh of this numerical simulation of design micro combustor model. The detail of meshing elements for each part are shown in table 3.2.

Table 3-1 Statistics mesh

Nodes	78 779
Elements	77 685

Table 3-2 Detail meshing elements size for each part

PART	**ELEMENTS SIZE**	**TYPE**
Thickness	0.2 e-0.02 mm	Soft
Unburned Gas Region	0.2 mm	Soft
Burned Gas Region	0.1 mm	Soft
Ignition Fluid Area	1 e-0.01 mm	Soft

3.4 Finding Mass Fraction of CH_4 and O_2 by Φ

From the design, a laminar flow at inlet of micro combustor with a flat velocity of inlet, U with feed temperature of 300K is maintained. To solve momentum and continuity equation, “cold flow” techniques is applied. After that, patching an initial temperature around temperature zone, the energy and species equation is solved. Then 1700K of temperature is applied to the designed patching zone to ensure enough energy to ignite propane-air mixture. After the flame was stabilized inside the micro combustor, diverse value of U and equivalent ratio of Φ.

To obtain blow out limit, the value of Φ is fixed and the value of velocity inlet, U is increased by step by step gradually. When maintaining value of Φ, the corresponding value of velocity inlet, U tend to propagate the flame away from the rings and it continues away the flame as the velocity inlet, U increased in value. Blow out limit is the flame is blown off the tube.

For the energy equation is given as:

$$\nabla . [\vec{u} (\rho E + p)] = \nabla . [k \nabla T - \Sigma_i h_i \vec{J_i} + (\bar{\bar{\tau}} . \vec{u})] + S_h \qquad (1)$$

Where

$$E = h - \frac{p}{\rho} + \frac{v^2}{2} \qquad (2)$$

h is sensible enthalpy and is defined for ideal gas as:

$$h = \Sigma_j Y_j h_j \qquad (3)$$

for incompressible flow given as:

$$h = \Sigma_i Y_i h_i + \frac{p}{\rho} \qquad (4)$$

Y_i =Mass fraction of species i and $h = \int_{T_{ref}}^{T} c_{p,i} \, dT$, where $T_{ref} = 298.15K$

Below is the calculation of mass fraction for propane-air mixture at equivalent ratio (Φ = 1.00). It is assumed that air is assumed to be mixture of 21 mol% oxygen and 79 mol% nitrogen. Using the given chemical reaction of one-step propane combustion;

$$C_xH_y + a(O_2 + 3.76N_2) \rightarrow xCO_2 + \frac{y}{2} \; H_2O + 3.76aN_2$$

$$C_3H_8 + a(O_2 + 3.76N_2) \rightarrow 3CO_2 + \; 4 \; H_2O + 3.76aN_2$$

$$a = \frac{x + \frac{y}{4}}{\Phi} = \frac{3 + 2}{1.00} = 5.0$$

$$C_3H_8 + 5(O_2 + 3.76N_2) \rightarrow 3CO_2 + \ 4\ \ H_2O + 18.8N_2$$

Finding the molar fraction (χ) of each species;

$$N_{C_3H_8} = 1;\ \chi_{C_3H_8} = \frac{N_{C_3H_8}}{N_{Total}} = \frac{1}{1 + 5.0 + 18.8} = \frac{1}{24.8} = 0.04032$$

$$N_{O_2} = 5.0;\ \chi_{O_2} = \frac{N_{O_2}}{N_{Total}} = \frac{5.0}{1 + 5.0 + 18.8} = \frac{5.0}{24.8} = 0.20161$$

$$N_{N_2} = 18.8;\ \chi_{N_2} = \frac{N_{N_2}}{N_{Total}} = \frac{18.8}{1 + 5.0 + 18.8} = \frac{18.8}{24.8} = 0.75806$$

Calculating the mix molecular weight (MW_{mix})

$MW_{mix} = \sum \chi_i \, MW_i$;

$MW_{mix} = \chi_{C_3H_8} M\,W_{C_3H_8} + \chi_{O_2} MW_{O_2} + \chi_{N_2} MW_{N_2}$;

$MW_{mix} = 0.04032(44.06) + 0.20161(32) + 0.75806(28.013)$;

$MW_{mix} = 29.46355 \frac{kg}{kmole}$;

Thus, the species mass fraction for C_3H_8 and O_2 can be determined by;

$$Y_{C_3H_8} = \frac{\chi_{C_3H_8} M\,W_{C_3H_8}}{MW_{mix}} = \frac{0.04032(44.06)}{29.46355} = 0.06029$$

$$Y_{O_2} = \frac{\chi_{O_2} MW_{O_2}}{MW_{mix}} = \frac{0.21897(32)}{29.46355} = 0.21897$$

These values of species mass fraction are then being input to the Fluent.

The reduced chemical kinetics mechanism for propane-air mixture which is 2-step propane-air mixture are follow from the journal of Sendyka et al shown at table 3.3 (Sendyka et al, 2015). The propane-air two step chemical mechanism equation are CO + 0.5 O2 = CO2. This part of numerical simulation are running base on this equation with ignition flame of 1700K start from initial velocity of 0.10 m/s to find blow out limit for the propane-air mixture of two-step of chemical mechanism.

Table 3-3 Propane-air two-step chemical reactions with Arrhenius coefficients (Sendyka et al, 2015)

REACTION NO.	**REACTION**	**PRE-EXPONANTIAL FACTOR, A_i $[kmol/(m^3.s)]$**	**ACTIVATION ENERGY, E_i $[J/kmol]$**
1	$C_3H_8 + 3.5O_2 = 3CO + 4\,H_2O$	5.62 e+09	1.256 e+08
2	$CO + 0.5O_2 = CO_2$	2.239 e+12	1.7 e+08
3	$CO_2 = CO + 0.5O_2$	5.0 e+08	1.7 e+08

3.5 Computational domain

Under computational domain, by using three-dimensional (3-D) simulation the numerical equations of fluid flow are solved by CFD. The computational domain in this study covered only by faces (3-D) on which boundary conditions are applied. The boundary condition for simulation on ambient temperature, equivalent ratio (Φ), the flow rate of air and propane, velocity inlet, U and many other. Table 3.4 below shown the general setup for starting the numerical simulation for propane-air mixture and 2-step propane-air mixture

Table 3-4 General setup

SOLVER	**SELECTION**
Type	Pressure-Based
Time	Steady
Velocity Formulation	Absolute
2D Space	Axisymmetric

For the model boundary only energy and species model are on. For energy, the energy equation are used in this simulation. On species model, the reaction is volumetric with chemistry solver of stiff chemistry solver. It also run with condition of inlet diffusion, diffusion of energy source and thermal source. All the boundary setup shown at table 3.5.

Table 3-5 Model setup

MODEL BOUNDARY	**ACTION**
Energy	On
Viscous	Laminar
Species	**Mixture Material** 1. Propane-Air Mixture 2. 2-Step Propane-Air Mixture **Reaction** Volumetric **Chemistry Solver** Stiff Chemistry Solver

	- Inlet diffusion (On) - Diffusion Energy Source (On) - Thermal Diffusion (On)

For material, the chemical mechanism equation use is propane-air mixture and 2-step propane-air mixture. Both chemical kinetic mechanism which is consist of propane (C_3H_8), water-vapour, carbon dioxide, oxygen and nitrogen for propane-air mixture and for 2-step propane-air mixture are consists carbon monoxide, oxygen will produce carbon dioxide as in chemical equation shown above in table 3.3. Table 3.6 shown the material setup and parameter used in this study.

Table 3-6 Material setup

Mixture	1. Propane-Air Mixture 2. 2-Step Propane-Air Mixture
Fluid	Air
Solid	Quartz (1.6 W/mK)

The boundary condition at inlet for this is simulation are based on momentum, thermal and species. At momentum part, the velocity been set up start from 0.1 m/s or 0.2 m/s with reference frame of absolute according to the type of thickness design micro combustor model used. From species, the mass fraction has been set up from calculation by equivalent ratio (Φ) of 1.00 to put the propane mass fraction is 0.06029and oxygen is 0.21897. For thermal, the temperature is been set up to 295K. For the boundary condition for outlet tube of micro combustor, the mass fraction for species set up to 0 for propane and 0.23 for oxygen. All the setup are shown in table 3.7.

Table 3-7 Boundary condition setup

CHEMICAL		**PROPANE, (C_3H_8)**	**OXYGEN, (O_2)**	**CARBON DIOXIDE, (CO_2)**	**WATER, (H_2O)**	**CARBON MONOXIDE, (CO)**
Propane -Air Mixture	**Inlet**	0.06029	0.21897	0	0	0
	Outlet	0	0.23	0	0	0
2-Step Propane -Air Mixture	**Inlet**	0.06029	0.21897	0	0	0
	Outlet	0	0.23	0	0	0

From all above the setup for running both chemical kinetic mechanism which is propane-air mixture and 2-step propane-air mixture. All the reference value are set following recommended from ANSYS-Fluent itself. To run the numerical simulation for this design of two-dimensional micro combustor model, the solution method, solution control and solution initialization are been set up. From the table 3.8 shown all the solution setup that been used for the numerical simulation.

Table 3-8 Solution setup

SOLUTION TYPE	SELECTION/SETUP
Solution Method	Pressure Velocity Coupling - SIMPLE
Solution Control	Simulation Starting Equation Selection **- Flow** After Cold Flow **- Flow**, C_3H_8, O_2, CO_2, H_2O, $Energy$
Solution Initialization	Starting Simulation Initialize Method – **Standard Initialization** Compute from – Inlet After Cold Flow Patch - Variable – **Temperature** - Value (k) – **1700** - Zone to Patch – **Ignition Fluid**

For reference value, it is been set up the reference zone of fluid. As for the others is set up to default which is the area is $1m^2$, the density is $1.225kg/m^3$, length is 1000mm, velocity is 1m/s, the temperature is 288.16K, viscosity is 1.7894e-05 kg/ms , enthalpy is 0 and lastly ratio of specific heat is 1.4.

3.6 Performing the numerical simulation for Propane-Air Mixture and 2-Step Propane-Air Mixture

The numerical simulation for this design of two-dimensional micro combustor model started with cold flow technique. Cold flow technique is a technique that use for supply the chemical gas into combustor fully before ignite the fluid. By doing this, the micro combustor are able to fill inside the micro combustor tube and easily to ignite the chemical gas. From this study, the cold flow technique is apply up to 50 to 60 number of iteration. To apply this technique is needed to use solution control settings by only select flow as the starting equation. After the flow of chemical are believe fill in the tube of micro combustor, the solution control equation option choose all six equation which is Flow, C_3H_8, O_2, $CO_2, H_2O, Energy$ was selected. After choose all six equation, the solution need to ignite. By that, solution need to initialize by patching the variable temperature at 1700K at ignition fluid zone to be able ignite the solution.

The numerical simulation of this study is monitored the flame produced, stabilization of flame and the blowout of the flame produced in tube of micro combustor. To able achieve the objective of the study, the inlet velocity, u acting as manipulation of this numerical simulation. Table 3.9 shown the inlet velocity, u used in this study.

Table 3-9 Inlet velocity used for both chemical kinetic mechanism

CHEMICAL KINETIC MECHANISM	THICKNESS	INLET VELOCITY, u (m/s)
Propane-Air Mixture	0.3 mm	**0.15, 0.20, 0.25, 0.26, 0.27, 0.28. 0.29, 0.30**
	0.5 mm	**0.15, 0.20, 0.25, 0.30**
	1.0 mm	**0.30, 0.31, 0.32, 0.33, 0.34, 0.35**
	1.2 mm	**0.30, 0.31, 0.32, 0.33,0.34 0.35**
2-Step Propane-Air Mixture	0.3 mm	**0.10, 0.15, 0.20, 0.25, 0.26, 0.27, 0.28, 0.30**
	0.5 mm	**0.10, 0.15, 0.20, 0.25, 0.30, 0.31, 0.35**
	1.0 mm	**0.20, 0.25, 0.30, 0.35**
	1.2 mm	**0.20, 0.25, 0.30, 0.31, 0.32, 0.33, 0.34, 0.35, 0.36, 0.40**

CHAPTER 4

4 RESULTS AND DISCUSSION

4.1 Result

Flame propagation in a narrow channel is a broad subject matter. Investigation of flame propagation characteristics in a narrow channel tube combustor is indeed a formidable task. In order to numerically study the phenomenon of flame propagation inside a meso-scale tube combustor, a detailed kinetics reaction mechanism is required that can lead to a higher computational cost. Therefore, results are only limited to demonstrate the capability of the concentric rings.

In this study, the determination of blowout limits is as follow. To find the blowout limit for each parameter for every design micro combustor, the needed to find the last value of inlet velocity, u to stable the flame at the concentric rings. Firstly, a stable flame is established in the combustor. For all cases, a stable flame can be achieved with the inlet velocity (U) of 0.10 m/s, 0.15 m/s, 0.20 m/s and 0.25m/s regardless of the equivalence ratio (ϕ) value. Then, the value of U is gradually stepped up with 0.1 m/s interval and further calculation is conducted until a converged solution is achieved.

4.1.1 Propane-Air Mixture

For this part show the data result for the numerical simulation using propane-air mixture. In this part, the design undergoes numerical simulation by using four different size of thickness. The thickness use is 0.3 mm, 0.5 mm, 1.0 mm and 1.2 mm. The data will be analyse to find the effect of thickness for propane-air mixture of design micro combustor model. A two-dimensional (2-D) steady state numerical simulation was performed using ANSYS Release 17.1 with Fluent.

4.1.1.1 Micro Combustor with Thickness 0.3 mm

From the data collected using 0.3 mm thickness of micro combustor, 0.15 m/s is select as starting inlet velocity, u for this numerical simulation for this thickness. The flame able to stabilize by using 0.15 m/s inlet velocity, u. From the figure 4.1, the flame slowly propagate toward the concentric rings. By number iteration 2500, the flame stabilize at the concentric rings. The flame produced shown clearly at the figure below.

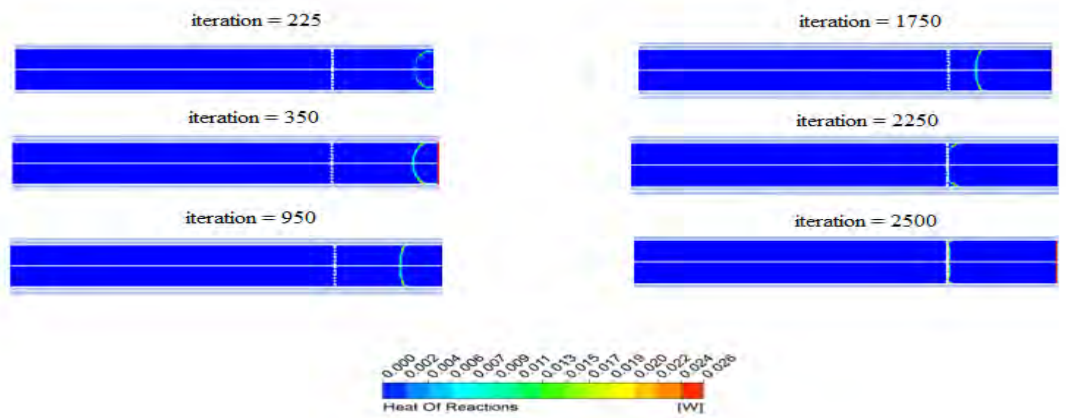

Figure 4-1 Flame stabilization at u =0.15 m/s with micro combustor 0.3 mm thickness

From this part numerical simulation, the increasing the value of u from 0.25 m/s to 0.29 m/s causes the flame to propagate away from the rings toward the outlet, then u = 0.28 m/s is considered as the blowout limit. This blowout limit for 0.3 mm thickness of micro combustor model is shown in figure 4.2. As shown, the flame is stabilize at value of u from u = 0.15 m/s until u = 0.28 m/s.

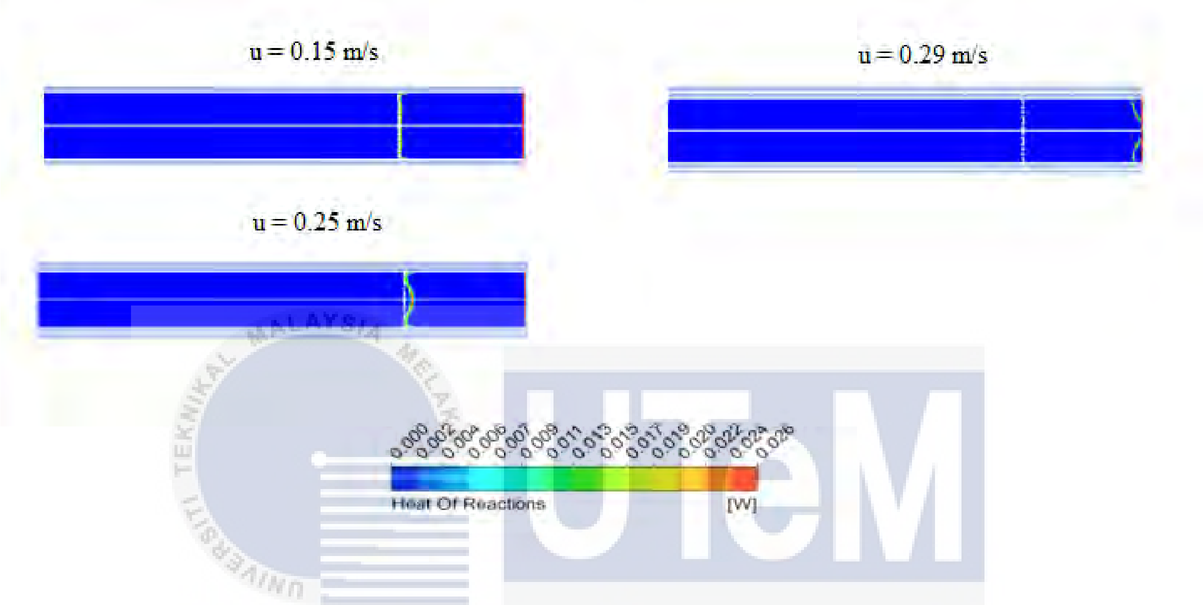

Figure 4-2 Solution blowout limit micro combustor 0.3 mm thickness

When the numerical simulation is running at value of u = 0.29 m/s, the flame cannot be stabilize at the concentric rings design at tube of micro combustor. Figure 4.3 shows, the flame inside the micro combustor is blown out at value of u = 0.29 m/s. The flame unable to stabilize at the concentric rings and move against the concentric rings location.

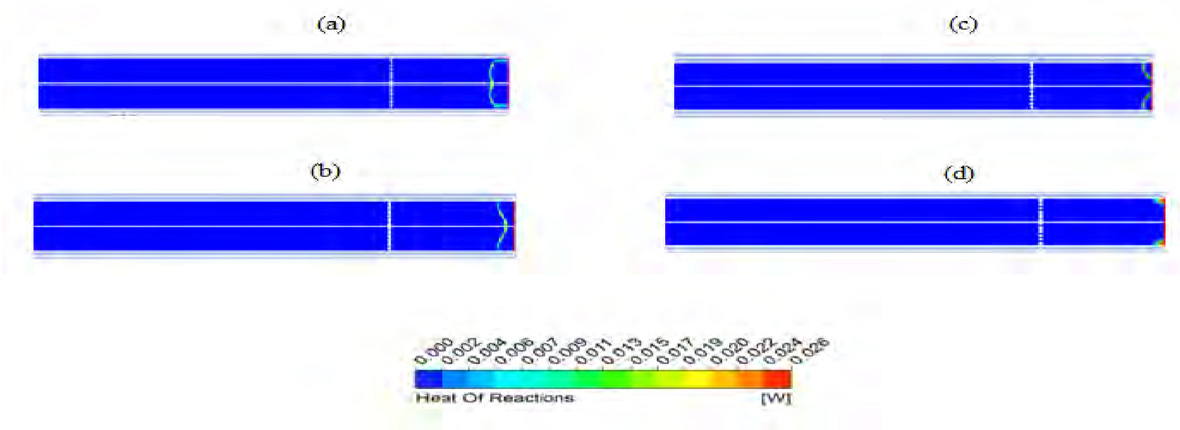

Figure 4-3 Flame blown out at u = 0.29 m/s micro combustor with 0.3 mm thickness

4.1.1.2 Micro Combustor with Thickness 0.5 mm

Another part of numerical simulation for propane-air mixture is using 0.5 mm size of thickness. For 0.5 mm of thickness, the flame also can be stabilize at 0.15 m/s. This is shown at figure 4.4 where the flame start to propagate toward the concentric rings and the flame stabilize at there. The movement of the flame shown at number of iteration of 2250 when the flame is stabilize.

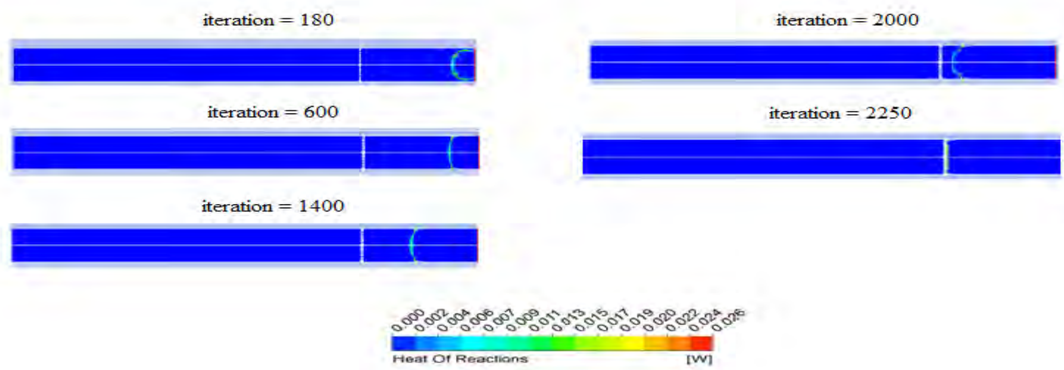

Figure 4-4 Flame stabilization at u = 0.15 mm micro combustor with 0.5 mm thickness

As the increasing value of u, the flame kept stabilize at the concentric rings. The flame stabilize at the concentric rings until the value of the u = 0.30 m/s. This is shown at figure 4.5 that the flame start move away from the concentric rings. This is shown that the blowout limit for this part of numerical simulation is when u = 0.29 m/s. This is because the flame is stabilize when the value of u = 0.15 m/s until 0.29 m/s.

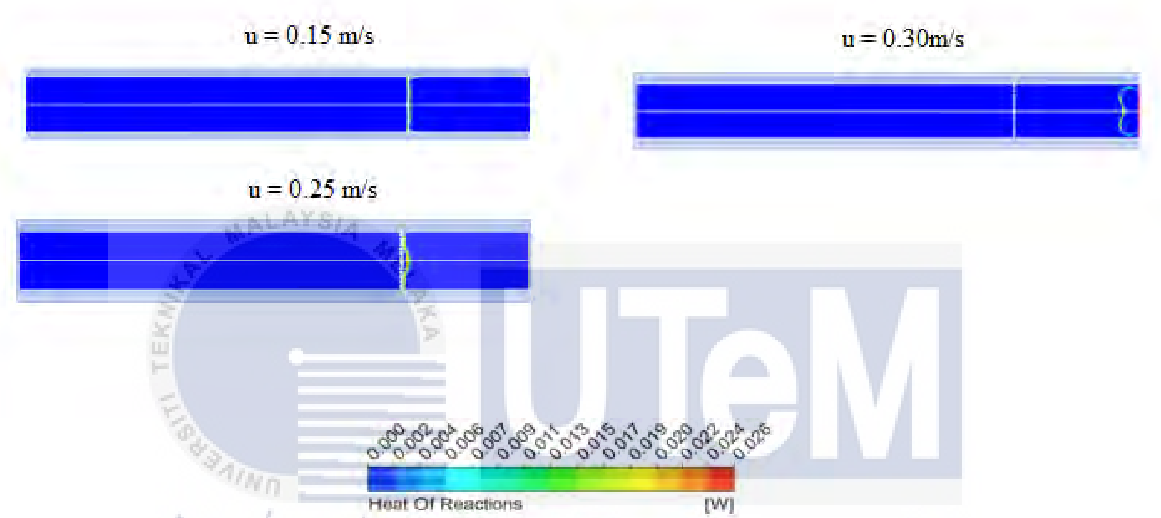

Figure 4-5 Solution blowout limit micro combustor with 1.0 mm thickness

As shown is figure 4.6, when the value of the flame at 0.30m/s, the flame is blown out at the tube of the micro combustor. From figure below, the flame are propagate toward the outlet of the flame.

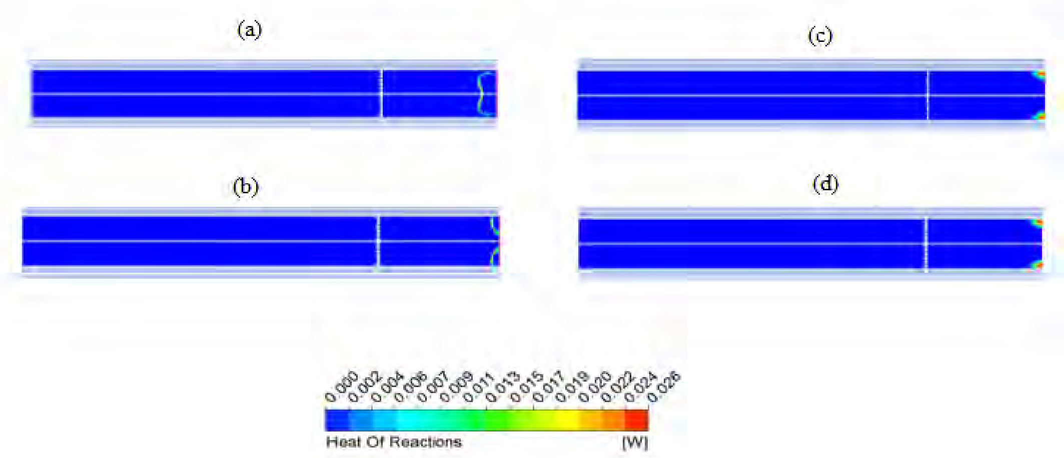

Figure 4-6 Flame blown out at u = 0.30 m/s micro combustor with 0.5 mm thickness

4.1.1.3 Micro Combustor with Thickness 1.0 mm

The next part for numerical simulation for propane-air mixture is micro combustor with 1.0 mm model design. For this simulation, the initial value of u used is u = 0.30 m/s. This is because the trend of blowout limit for propane-air mixture is increasing due to increasing size of the thickness. When running the numerical simulation at u = 0.30 m/s, flame can be stabilize but it takes higher number of iteration to the flame able to stabilize at the concentric rings design at the tube of micro combustor as shown in figure 4.7.

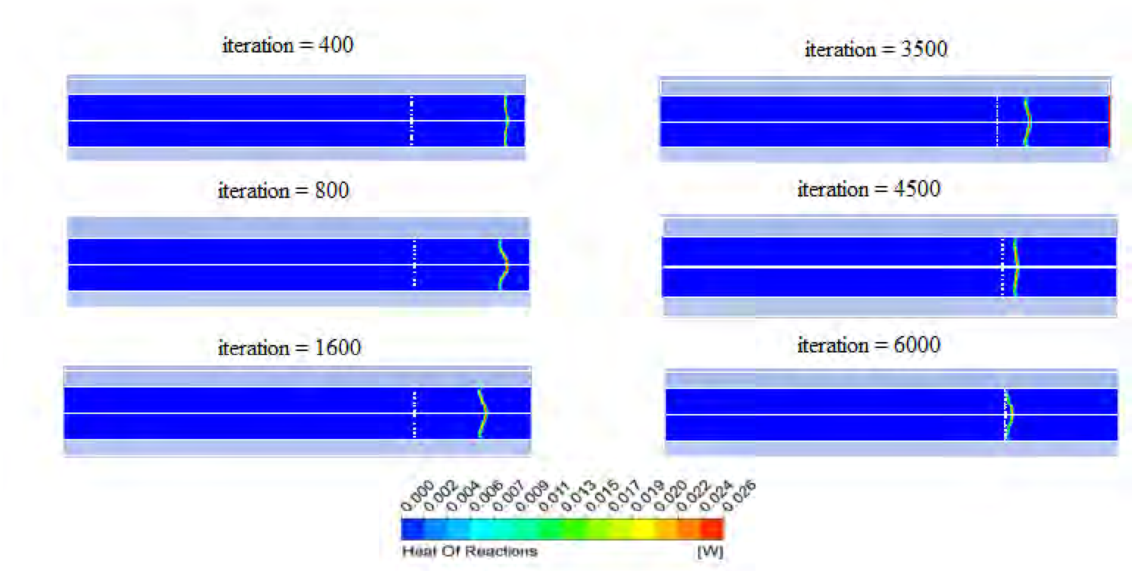

Figure 4-7 Flame stabilization at u = 0.30 m/s micro combustor with thickness 1.0 mm

From the figure 4.8, the flame blown out at value of u = 0.34 m/s. From that, the blowout limit for micro combustor with 1.0 mm of thickness is u = 0.33 m/s. By that, the flame is stabilize at u = 0.30 m/s until 0.33 m/s in this study.

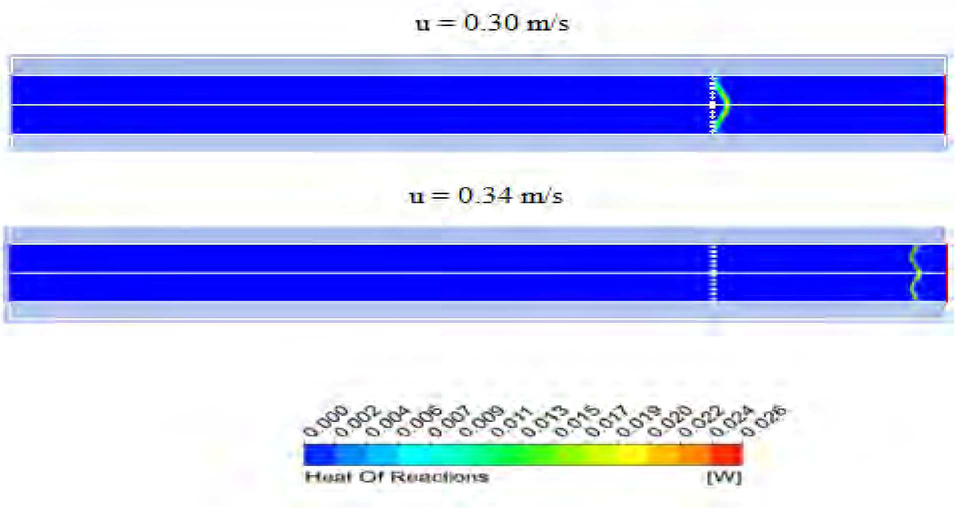

Figure 4-8 Solution blowout limit micro combustor with 1.0 mm thickness

The flame is blown out starting too blown out at value of u = 0.34 m/s. From figure 4.9, shown how the flame is blown out inside the tube of micro combustor. It show that the flame is propagate toward the outlet of the micro combustor.

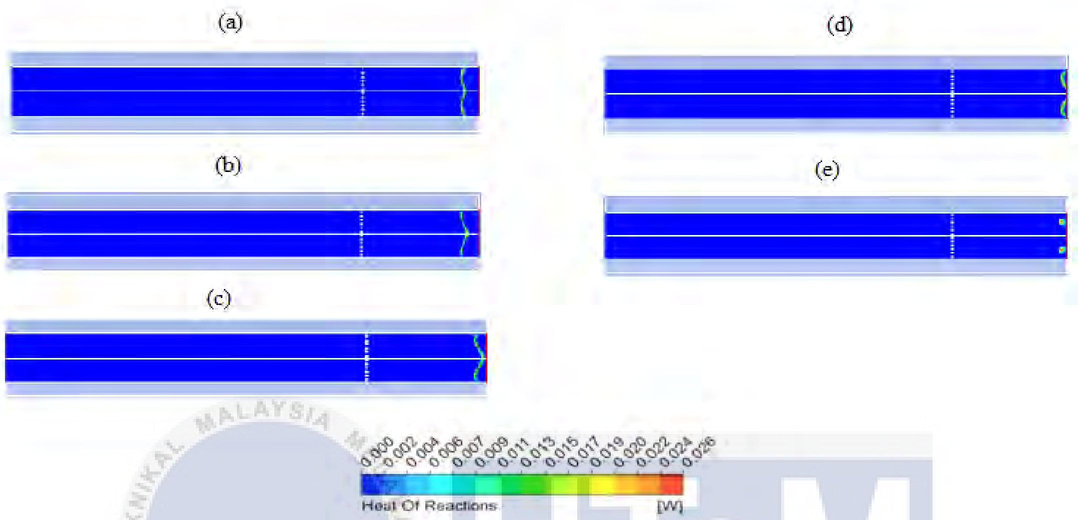

Figure 4-9 Flame blown out at u = 0.34 m/s micro combustor with 1.0 mm thickness

4.1.1.4 Micro Combustor with Thickness 1.2 mm

The last part of the first part of the numerical simulation is micro combustor with thickness 1.2 mm. As shown in figure 4.10 shows that, the micro combustor flame also stabilize at 0.30 m/s. The flame propagate towards the concentric rings and stable at value of u = 0.30 m/s. The thicker the thickness of the micro combustor, the higher number of iteration is needed to stabilize the flame inside the tube of micro combustor within the blowout limit of the micro combustor itself.

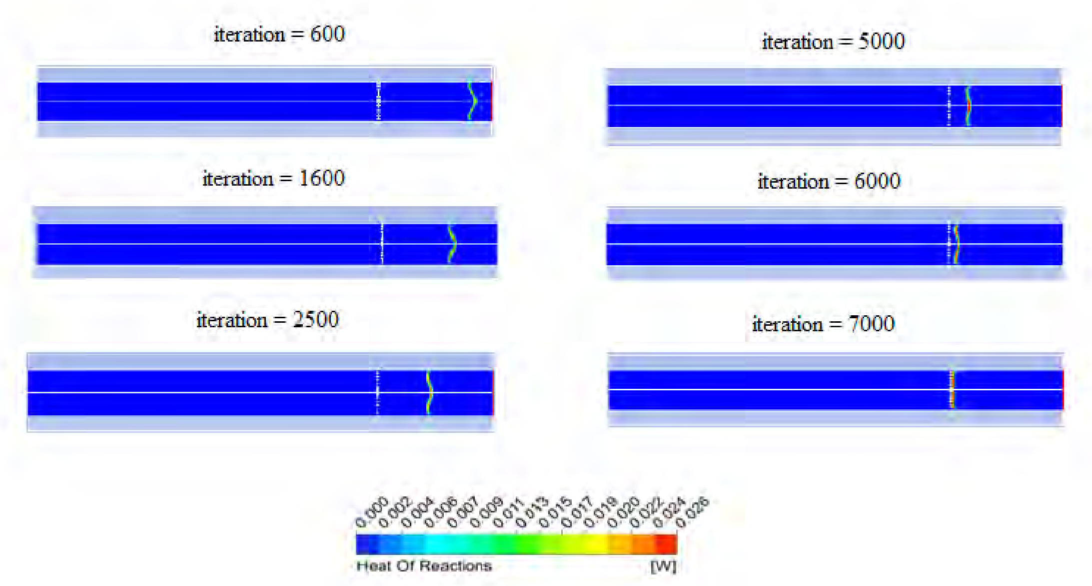

Figure 4-10 Flame stabilization at u = 0.30 m/s micro combustor with 1.2 mm thickness

The blowout limit for this 1.2 mm of micro combustor for propane-air mixture is u = 0.34 m/s. From the figure 4.11, the flow of the flame inside the tube of micro combustor is shown that the flame will blow out at u = 0.35 m/s. For that, the flame will stabilize with this design micro combustor at u = 0.30 m/s until 0.34 m/s.

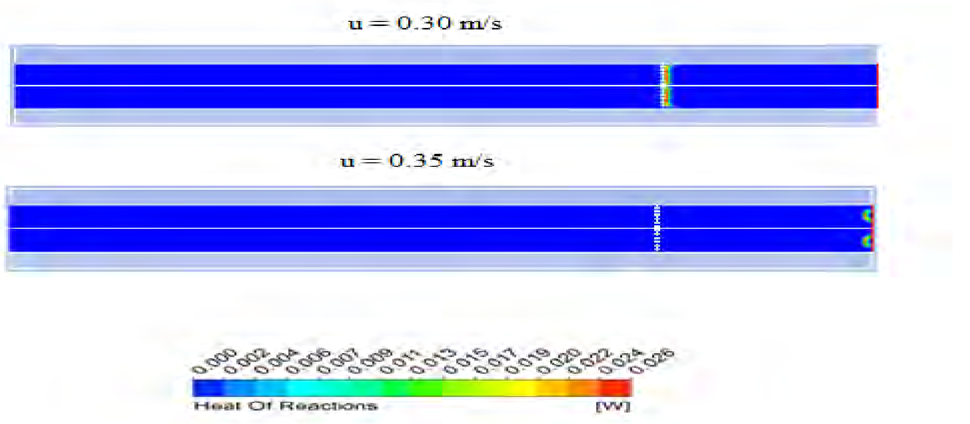

Figure 4-11 Solution blowout limits micro combustor with 1.2 mm thickness

The flame are blown out at u = 0.35 m/s. The flame movement inside the micro combustor is toward the outlet of the micro combustor show at figure 4.12. By that, it is prove that the blowout limit for the 1.2 mm thickness of micro combustor is when u = 0.34 m/s.

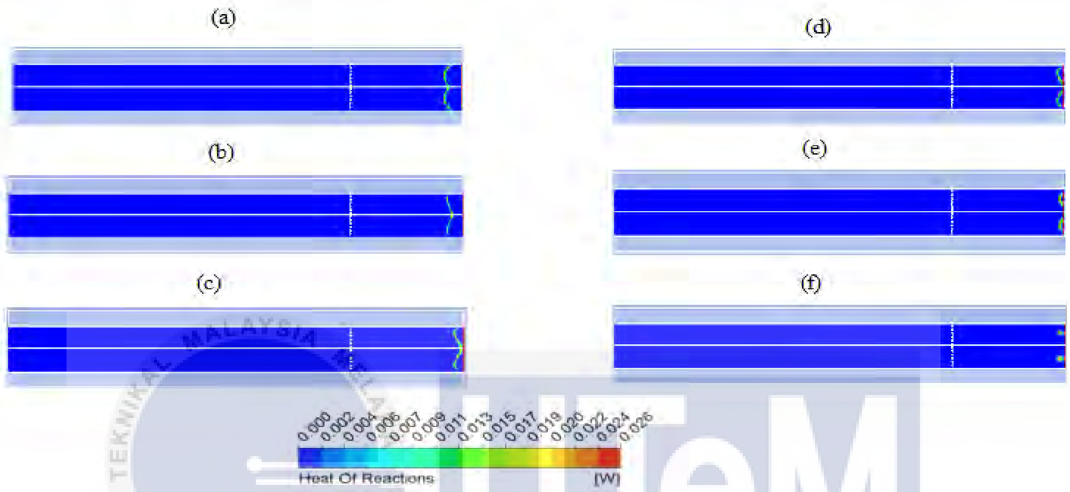

Figure 4-12 Flame blown out at u = 0.35 m/s micro combustor with 1.2 mm thickness

4.1.2. 2-Step Propane-Air Mixture

For this part show the data result for the numerical simulation using 2-step propane-air mixture. In this part, the design also undergoes numerical simulation by using four different size of thickness which 0.3 mm, 0.5 mm, 1.0 mm and 1.2 mm. The data will be analyse to find the effect of thickness for 2-step propane-air mixture of design micro combustor model. A two-dimensional (2-D) steady state numerical simulation was performed using ANSYS Release 17.1 with Fluent.

4.1.2.1 Micro Combustor with Thickness 0.3 mm

For the first part for second numerical simulation for chemical kinetic mechanism of 2-step propane air mixture is 0.3 mm of thickness of micro combustor. For this part shown in figure 4.13 where the flame is stabilize at u = 0.10 m/s which is the starting value of u choose for running the numerical simulation by this micro combustor with thickness 0.30 mm design. The flame slowly propagate toward the concentric rings and stable at there.

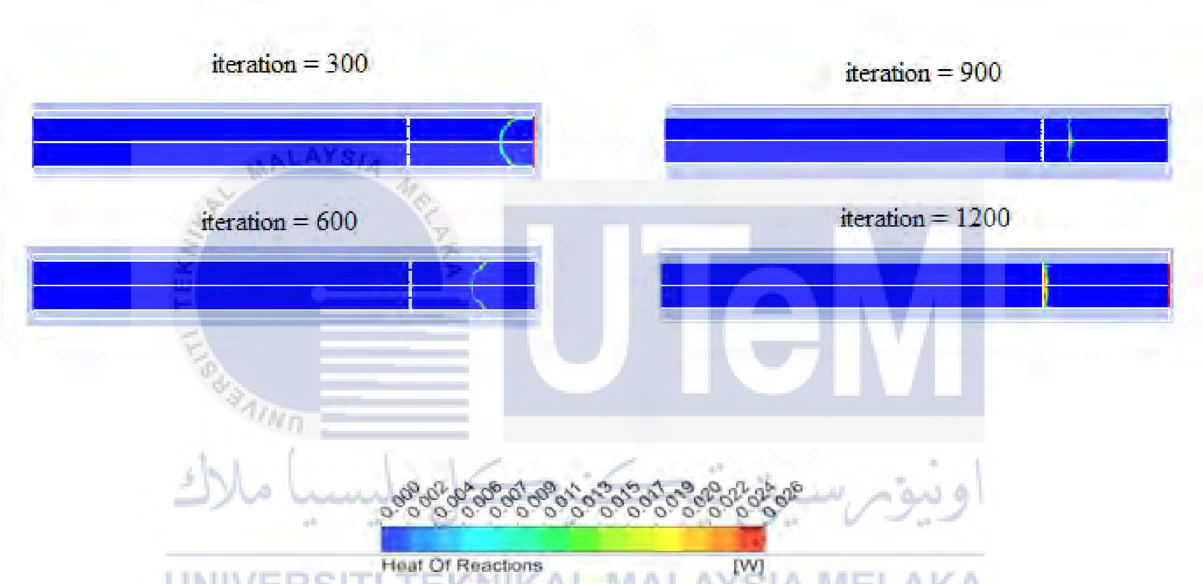

Figure 4-13 Flame stabilization at u = 0.10 m/s micro combustor with 0.3 mm of 2-step propane-air mixture

The flame is stabilize at several value of u which is u = 0.10 m/s until 0.29 m/s. At the value of u = 0.30 m/s, the flame starting to propagate away from the concentric rings and move toward the outlet of the micro combustor tube at burned gas region. From figure 4.14 shows that the flame stabilize at concentric rings and the flame started to propagate away from the concentric rings. By that, the blowout limit for this design of micro combustor is u = 0.29 m/s. From figure 4.15 shows that the temperature contour of the micro combustor when the flame is stabilize. From that figure, at the outlet of the tube, the temperature started to lose heat due to increasing value of u.

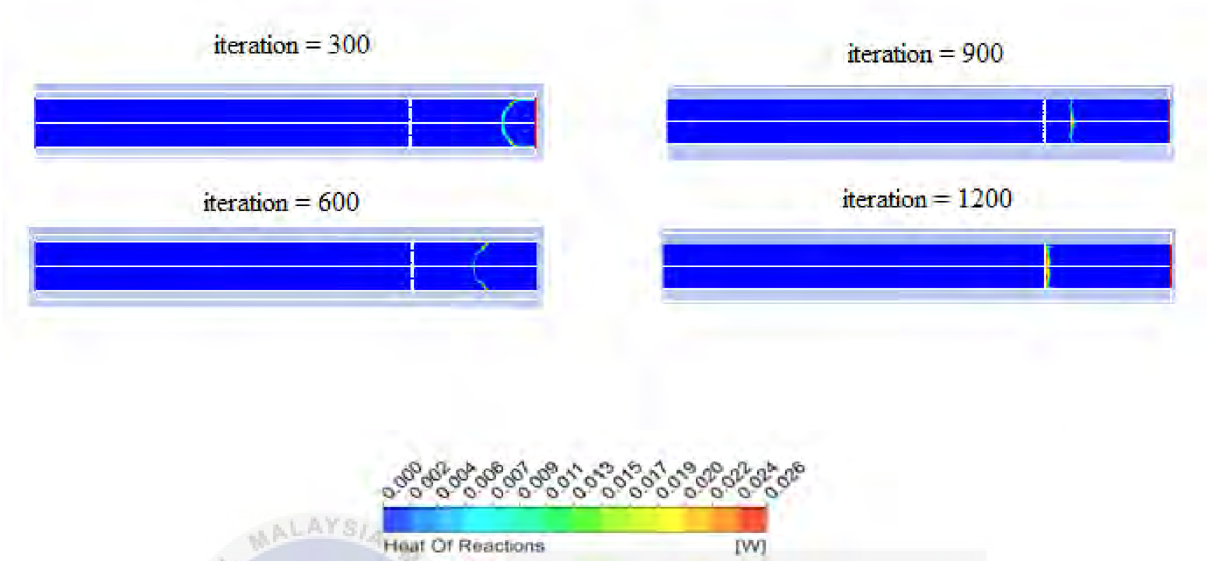

Figure 4-14 Solution blowout limits micro combustor with 0.3 mm of 2-step propane-air mixture

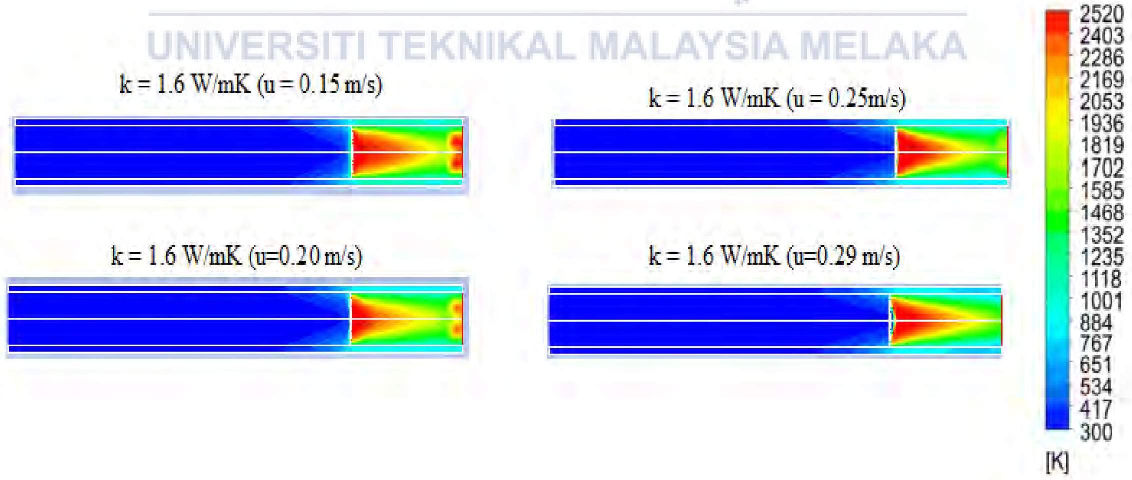

Figure 4-15 Temperature contour for micro combustor with 0.3 mm thickness

The flame are blown out at u = 0.30 m/s. The flame movement inside the micro combustor is toward the outlet of the micro combustor show at figure 4.16. By that, it is prove that the blowout limit for the 0.3 mm thickness of micro combustor is u = 0.29 m/s as the flame started to propagate away from concentric rings when the value u = 0.30 m/s.

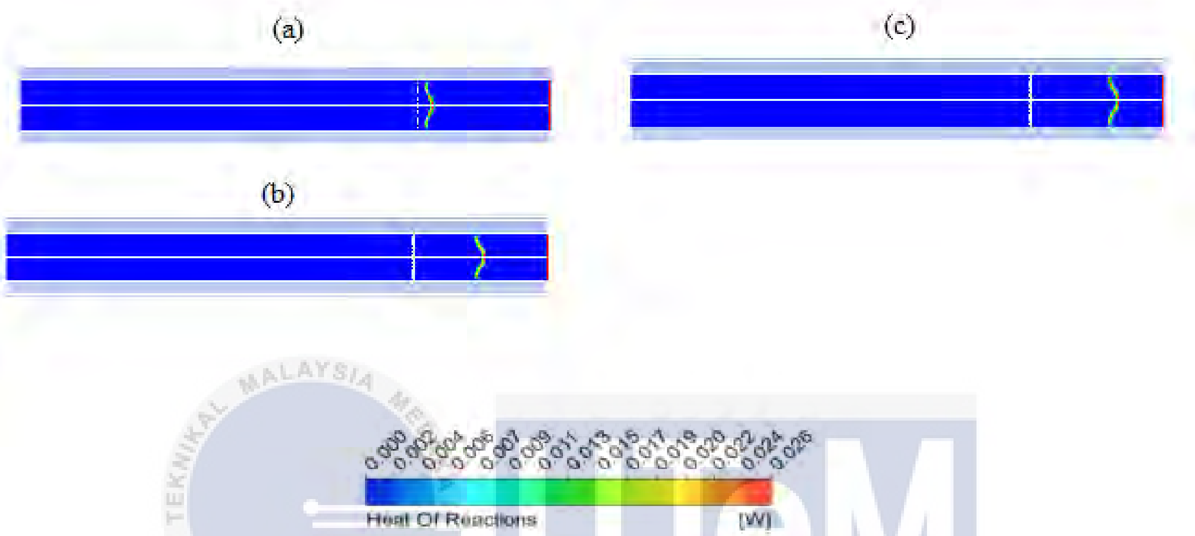

Figure 4-16 Flame blown out at u = 0.30 m/s micro combustor with 0.3 mm thickness of 2-step propane-air mixture

4.1.2.2 Micro Combustor with Thickness 0.5 mm

The next part of the second numerical simulation is using micro combustor with 0.5 mm thickness. The flame can be stabilize at u = 0.10 m/s as the starting value of u using in this numerical simulation. From figure 4.17 shows that the flow of flame is stabilize at concentric rings.

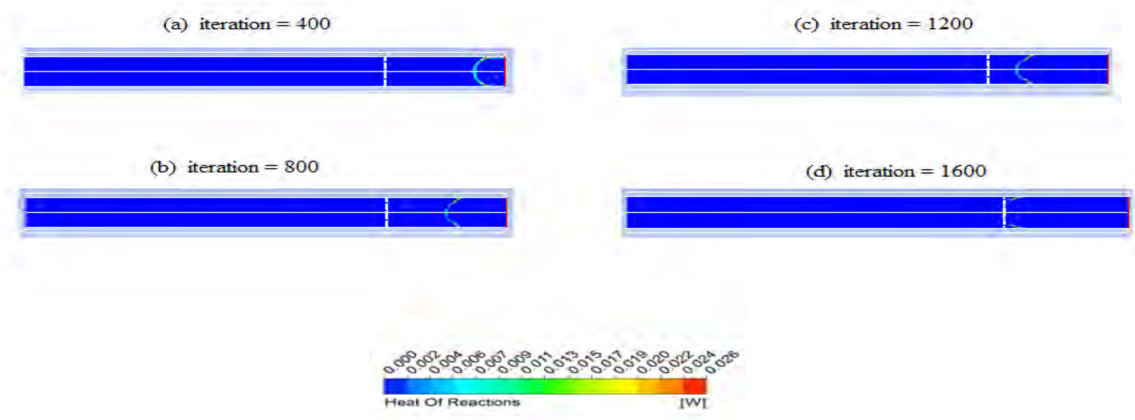

Figure 4-17 Flame stabilization at u = 0.10 m/s micro combustor with 0.5 mm thickness of 2-step propane-air mixture

As increase the value of u, the flame is still stable at the concentric rings until it reach the blowout limit. From the figure 4.18 shows that the flame is stabilize at concentric rings using various value of u. At value of u = 0.31 m/s, the flame start to propagate away from the concentric rings. By this, the blowout limit for 0.5 mm thickness using 2-step propane-air mixture is u = 0.30 m/s. Figure 4.19 shows that the temperature contour of this design. As increasing the value of u, the heat is increase at the concentric rings and lose heat at the outlet of the micro combustor tube.

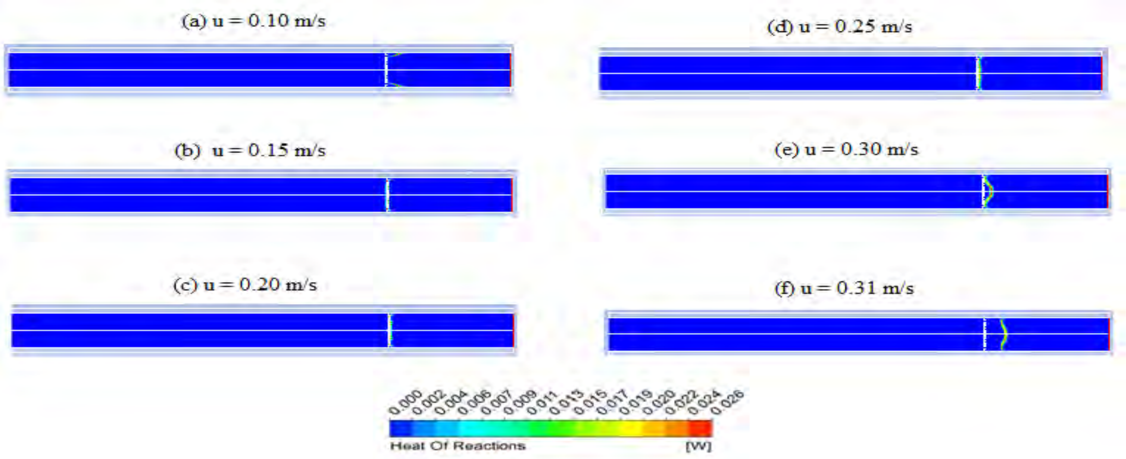

Figure 4-18 Solution blowout limits micro combustor with 0.5 mm thickness of 2-step propane-air mixture

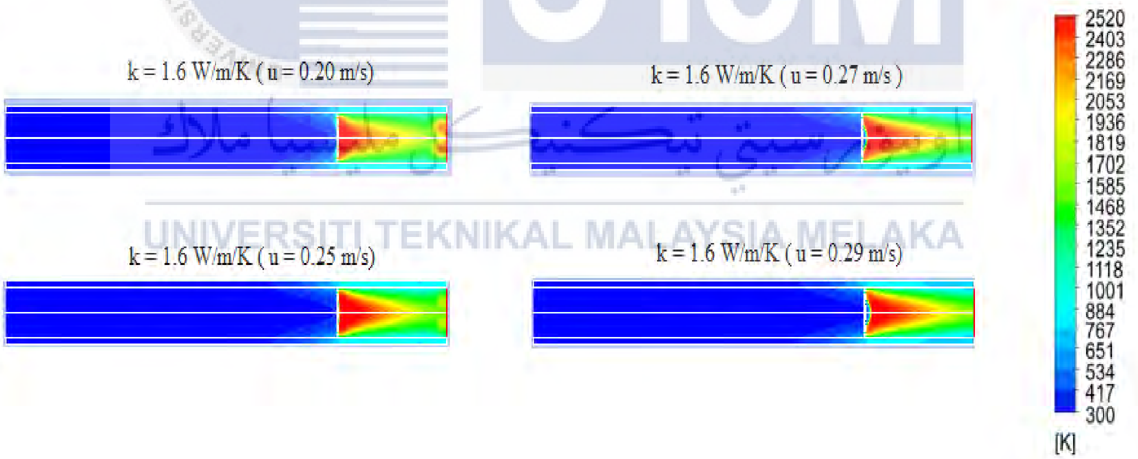

Figure 4-19 Temperature contour for micro combustor with 0.5 mm thickness

The flame are blown out at u = 0.31 m/s as shown is figure 4.19. The flame is propagate toward the outlet of the micro combustor show at figure 4.20. By that, it is prove that the blowout limit for the 0.5 mm thickness of micro combustor is u = 0.30 m/s as the flame started to propagate away from concentric rings when the value u = 0.31 m/s.

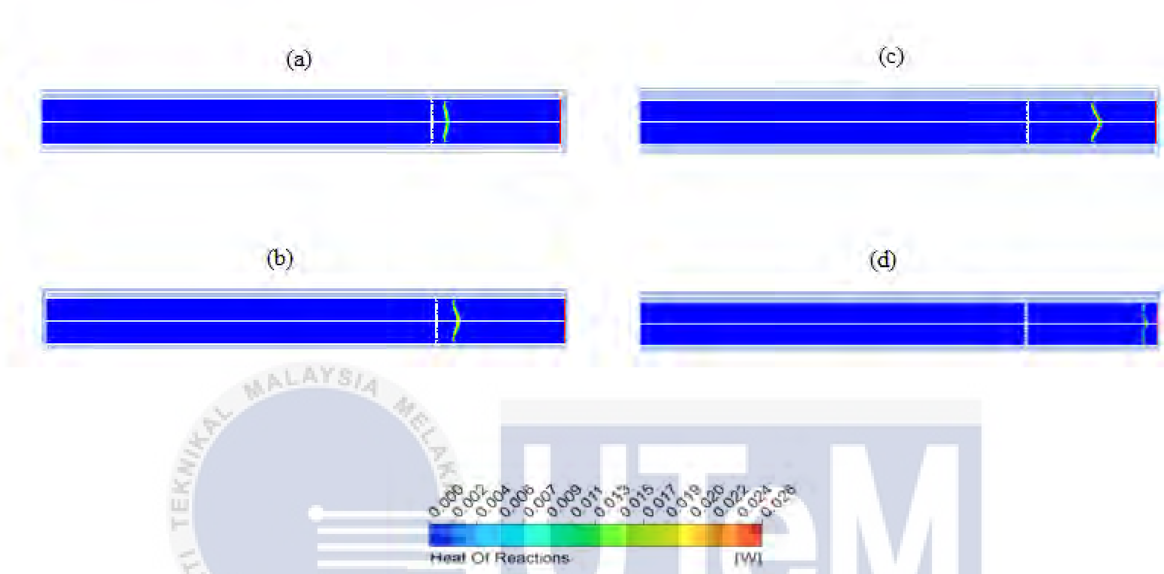

Figure 4-20 Flame blown out at u = 0.31 m/s micro combustor with 0.5 mm thickness of 2-step propane-air mixture

4.1.2.3 Micro Combustor with Thickness 1.0 mm

The third part of the numerical simulation for 2-step propane-air mixture is micro combustor with thickness 1.0 mm. Figure 4.21 shows that flame is stabilize at u = 0.20 m/s for the starting value of u for this part of numerical simulation. The flame is propagate toward the concentric rings and stable at the location of the concentric rings. The flame produced brightly and clear at the tube of micro combustor.

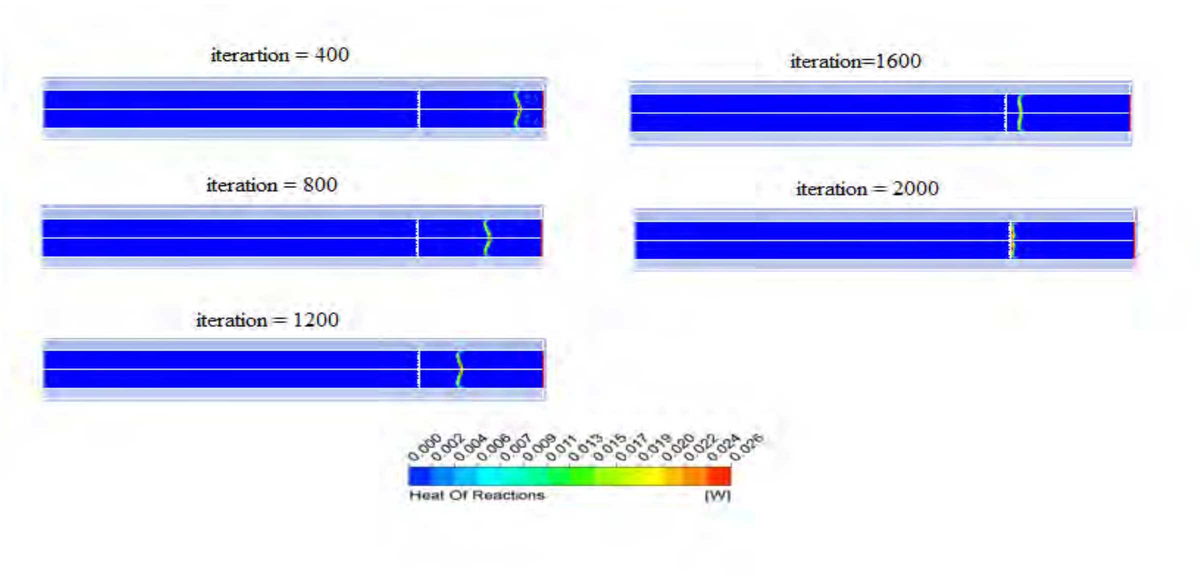

Figure 4-21 Flame stabilization at u = 0.20 m/s micro combustor with 1.0 mm thickness of 2-step propane-air mixture

From figure 4.21, shows that flame is stable at several value of u when running the simulation. The flame start to propagate away from the concentric rings at u = 0.35 m/s. From the data that collected from running this simulation, at value of u = 0.35 m/s is the starting the inlet velocity of the micro combustor that the flame is propagate away from the concentric rings which is use to stabilize the flame. By that, the blowout limit for this numerical simulation is when u = 0.34 m/s.

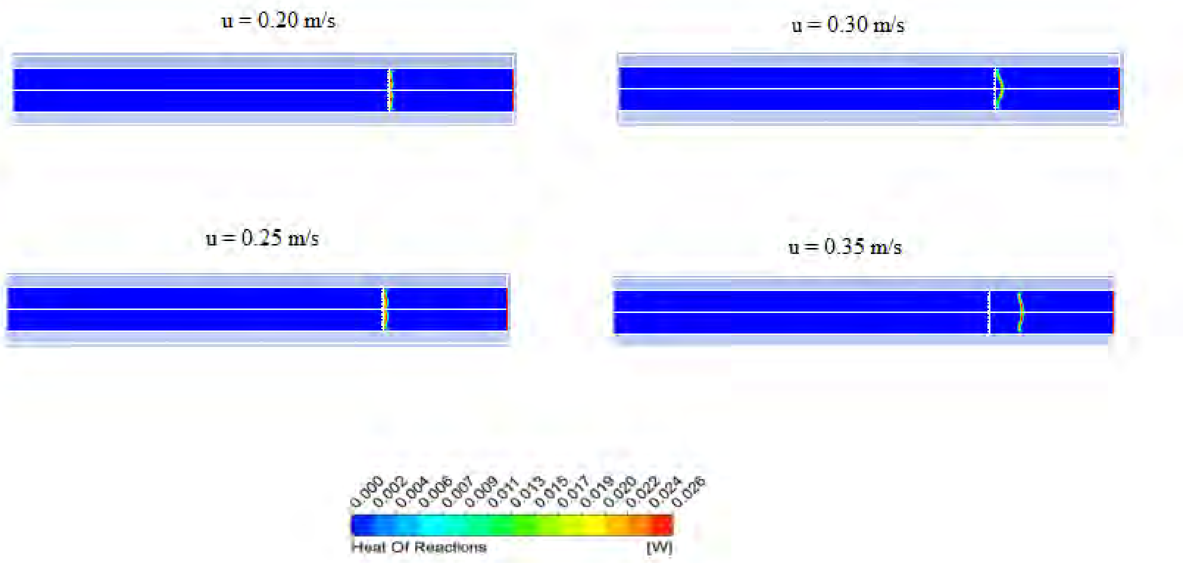

Figure 4-22 Solution blowout limits micro combustor with 1.0 mm of 2-step propane-air mixture

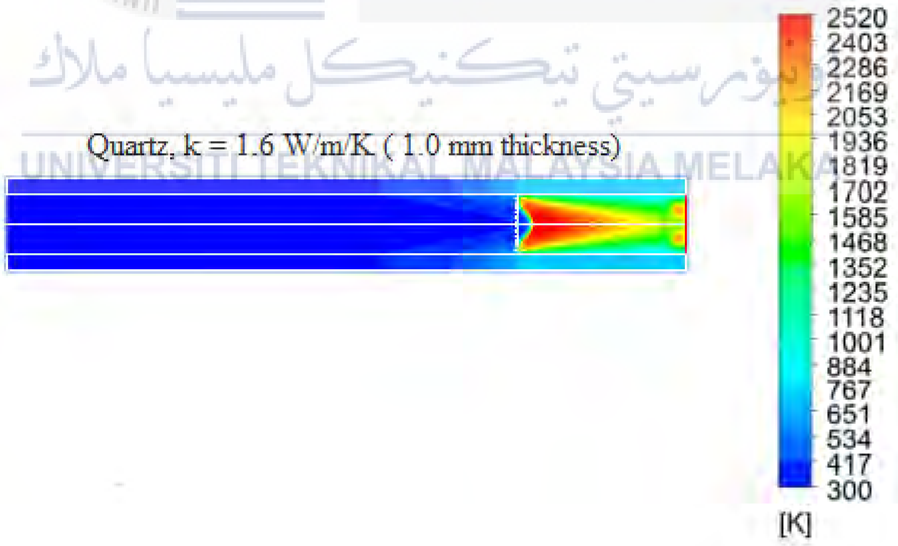

Figure 4-23 Temperature contour for micro combustor with 1.0 mm thickness

As the increase value of u, the flame start to propagate away from the concentric rings. Figure 4.24, it show that the flame move from the concentric rings toward the outlet of the micro combustor and the flame blown out. As the result, the blowout limit for this part of simulation micro combustor design with thickness 1.0 mm is u = 0.34 m/s as when flame started blown out at u = 0.35 m/s.

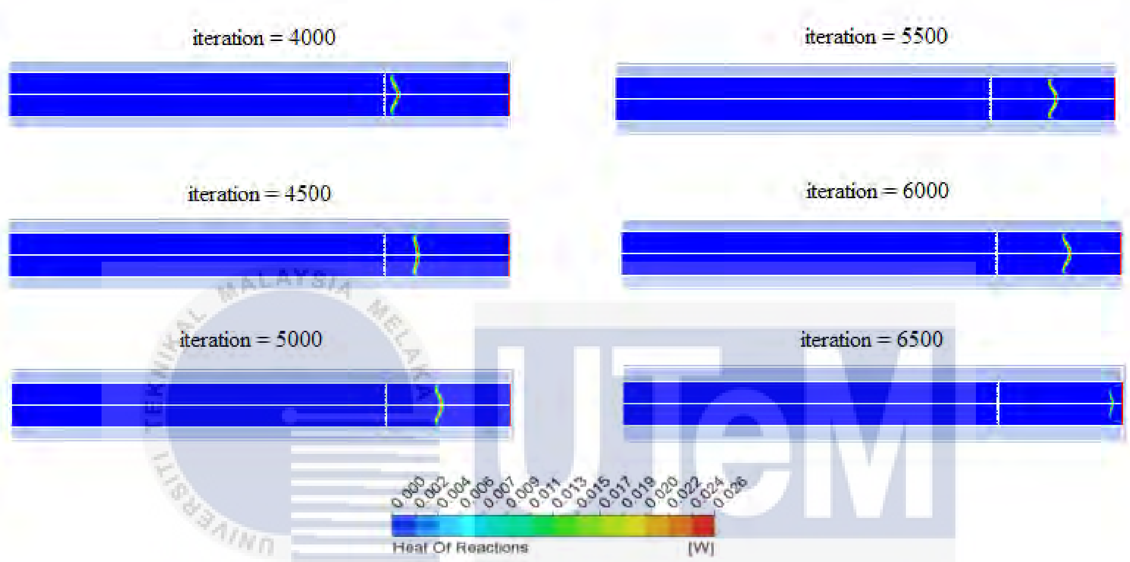

Figure 4-24 Flame blown out at u = 0.35 m/s micro combustor with 1.0 mm thickness of 2-step propane-air mixture

4.1.2.4 Micro Combustor with Thickness 1.2 mm

The last part of the numerical simulation for 2-step propane-air mixture is micro combustor with thickness 1.2 mm. Figure 4.25 shows that flame is stabilize at u = 0.20 m/s for the starting value of u for this part of numerical simulation same like the simulation for thickness 1.0 mm. The flame is propagate in the direction of the concentric rings and steady at the place of the concentric rings.

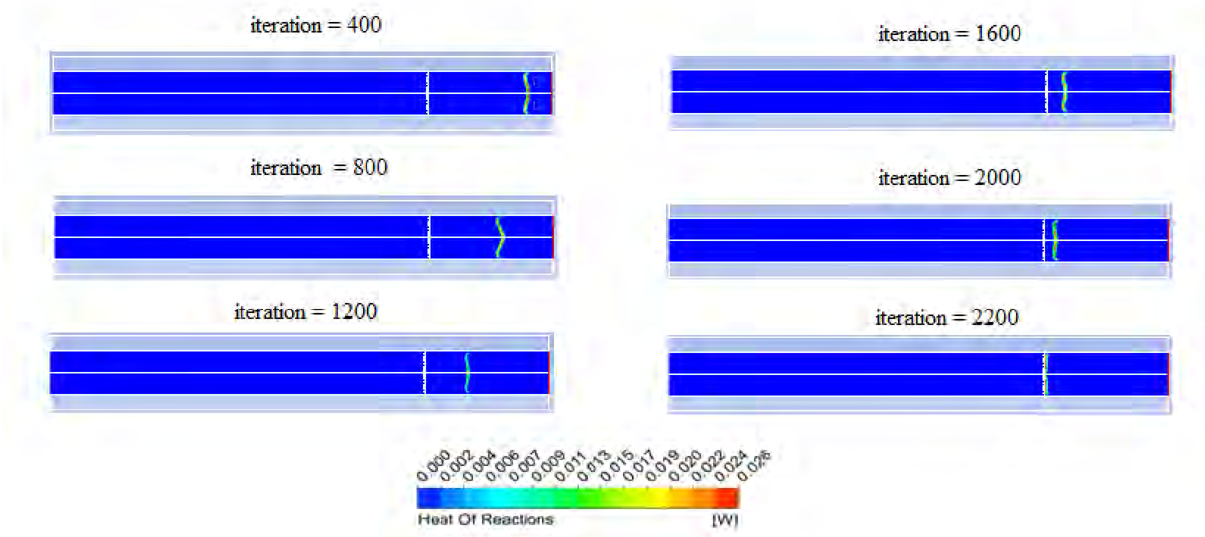

Figure 4-25 Flame stabilization at u = 0.20 m/s micro combustor with 1.2 mm thickness of 2-step propane-air mixture

From the data collected shows in figure 4.26, the flame inside the micro combustor start to propagate away from concentric rings at value of u = 0.36 m/s. The flame produced inside the micro combustor is stable at the concentric rings until the value of u = 0.35 m/s. From the result, the blowout limits for this micro combustor design is u = 0.35 m/s. From figure 4.27, shows one of the example for stable flame at concentric rings for micro combustor at value of u = 0.20 m/s.

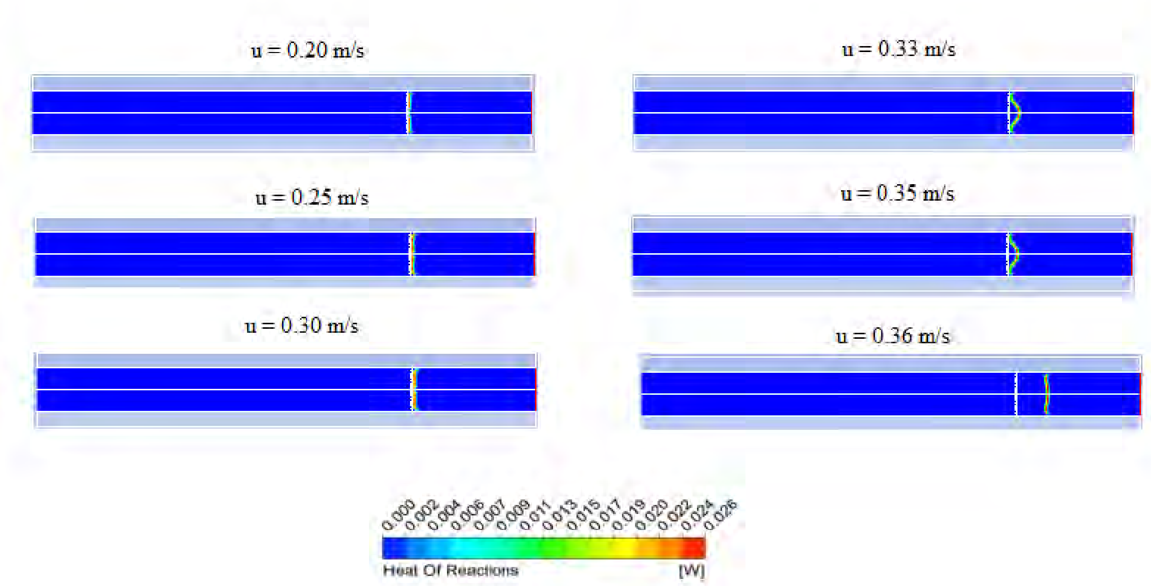

Figure 4-26 Solution blowout limits micro combustor with 1.2 mm of 2-step propane-air mixture

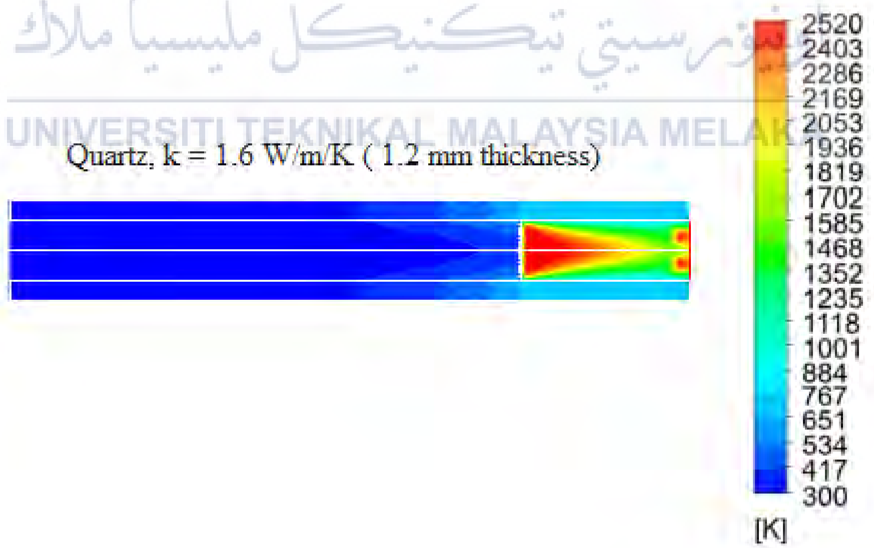

Figure 4-27 Temperature contour for micro combustor with 1.2 mm thickness

To prove that the blowout limit is at u = 0.35m/s, the last value of u that stable at the concentric rings. From figure 4.28, the flame slowly propagate away from the micro combustor. The flow of flame at u = 0.36 m/s blown out is shown at figure below. This is prove that the blowout limit for this micro combustor is u = 0.35 m/s.

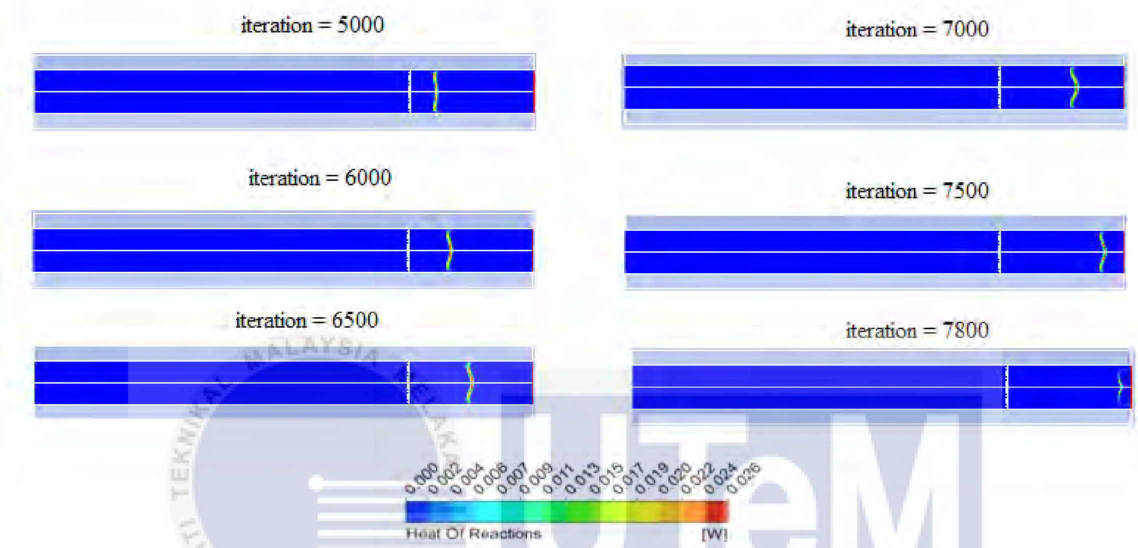

Figure 4-28 Flame blown out at u = 0.36 m/s micro combustor with 1.2 mm thickness of 2-step propane-air mixture

4.2 Discussion

For the discussion, all the blowout limit for each numerical simulation and each type of design has been found. At the initial stage of the experiment, the effect of thickness of micro combustor with respect to the unburned solid on the flame stabilization at the concentric rings was investigated. The thickness of micro combustor test are 0.3 mm, 0.5 mm, 1.0 mm and 1.2 mm for both chemical mechanism which is propane-air mixture and 2-step propane air mixture. The result of the data collected is shown in Table 4.1.

Table 4-1 Result of the Blowout limit with Various Thickness of Both Chemical Mechanism

Thickness of Micro Combustor (mm)	**Blowout Limit (m/s)**	
	Propane- Air Mixture	**2-Step Propane-Air Mixture**
0.3	0.28	0.29
0.5	0.29	0.30
1.0	0.33	0.34
1.2	0.34	0.35

The flame blowout limit in this work is defined as limit where the flame is stabilized near the combustor inside the micro combustor. In this study, the micro combustor model is in 2-D. When the flame was not stable at concentric rings design inside the micro combustor rings, the flame will blow out. This phenomenon is called flame quenching. From table 4.2, show the maximum value of u that can be stabilize for each design of the micro combustor. When the flow of the chemical flow reach the maximum value u, the flame start to propagate away from the stabilize area and the phenomenon flame quenching is occur.

Comparing between chemical reaction of propane-air mixture and thickness show the trend that the more thick the micro combustor thickness, the higher the blowout limits for chemical reaction. The same result are also repeating when reducing the chemical mechanism which is 2-step propane-air mixture. From figure 4.29, the trend shown in graph that the blowout limits for each thickness test is increasing directly proportional due to increasing size of the thickness. From this, effect of thickness give the great impact toward the blowout limit for each chemical reaction use in case for this research study of propane-air mixture and reduced chemical kinetic mechanism.

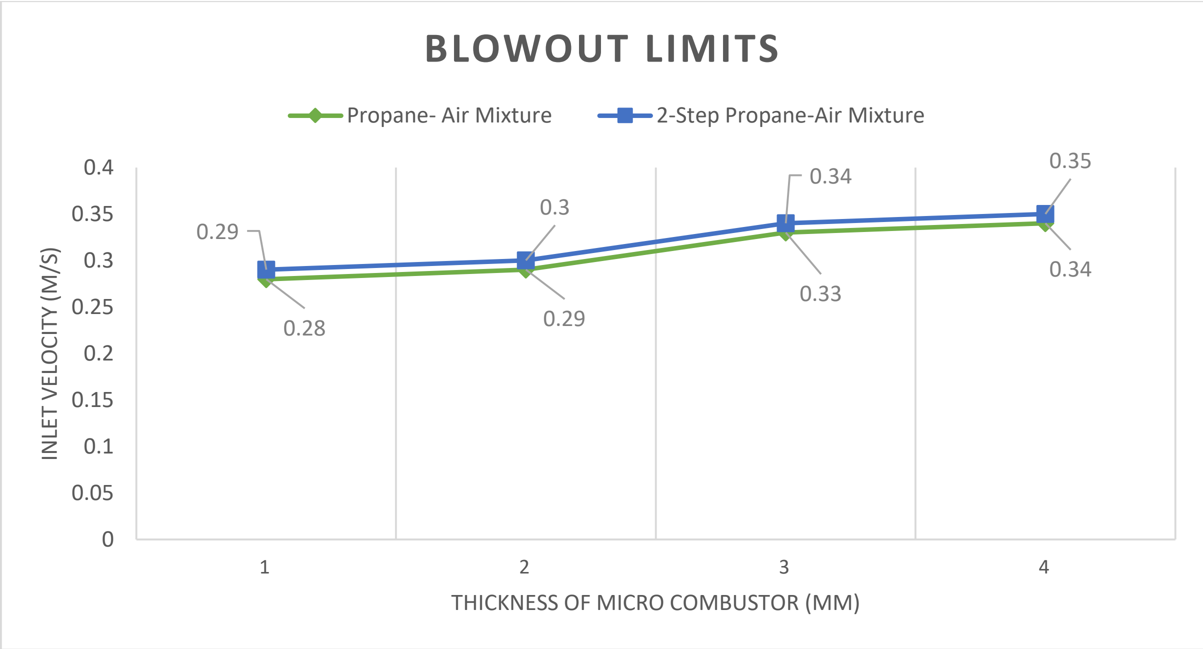

Figure 4-29 Graph of blowout limit for both chemical mechanism

From bar chart in figure 4.30 shows that the comparison of the blowout limit between propane-air mixture and 2-step propane-air mixture within four different thickness of micro combustor. From that each of the thickness brings the effect toward the different chemical mechanism use. Compare between both chemical within various size of thickness increase the blowout limit for the micro combustor. From the result collected, every size the thickness of micro combustor will increase for 0.1 m/s as the chemical kinetic mechanism is reduced to one step which is from 1-step propane-air mixture to 2-step propane-air mixture. For example, the blowout limit for micro combustor with 0.3 mm increase by 0.1 m/s as the propane-air mixture reducing chemical kinetic mechanism to 2-step propane-air mixture.

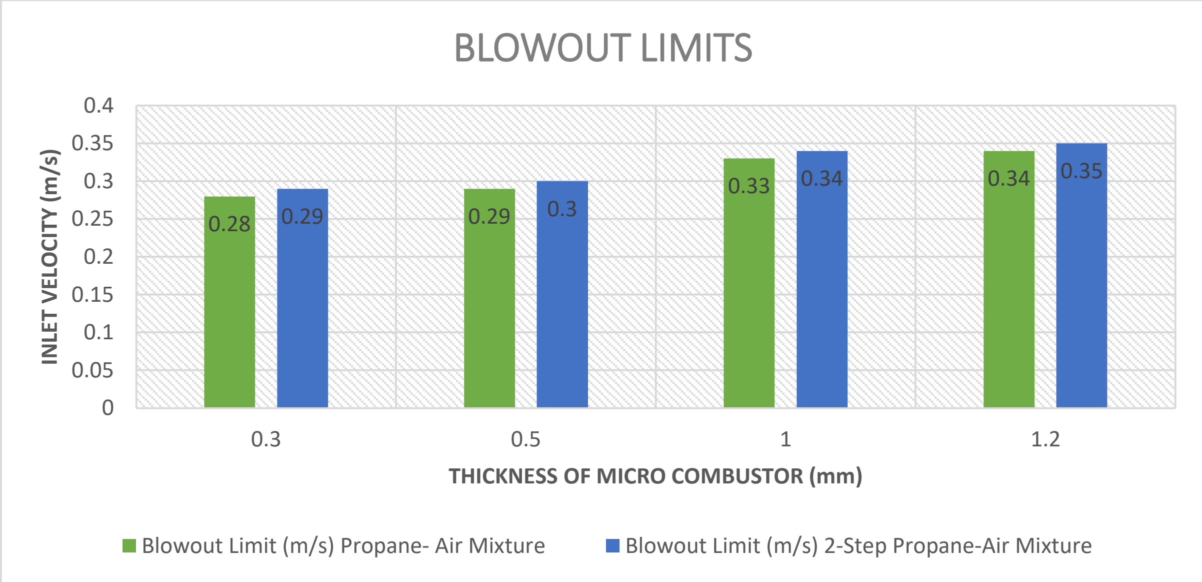

Figure 4-30 Bar chart of blowout limits for both chemical mechanism between various thicknesses of micro combustor

4.3 Summary

From the data result and discussion, there obviously shown that effect of thickness towards the blowout limits for both chemical mechanism. Quartz are chosen as material that have value of k = 1.6 W/mK thermal conductivity to found out the blowout limit. Each of the result are shown from the trend produce by the graph and bar chart from figure 4.29 and 4.30.

The results also show that the blowout limit can be significantly improved by increase the size of the thickness of the micro combustor. The thickness of the micro combustor influence the blowout limit for the micro combustor design. There also has strong possibility that by using different type of the chemical reaction such as methane-air mixture will also repeated the result which is increase in blowout limits due to increasing the size of the thickness.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

As conclusion, the numerical simulation of 2-D micro combustion with different thickness with reduce chemical kinetics mechanism was conducted to determine the effect of thickness toward the blowout limit of the micro combustor design. All the numerical simulation was conducted using ANSYS-Fluent 17.1 as the simulation medium on this research study. The micro combustor was design with different thickness which is 0.3 mm, 0.5 mm, 1.0 mm and 1.2 mm. For chemical use is propane-air mixture and it's reduce chemical kinetics mechanism which is 2-step propane-air mixture.

From chapter four, the results and discussion shows that every thickness of the micro combustor design can be utilize a reduced kinetics mechanism to stimulate combustion in micro combustion in micro combustor with concentric rings. Every design of micro combustor were succeed to determine the blowout limit for both chemical reaction mechanism. The results shows that there was increasing value of blowout limit which is u = 0.01 m/s for every thickness been design comparing between both chemical reaction mechanism.

As for the result of this study, it is shown that the thickness of the micro combustor affects the blowout limits. The flame produced inside the tube of micro combustor was stabilized at the concentric rings. Each of numerical simulation which was conducted yields different value of the blowout limit. The thickness of the micro combustor plays important role on stabilize the flame. By increasing the thickness of the micro combustor, the blowout limit produced was increasing and also increasing when using reduced chemical kinetic mechanism. The more thick the thickness for micro combustor, the higher the blowout limit for every micro combustor designed.

5.2 Recommendation

The concentric rings designed were able to stabilize the flame inside the micro combustor. The concentric rings inside the tube of the micro combustor helps the flame stabilize inside the micro combustor. Using thicker of thickness of micro combustor increase the blowout limits the designed micro combustor. The higher the blowout limits for the micro combustor designed, the more energy can be produced inside the tube of the micro combustor. However, in this study does not study the effect of thermal conductivity (k) of material to find the blowout limits of the micro combustor designed. Other than that, in this study also does not study different chemical reaction for example methane-air mixture. For further study on this research, suggest to use different type of chemical reaction and also reduced the equivalent ratio for the chemical reactions. To demonstrate that the combustor is relevant in the real world application, conduct the experiment using a coupling system to convert the heat energy of the combustor into electrical energy is suggested to be developed.

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LIST OF APPENDICES

APPENDICES

APPENDIX A1

GANTT CHART FYP I

TASK \ WEEK	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Literature Review	■	■	■	■	■	■	■	MID SEMESTER BREAK	■	■	■	■	■	■	■	■	■	■	■
Introduction of Study (Discuss with supervisor of background project, problem statement, scope and objective)	■	■	■																
Study of ANSYS-Fluent (Exercise tutorial of ANSYS-Fluent)			■	■	■	■													
Preparation of Progress Report I						■	■												
Submission of Progress Report I (Submitted at 19 Oct 2016)							■												
Setup parameter of simulation for FYP I (Setup Chemical Reaction)									■	■	■								
Numerical Simulation (Start simulation to find blow out limit)										■	■	■	■						
Preparation of draft final report													■	■	■				
Submission of Draft Final Report (Submitted at 16 Dec 2016)															■				
Seminar Presentation (Seminar FYP I (10-12 Jan 2017)																			■

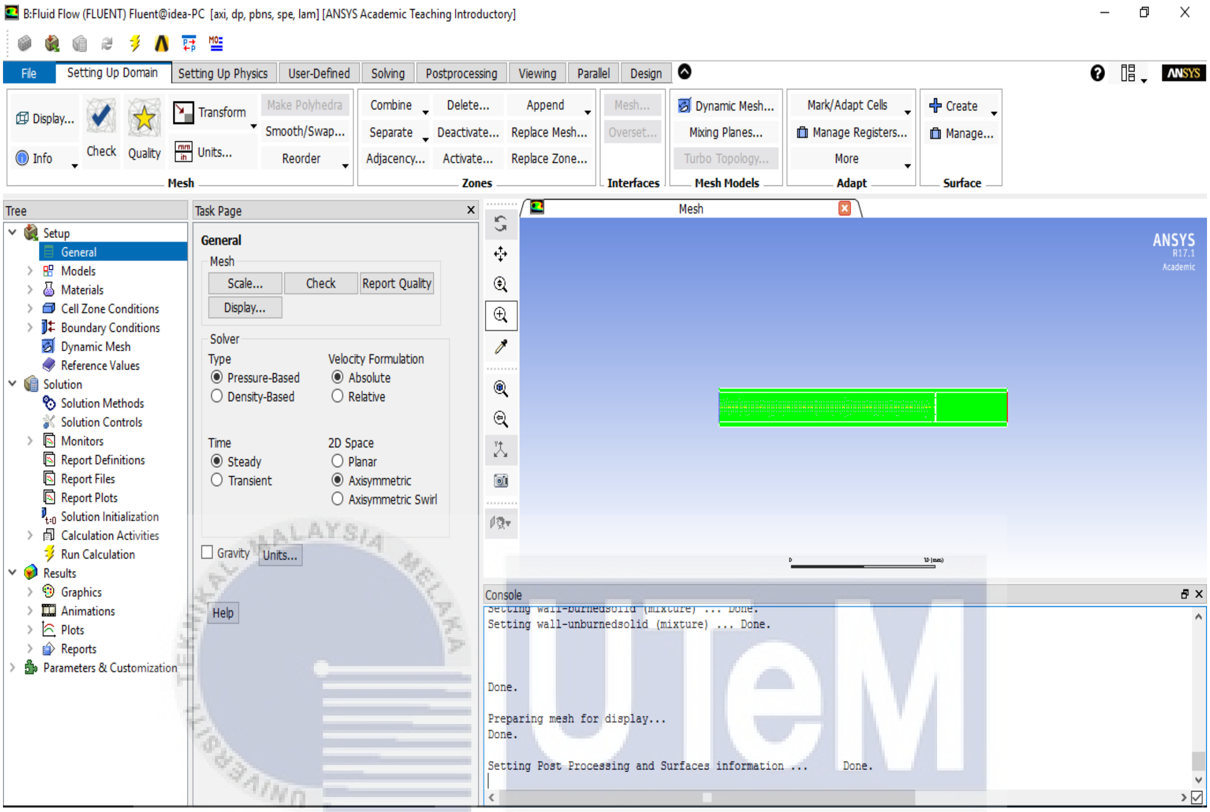
APPENDIX A2

GANTT CHART FYP II

TASK / WEEK	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Literature Review	■	■	■	■	■	■	■	MID SEMESTER BREAK	■	■	■	■	■	■	■	
Setup the parameter for numerical simulation	■	■														
Start Running The Numerical Simulation for Propane-Air Mixture			■	■	■											
Analysis The Result for The First Part of Simulations.				■	■	■										
Preparation of Progress Report II						■	■									
Submission of Progress Report II (Submitted at 31 March 2017)							■									
Start Running The Numerical Simulation for 2-Step Propane-Air Mixture									■	■	■					
Analysis The Result for The Second Part of Simulations.										■	■	■				
Preparation of Final Report													■	■	■	
Submission of Final Report (Submitted at 23 May 2017)															■	
Seminar Presentation (Seminar FYP II (29-32 May 2017)																■

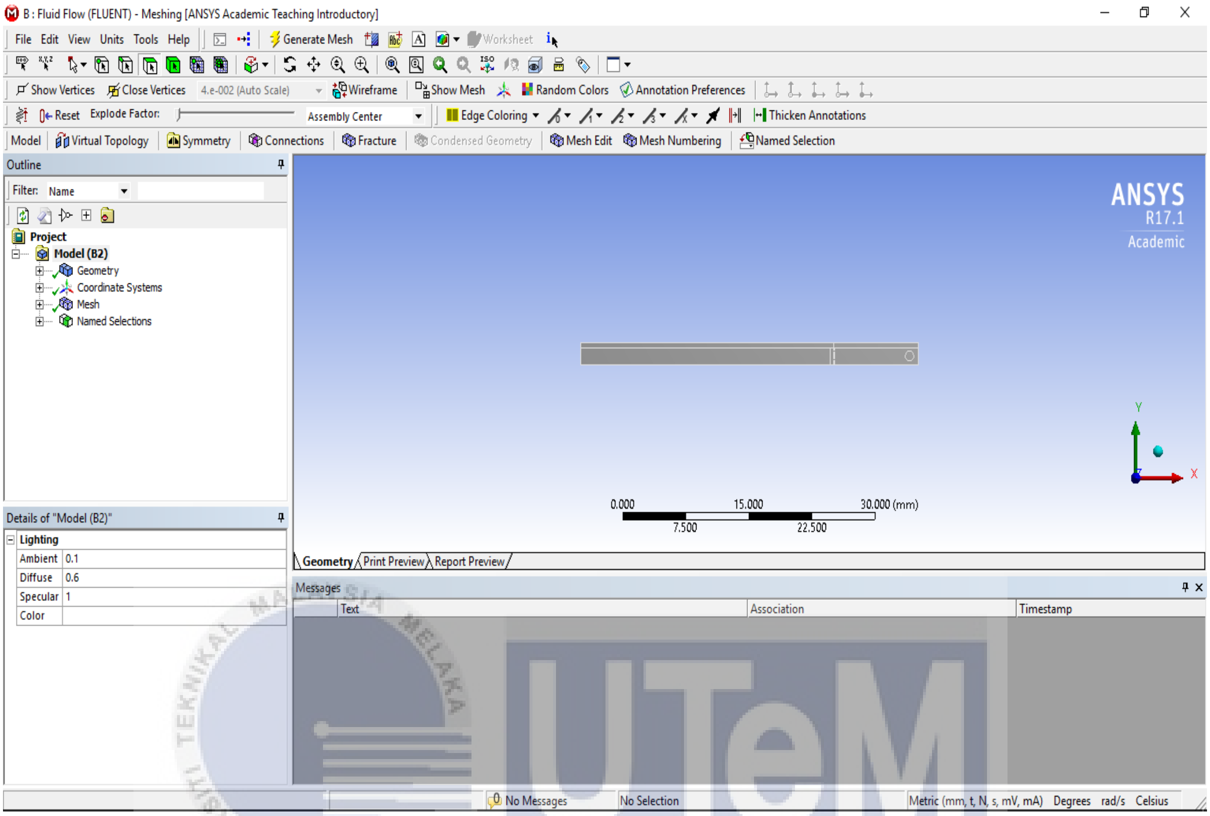
APPENDIX B1

GEOMETRY INTERFACE ANSYS 17.1



APPENDIX B2

MESHING INTERFACE ANSYS 17.1



APPENDIX B3

SETUP & SOLUTION INTERFACE ANSYS-FLUENT 17.1