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

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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 : ……………………………….

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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.

Signature : ....

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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).

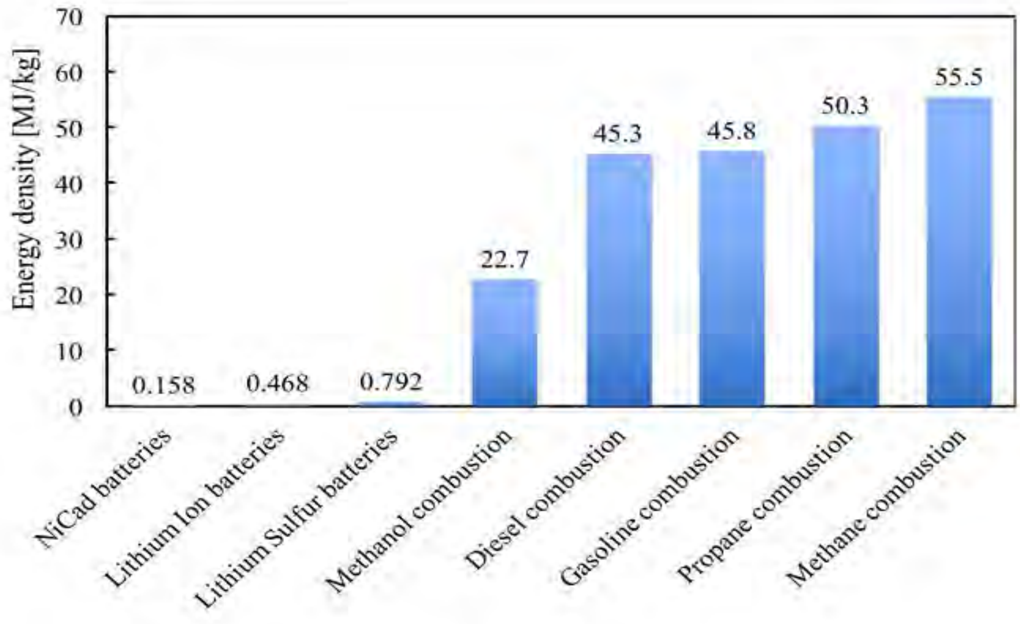

Figure 1.1: Energy Density of Conventional Batteries and Hydrocarbons Fuels (Kaisare and Vlachos, 2012)

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.

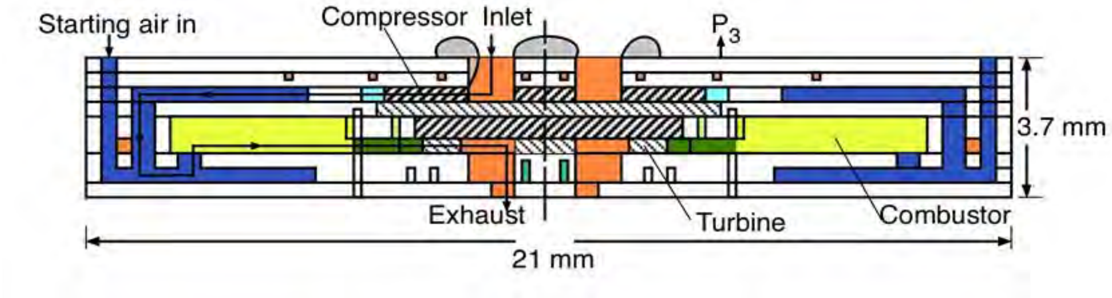

Figure 1.2: Schematic Diagram of the MIT Micro Gas Turbine (Yuasa et al. 2005).

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).

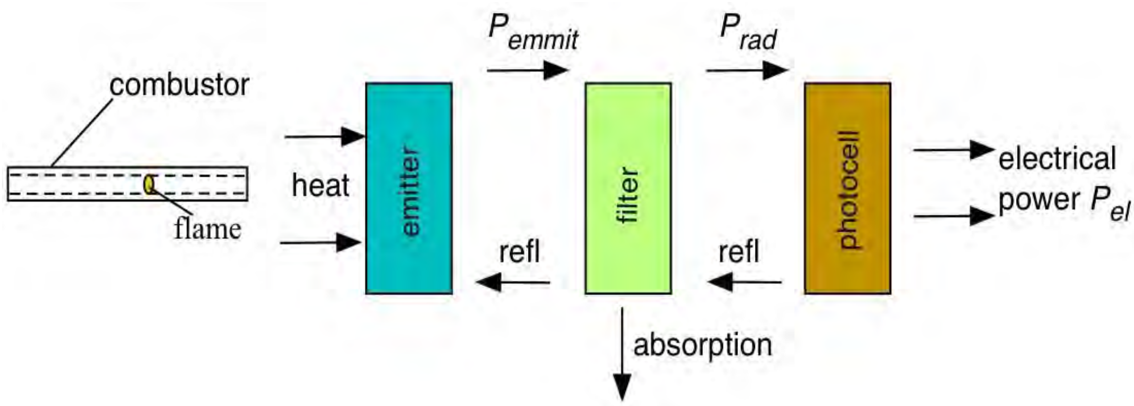

Figure 1.4: Schematic of a Micro-Thermos Photovoltaic Unit (Chia et al. 2007).

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).

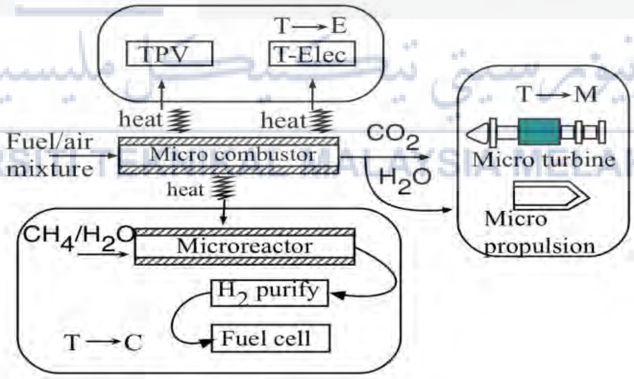

Figure 1.5: Utilization of Micro Combustor (Kaisare and Vlachos, 2012)

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.

4. To investigate the effect of exhaust gas heat recirculation on the flame stability. Numerical simulations are also employed to examine the important parameters that contribute to the changes of experimental results.

1.5 SCOPES OF PROJECT

In complete this project a counter current micro combustor were been design by using CAD software. For further analysis the dimension and the parameter of the combustor were produce in 3-D dimension before using the ANSYS Fluent Software. ANSYS Fluent Software were been used to analysis the different parameter such as material and thermal conductivity.

CHAPTER 2

LITERATURE REVIEW

This chapter summarizes the previous well-known experimental and numerical works that have been performed in field of micro power generation for combustor. Majority of the work are related to the used of hydrocarbon fuels as the main fuel sources. It is very important to stabilize the flame inside that to counter current micro combustor. In chapter one, the various mechanisms and methods of the counter current micro combustor in a narrow combustor channel. Besides that, the important terminologies in field of micro combustion are also explained.

2.1 FLAME STABILIZATION IN MICRO COMBUSTORS

Generally, flame can be stabilized within the certain limits in the micro combustor. These limit are called as the flammability. The definition of the flammability limits is the range of mixture strength of which a particular flame propagates within these limits (Turns, 2000) and any fuel-air mixture has a certain propagation speed. When the fuel-air mixture is ignited, the flame propagates towards the fresh unburned mixture with a velocity approximately near the propagation speed. For micro power applications, stationary or also known as stable flame is preferred. In theory, the flame can be made stable by adjusting the mean flow velocity of the unburned mixture to match the flame propagation speed. However, in practice, it is difficult to stabilize flame in narrow channel combustors. This difficulty is mainly due to the complexity of interaction between the combustor wall and the flame. At the gas-wall interface, a highly intensified heat loss from the combustor wall and radical destruction occurs (Feng et al. 2010). In addition, to stabilize the flame in micro combustors that have several methods have been introduced. The proper thermal management is essential required to overcome the flame quenching. The utilization of the heat recirculation mechanism can be significant enhance the flame stabilization limits (Fan et al. 2012).

Furthermore, types of combustors, the excess enthalpy from the combusted product is utilized to pre-heat the air – mixture and fuel. The example of the combustors are shown in Figure 2.1. The flow in the micro combustor is categorized as the laminar. The laminar is the mixing process of fuel and air is relatively slow. The mixing process is performed by the molecular diffusion and chaotic advection (Stroock et al. 2002). The mixing process can be improve by enhance flame stabilization, a mixer can be introduced (Hessel et al. 2005). A static mixer improves the molecular diffusion by increasing the surface area that is in the contact with the two incoming fluids (Wong et al. 2004). Fudhail et al. say in the paper that is essential to fully understand the underlying factors that affect the combustion of the stability in meso and micro – scale combustors (Fudhail et al. 2015). Fudhail et al. also say 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). 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 have been proposed by (Tang et al. 2015). Hydrogen has high reactivity and its combustion offers many advantages such as good lean burn stability, low minimum ignition energy and no greenhouse emissions (Chenglong et al. 2013). The key issue of ultra – micro gas turbines (UMGT) combustors is to realize stable and low emission combustion of hydrocarbon fuels such as propane, butane and kerosene (Takashi et al. 2013). One technique for extending conventional flammability limits and increasing burning speed is the use of heat recirculation to the increase the enthalpy in the reaction zone above the adiabatic conditions (Erica et al. 2014).

In addition, the various approaches have been employed to improve the flame stability in micro and also meso scale combustors. Thermal management is a frequently adopted strategy to anchor flames in small combustors. The Swiss – roll configuration has been implemented. Liu et al. was investigated the effect of wall thermal conductivity on the flame stability of a mesoscale channel with fibrous medium. Their work show that the stationary flame regime is extended with the decrease of the wall thermal conductivity (Liu et al. 2016). Besides that, Kang and Veeraragavan was point out that the flame stability limit of a mesoscale combustor grows lager when it is made of thermally orthotropic materials comparing to conventional isotropic materials (King and Veeraragavan, 2015).

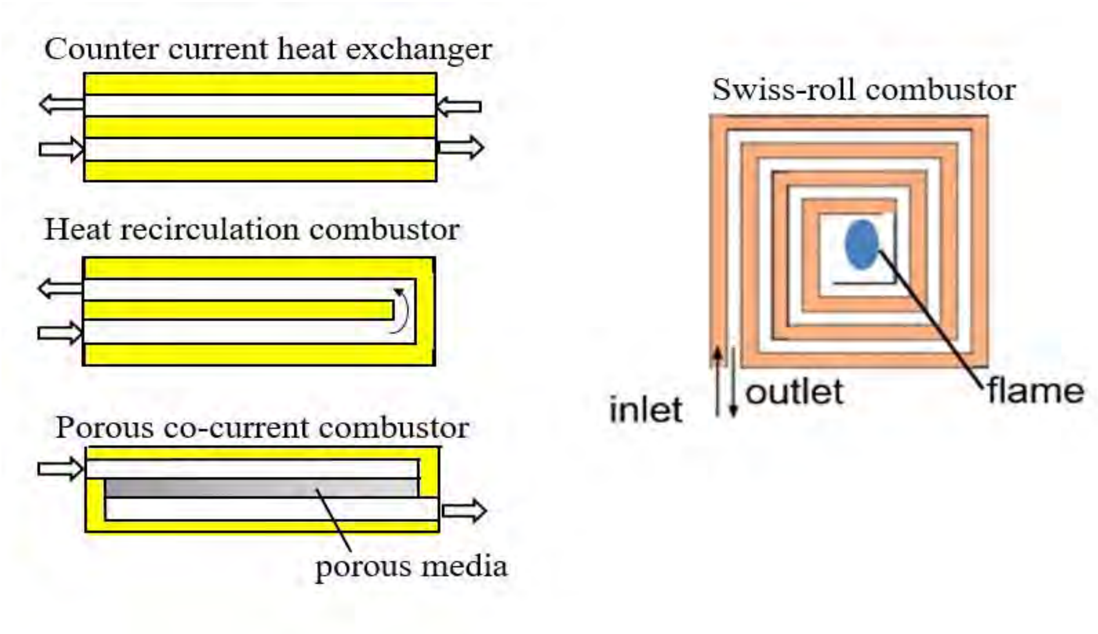

Figure 2.1: Various Geometries of Heat Recirculation Micro Combustors (Kaisare and Vlachos, 2012)

The modification of the laminar flow pattern inside the micro combustors causes the chaotic mixing process can be enhanced. The other ways to alter the flow pattern of the combustors by having the obstacles. A bluff body can be put in the middle of the combustor (Wan et al. 2012). A part from that, the irregularity of the combustor wall can also improve the chaotic mixing. A backward – facing step of the combustor can significantly improve the mixing of the fuel mixture and prolonged the residence time, which are subsequently increase the flame stabilization limits (Yang et al. 2014). The utilization of the catalysts in the micro combustors can also improve the flame stabilization limits through enhanced mass transfer (Maruta et al. 2002). In a catalytic combustor, the combustion of the reactants generates significant lower flame temperature than non – catalytic combustors. This phenomena occurs because the low combustion temperature leads to the reduction of the thermal stress related problem (Maruta et al. 2002). In addition, the materials of the catalytic consist of three major components which are the catalytic, substrate and support. The metals with the specific compositions such as Pt, Pd, and Rh are the most widely used in the catalytic combustion. There are many methods to deposit catalytic in the micro burners. The use of the catalytic wires in micro combustors is probably the easiest way to introduce catalysts in combustors (Kikas et al. 2003). In Figure 2.2 presented the thin – film coated with catalyst can also be implanted in a micro combustor. There are a few drawbacks of using catalyst in micro combustor. The interaction between the heterogeneous and homogeneous combustion is very complex (Li et al. 2012). The result of the conducting experiment can be difficult since there could be many variable to be controlled.

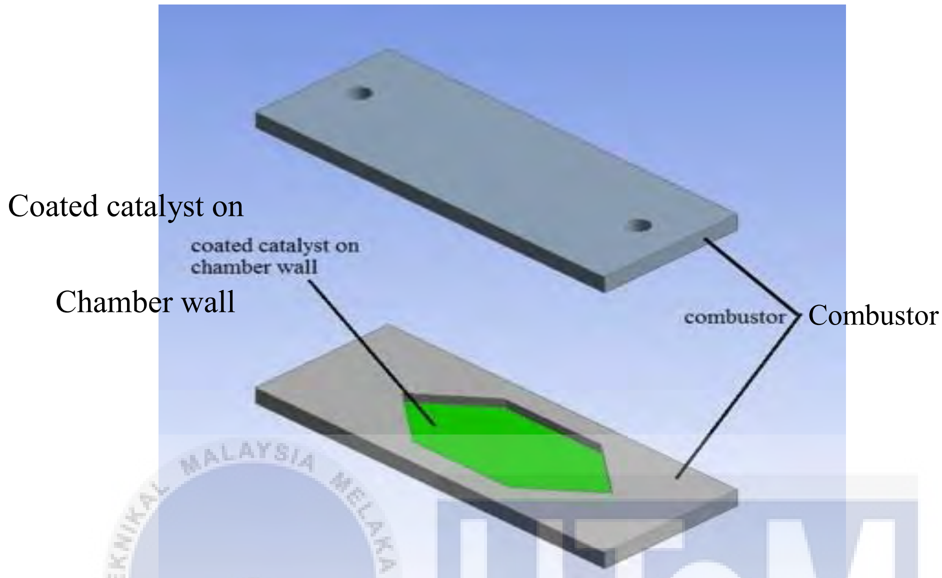

Figure 2.2: Schematic Of Micro – Catalytic Combustor With Thin – Film Coated.

However, there exist some challenging's to maintain a stable flame in micro combustors. In the first place of the stabilization of the combustors, the large surface – area – to – volume ratio leads to a sharp increase of heat loss ratio when the combustor dimension was reduced. In addition, the residence time of gaseous mixture is sometimes not sufficient to achieve a complete combustion. The owing to those problems, various unstable flame behaviours occur in micro scale and also meso scale of combustors (Alipoor and Mazaheri, 2014). Yadav et al. was experimentally investigation the performance of micro combustor with three rearward steps. Their result showed that the flame stability limits can be expanded significantly. Wan et al. and Fan et al. was developed a micro bluff – body combustor with excellent flame stabilization performance (Wan et al. and Fan et al. 2015).

2.2 FLAME QUENCHING

In the designing a reliable micro combustor is the phenomena of incomplete combustion due to the flame quenching (Hua et al. 2005). The definition of the quenching is a condition where the flame extinguishes upon entering a small channel. There are two type of the mechanism which are thermal and radical quenching that cause flame quenching. The thermal quenching occurs when the heat was generated by the combustion process. It is not sustainable due to heat losses to the ambient. In addition, micro combustor scale the heat losses is not only due to the radiation, but the heat losses by the convection and conduction heat that it is largely contributed to the heat losses (Fernandez, 2002). The radical quenching occurs when the radical from the flame are diffused to the walls, resulting to radical species depletion (Kim et al. 2006). Both radical and thermal quenching play an important role in determining distance of the channel of flame. Generally, the quenching distance depends on the reaction rate, temperature, species and radical concentration. The important of knowing the quenching distance is for mainly for designing a fire – resistant device. To determine the quenching distance, the experiment was conducted which are a visual observation on a particular flame at the end of a circular tube when the reactant is disconnected, and one more things the diameter of the tube was considered larger than the quenching distance.

Next, the effect of the thermal and the radical quenching on the flame propagation are dominant in the mesco and micro – scale of the combustion (Daou and M.Matalon, 2002) (Saiki and Suzuki, 2013). In order to minimize the quenching problem, a proper operating condition and optimization of combustor design was selected (V.Shirsat and Gupta, 2011). They (Miesse et al. 2004) have performed outstanding experimental works to show the possibility of the combustion of the gaseous hydrocarbon fuels in their designed micro scale combustor which are shown in Figure 2.3. The combustion of the methane and propane – air mixture is achievable even in tube with 0.75 mm of diameter. The combustion is made possible by minimizing heat losses to the ambient. The heat losses was reduced by the insulating the combustor walls. The used of the materials that is susceptible to radical quenching as the combustor wall makes the combustion sustainable.

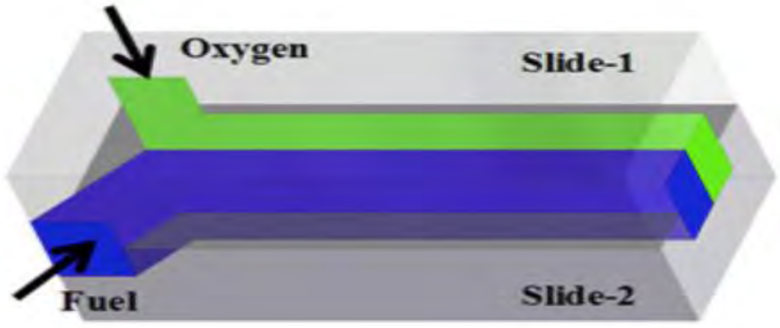

Figure 2.3: Schematic Diagram of the Designed Combustor (Miesse et al. 2004)

2.3 RESIDENCE AND CHEMICAL REACTION TIME

The definition of the residence time is the physical time available for the reactant to combust. The formula of the combustor residence:

$$\tau_{Residence} = \frac{volume}{volume\ flow\ rate} = \frac{VP}{\dot{m}RT} \qquad (2.1)$$

While the chemical reaction can be approximated as follows

$$\tau_{chemical\ reaction} = \frac{[fuel]_0}{A\,[\,fuel]^0\,[O_2]^b\,e^{\frac{-E_a}{RT_O}}} \qquad (2.2)$$

From the equation (2.1) and (2.2), it is shown that the residence time has an indirect relationship with the mass flow rate. The chemical reaction time depend on the type of fuel, temperature and also pressure of the mixture. In order to sustain combustion in any combustor, residence time should be larger than chemical reaction time (Law, 2007). In addition, the specific term of other equation named as Damkohler number (Da_h), which is quantify of this time limitation. Da_h is defined as the ratio between the residence time reactions to the characteristic chemical reaction time.

$$Da_h = \frac{\tau_{residence}}{\tau_{chemical}} \qquad (2.3)$$

For this equation, the value of the Da_h should be greater than one (1) to ensure combustion in micro combustor (Spadaccini et al. 2002). By enlarging the volume of the combustion chamber to increase the residence time is not an option in micro combustion. In addition, the way to elevate the residence time in micro combustor by reducing the mass of flow rate. The reduction of the flow rate it can be decrease the power density for energy conversion. The all constrains was considered as the best possible way to achieve Da_h that greater than one (1) is by reducing the chemical reaction time. Besides that, the chemical reaction is decrease and the high combustion temperature is required (Ronney, 2003) to withstand the high flame temperature by greatest the limitation.

2.4 METHOD OF FLAME STABILIZATION FOR MICRO COMBUSTORS

2.4.1 Excess Enthalpy Combustors

The stable flame in narrow channel of the combustor can be achieved by the recirculating the heat produced from the combusted products to the incoming fuel mixture. In conventional combustor devices like the internal combustion engine, a portion of the burned product gases is re – circulated and injected into the fuel – air mixture to reduce the amount of oxides of nitrogen (NOx). In the other word, the applications of micro combustor is the purpose of the heat recirculation is to minimize heat loss and also to expand the flame stabilization limits. The schematic diagram of the combustor is shown in Figure 2.4. The enthalpy from the hot burned gas is utilized to pre – heat the incoming fuel and air mixtures, which results to the enhancement of combustion reaction.

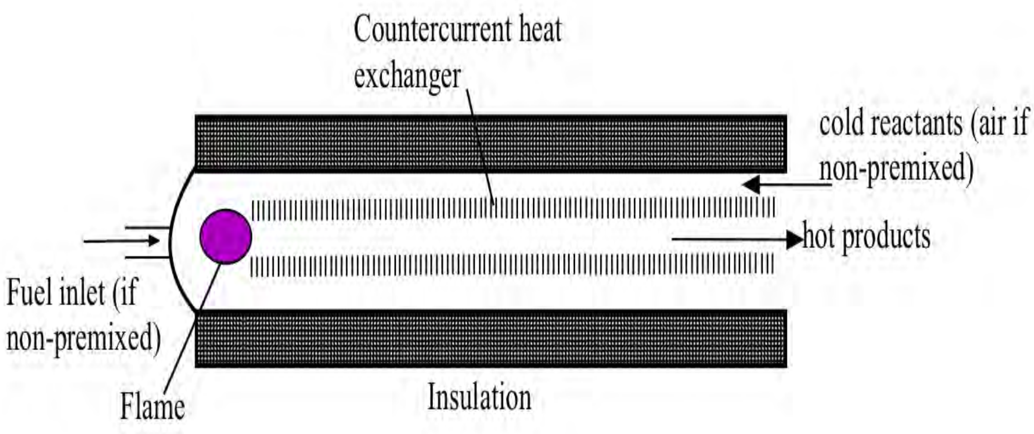

Figure 2.4: Schematic of a Heat Recirculation Burner System (Weinberg et al. 2002)

This mechanism of the flame stabilization is called as the excess enthalpy principle (Sitzki et al. 2001). In excess enthalpy of micro combustor, the flow of the reactant and the combustion products occurs in the adjacent channel and in an opposite direction. This condition causes the unburned mixture of preheated by the high temperature exhaust gas and the total of enthalpy is greatly increased (Bei-Jing and Jian-Hua, 2010).

There are two type of pre – heating methods which are direct method and in direct preheating methods (Raimondeau et al. 2002). The Direct method is a condition where the heat was transferred through the conduction and radiation from the burned gas to unburned gas region. This method is normally applied in a single channel (SC) of micro combustor. The indirect pre – heating method is the burned gas can be reversed to pre – heat the unburned reactants coming into the combustor inlet. This method is mainly utilized in counter – current heat recirculation combustors.

The Swiss – roll (SR) combustor is probably the most popular configuration for combustors with the heat recirculation. This type of the combustor employ indirect pre – heating mechanism. Figure 2.5 shown the combustion zone was located in the centre where the flame stabilizers there. Both inlet and outlet are in the form of spiral shape so that the heat can be exchanged. The inlet channel is flanked with solid structures, which provides larger surface area for heat exchanged. To vary this surface area, the number of turns can be exchanged without affecting the diameter of the combustion zone.

Figure 2.5: Image of a Typical Swiss – Roll Combustor (Chou et al. 2011)

These study was focus on the flame and the major objective is to counter current of micro combustor. The combustion of both propane and butane – air mixture in a toroidal Swiss – roll meso – scale combustor has been demonstrated (Sitzki et al. 2001). Flameless mode was observed even without the use of catalyst. It was reported that flame could even be stabilized s very low Reynolds number and highly lean mixture. The combustor is made of stainless steel and has a maximum of 4 channel turns. The inner diameter of the combustion chamber is fixed at 3.5 mm and the propane mixed with the air used as the fuel sources of the combustion.

A counter current of heat recirculation combustor that also utilizes the concept of indirect pre – heating methods has been proposed. The heat exchanger is modelled as a divider between the reactants and the product stream as depicted in Figure 2.6. The combustion of the unburned gas occurs in a well – stirred reactor. The hot burned gas then flows through the exhaust outlet where the unburned gas on the other side is pre – heated by conduction on the both side of the wall.

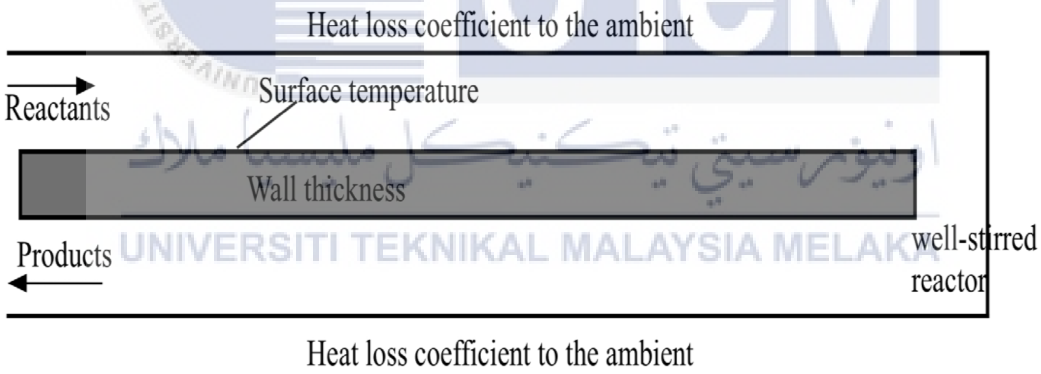

Figure 2.6: Counter – Current Heat Recirculation Combustor (Ronney, 2003)

Heat recuperation is one of the indirect methods pf pre – heating the unburned reactants. The heat recuperation is defined as the temporal thermal coupling between the hot product and cold reactant streams. This coupling can be done through the periodic flow reversal in reverse flow (RF) reactors as shown (Niket et al. 2007). The micro combustor s with heat recuperation mechanism for micro – thermos photovoltaic (TPV) system has been experimental investigated (Yang et al. 2014). The exhaust gas produced from the combustion of hydrogen air mixture is re – circulated to pre – heat the outer wall of the combustor. The incoming inlet feed is also pre – heated. The temperature will increase 70 K to 110 K while the useful radiation energy improves up to 83 % (Yang et al. 2012).

2.4.2 Combustor Geometry

There are substantial experimental works that have performed to examine the effect of the combustor geometry on the flame stability and the efficiency of the combustor (Deshpande and Kumar, 2013). In addition, the micro combustor have the wall thickness, gap width or also known as inner diameter, and combustor length are the geometrical parameter that can be changed. The combustor wall plays an important role in the thermal management and power conversion. Next, having the relative high and constant temperature along the wall, the electrical power output can be obtained (Yang et al. 2012). The high surface to the volume ratio of the micro combustor leads to numerous heat losses through the wall that can improve the flame stabilization limits and also to reduce of the heat losses. In addition, the smaller gap width leads to higher heat losses that negatively affects the flame stabilization limits (Kaisare and Vlachos, 2007). They also stated that in order to design an efficient micro combustor and it is important to set the gap width between 0.6 mm to 1.2 mm. This range is deemed as an optimum range for a micro combustor.

The experimentally demonstrated combustion in micro combustor that made of two type of materials which are ceramic and steel (Junwei and Beijing, 2008). They concluded an ideal micro combustor should be made of the materials with the high wall thermal conductivity but low emissivity. The main of the drawback of using a straight tube as the combustor is the difficulty to control the position of the flame. The improvement on the design of the combustor have been suggested to solve the problem. A backward facing step combustor as shown in Figure 2.7. It is considered as the best practical alternative to straight cylindrical tube shape combustor (Li et al. 2009). The mixing process of the fuel and the air can be enhanced. The flame position can be controlled in the proposed of the combustor.

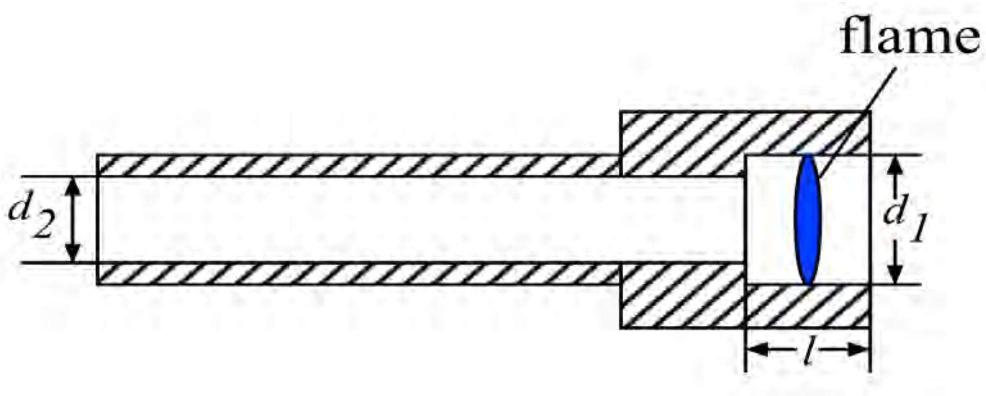

Figure 2.7: Backward Facing Step of Combustor.

The flame stability on the combustor geometry, it is challenging to maintain a stable flame in micro combustors. In the first place, the large surface - area – to – volume ratio leads to a sharp increase in the heat – loss ratio when the combustor dimension is reduced. Moreover, the residence time of gasses mixture is sometimes insufficient to obtain a complete combustion. Owing to those difficulties, various unstable flames occurs in micro and meso scale of the combustor (Wang et al. 2013).

2.4.3 Combustors with Flame Holders

The flame blowout limits of combustors with a flame holder is defined as the largest combustible velocity. It was obtained by gradually increasing the inlet velocity in small interval. When the flame blowout occurs, the combustion is completely extinguished and the temperature field becomes uniform with a same value as the incoming mixture (Jianlong W et al. 2016).

The flame can be stabilized by the inserting a bluff body in the combustion chamber of the micro combustor (Wan et al. 2012). A simple yet effective way of the extended flame stabilization limits has been demonstrated (Fan et al. 2014). The bluff body is inserted into a planar micro channel combustor. The experiment result shown that blow off limits are greatly extended with the presence of the bluff body. A stainless steel wire mesh was placed between the burned and the unburned gas region. The experiment result show that flame can be stabilized for both gas and liquid fuel. The wire mesh improves the heat transfer from the hot burned gas to the unburned gas region and give the good result for flame stabilization limits. The tube with the mesh can also be considered as the combustor with the heat recirculation since the wire mesh effectively re – distributed the heat from the burned gas to the unburned gas region as illustrated that shown in Figure 2.8.

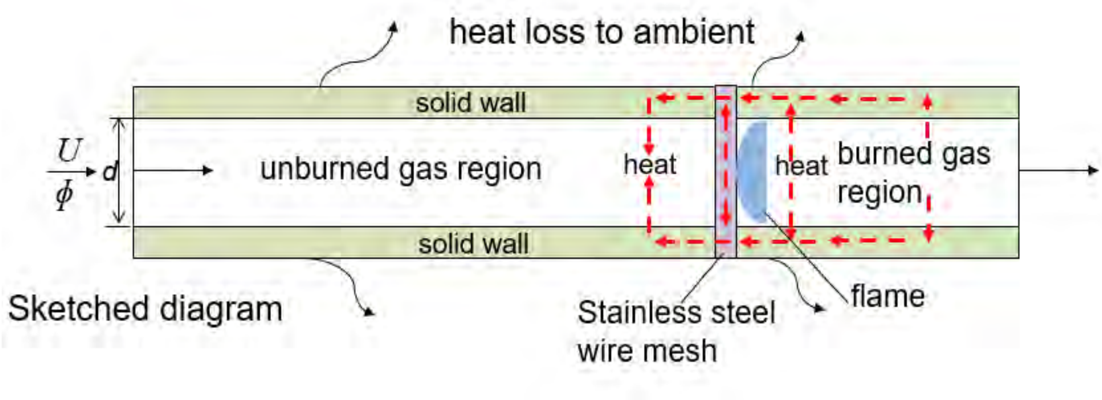

Figure 2.8: Illustrated Diagram of a Single Channel Combustor with Wire Mesh.

Another effective way of flame stabilization for combustors is to form a recirculation zone in the flow field by using a flame holder. Yang et al. was study the flame stabilization in micro combustors with a backward facing step. Khandelwat et al. was experimentally investigated the performance of a micro combustor with three rearward steps. Their results showed that the flame stability limits can be expanded significantly. Fan et al. was developed a micro bluff – body combustor with excellent flame stabilization performance (Fan et al. 2013, 2014). In addition, Wan et al. was investigate flame behaviour of CH_4 / air mixtures in micro and also meso scale combustors with wall cavities. It was demonstrated that the flame stability was greatly improved and stable symmetric flames were observed over a wide range of inlet velocity (Wan et al. 2015).

2.4.4 Combustors with Catalyst

The main function of the catalyst is to drive and increase the endothermic reactions that can possibly improve the combustion efficiency (Vlachos and Caratzoulas, 2010). In addition, the combustion with catalyst also requires of lower activation energy. The radical depletion on the combustor wall can be effectively eliminated which lead to the reduction of the radical quenching (Li et al. 2010). Furthermore, the several benefits of the catalyst are immobility of heat release zone, no quenching limits, and also moderate reactions

(Zhou et al. 2009). Hydrogen is favoured against the hydrocarbon fuels in the catalytic combustion. The reason why hydrogen can catalytically react with the air even without an ignition source (Choi et al. 2008). Besides that, the problem of the catalytic for micro combustor are the catalyst deactivation. This deactivation is caused by the thermal control related to hot spots, travelling heat waves and wrong way behaviours (Di Benedetto et al. 2009).

In addition, for CH_4 / air flames and the phenomena does not occur and the flame stability was greatly improved (Wan et al. 2015). The stable symmetry flames were observed in the meso scale cavity – combustor over a wide range of inlet velocity, which did not appear in the straight channel of the same dimension. Ran et al. was numerically studied the catalytic combustion characteristic of methane in a micro channel with concave or convex wall cavities, and they showed that obvious recirculation zone is formed in the cavity which results in a larger extinction limits (Ran et al. 2015).

2.5 COMBUSTORS WITH LIQUID FUELS

The general liquefied gaseous fuels like propane and butane are suitable fuels for micro combustor (Vican et al. 2002). In addition, the methane might not be suitable to be used as the primary fuel sources for micro combustor since it requires larger storage requirement and high ignition temperature (Smyth et al. 2009). Hydrogen is the preferred fuels for micro combustor. It have high burning velocity, short reaction time, fast vaporization rate and also high heating value (Watson and Bergthorson, 2012). The practically of the gaseous fuels is questionable and is mainly contributed by the storage and mobility problem (Park et al. 2012). In other word, the utilization of liquid fuels can eliminates the problem (Vijayan and Gupta, 2011).

However, the primary challenge in liquid fuel combustion is to establish clean and efficient combustion (Kyritsis et al. 2004). They was introduced a catalytic combustor that utilized as the fuels. It is atomized and dispersed into the combustion chamber by using an electro sprayed system (Kyritsis et al. 2004). In 2009, (Sadasivuni and Agrawal, 2009) was proposed a flow – blurring injector to generate fine kerosene fuel droplets in a counter – flow for micro combustor. The flat flame was generated with a considerably low emission and the result show that 94% of the heat released can be retained.

CHAPTER 3

METHODOLOGY

3.1 OVERVIEW OF METHODOLOGY FOR COUNTER CURRENT COMBUSTORS

One of the approaches to demonstrate the function of the wire mesh in enhancing heat in the counter current micro combustor is by performing numerical simulations. Three – dimensional numerical simulation is essential. In 3-D model, the stainless steel wire mesh can be added as such that it is inter – connected to each other up to the outer wall of combustor resulting to a three directional of thermal path. In addition, this case study of the counter current of micro combustion with responding to the temperature and reaction of combustion. For this case study, ANSYS – Fluent software is a software that have capabilities for user to able understanding of model flow.

3.2 NUMERICAL MODEL SET UP

The numerical set up for case study on the title investigation flame stabilization in counter current micro combustor in 3-D numerical model analysis. Next, there is needed to set up the chemical reaction equation and some parameter which start from the design of the micro combustor until the parameter been set up. After that, the numerical simulation is running and data analysis was recorded. This numerical simulation of the flame stabilization of the counter current that only cover on 3-D numerical model which are single tube with single wire mesh, double tube with single wire mesh and lastly double wire mesh (single piece). The element used in this case study are processing, solver and post processing that included the result displays.

This numerical simulation was carries with same blowout limit for flame stabilization into the model design before focusing more on the temperature and reaction of the simulation. The steady-state numerical simulation was performed using ANSYS - Fluent (ANSYS, 2012) are:

1. Designing 3-D numerical model of counter current micro combustor
2. Meshing graphical
3. Finding Mass Fraction of CH_4 / and O_2 by equivalent ratio.
4. Computation domain
5. Run and calculate the result with constant inlet velocity, *U* and equivalent ratio.

3.3 THREE DIMENSIONAL (3-D) NUMERICAL SETUP FOR SINGLE TUBE WITH SINGLE WIRE MESH OF COUNTER CURRENT

A three-dimensional (3-D) numerical simulation of propane-air combustion in micro scale cylindrical tubes with stainless steel wire mesh is also performed. Experiments were performed to counter current micro combustor by the simulation. Counter current micro combustors of 3-D model was designed according to the objective of this case study. The designing of the model was divided into three category which are single tube with single wire mesh, double tube with single wire mesh and double tube wire mesh (single piece). Figure 3.1 shows the 3-D geometry model of the single tube with single wire mesh. For this design, the diameter of the 3-D model is 8.0 mm. The length of the combustor is 40.2 mm which divided into two parts namely the unburned and burned gas region by a stainless steel wire mesh. The location of the wire mesh is 30 mm, which is measured from the centre of the combustor inlet to the left side of the wire mesh. This value is chosen to ensure that the flow will be fully developed before passing through the wire mesh. The wall thickness is modelled as a solid phase where only the energy equation is solved.

Three-dimensional (3-D) conductive heat transfer is assumed on the wire mesh with the value of wall thermal conductivity *(k)* is set to 1.6 W/mK, which represent the typical value of *k* for stainless steel (Zhou et al. 2009). The fuel type used is propane (C_3H_8)-air mixture. To reduce the computational loads, the gas thermal conductivity, viscosity, and mass diffusivity values of the mixture are assumed to be constant, which are based on Fluent (default values option shown in Table 3.1).

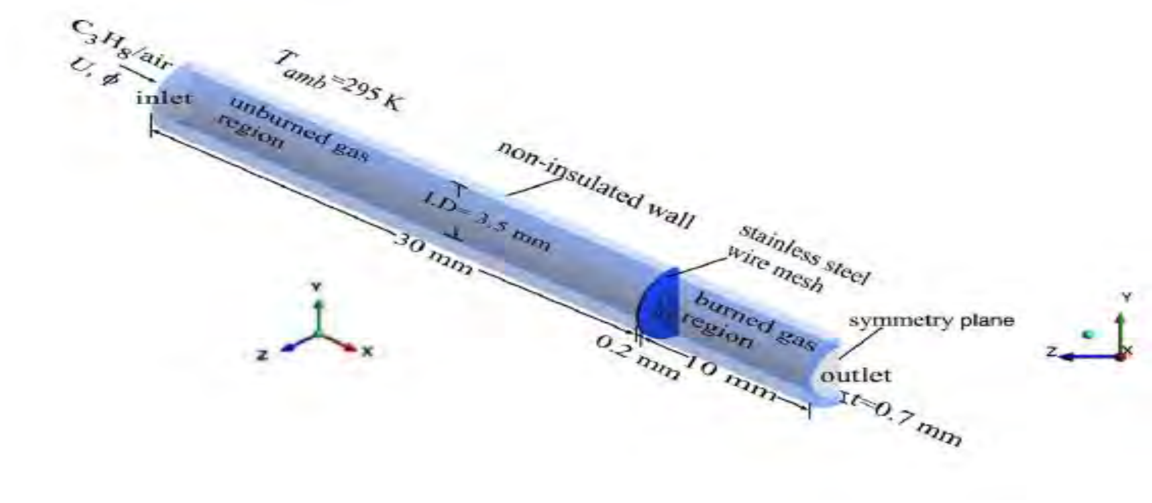

Figure 3.1: The 3-D Geometry of Counter Current Single Tube with Single Wire Mesh

Table 3.1: Values of Gas Mixture Properties by Fluent Default Option

Thermal Conductivity (W/m.K)	Viscosity (kg/m.s)	Mass Diffusivity (m^2/s)
0.0454	1.72 x10^{-5}	2.88 x 10^{-5}

3.4 THREE DIMENSIONAL (3-D) NUMERICAL SETUP FOR DOUBLE TUBE WITH SINGLE WIRE MESH OF COUNTER CURRENT

For this 3-D model, the first step is to design a double tube with single wire mesh of the counter current. This design, the diameter of the 3-D model is 8.0 mm. The length also same as the previous model which is 40.2 mm which divided into two parts namely as unburned gas region and burned gas region by a stainless steel wire mesh but have double tube of the combustor that shows in Figure 3.2 The location of the wire mesh is 30 mm, which is measured from the centre of the combustor inlet to the left side of the wire mesh. This value is chosen to ensure that the flow will be fully developed before passing through the wire mesh. The wall thickness is modelled as a solid phase where only the energy equation is solved. Figure 3.3 shows computational domains counter current (dimensions in mm) with the thickness diameter is 8.0 mm.

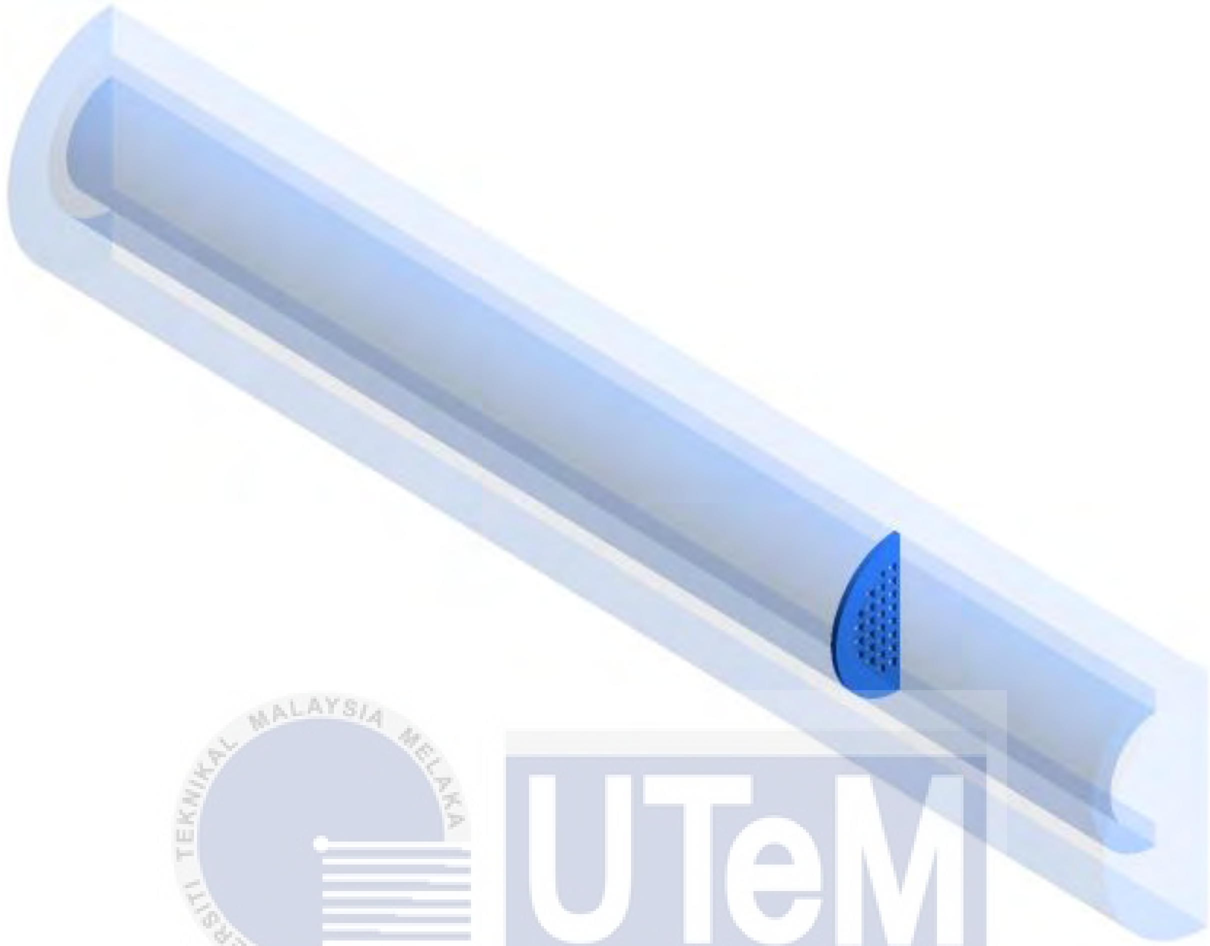

Figure 3.2: The 3-D Geometry of Counter Current Double Tube with Single Wire Mesh. The Inlet Velocity, U is 35 cm/s and Equivalent Ratio, Φ is 1.0.

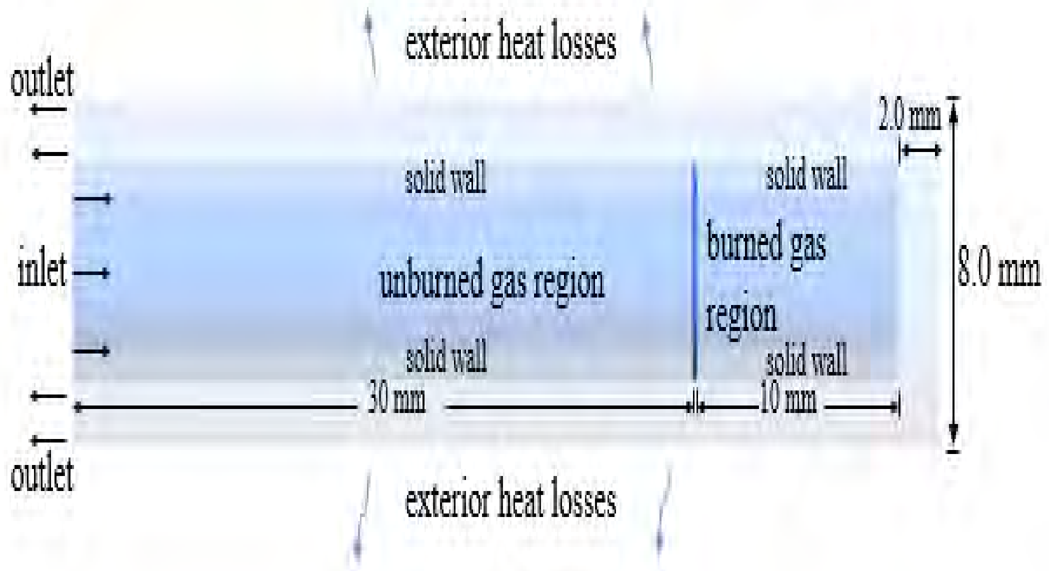

Figure 3.3: Computational Domains Counter Current

3.5 THREE DIMENSIONAL (3-D) NUMERICAL SETUP FOR DOUBLE WIRE MESH OF COUNTER CURRENT COMBUSTOR

For this three dimensional (3-D) model, the first step is to design a double wire mesh of the counter current combustor with (single piece body). This design, the diameter of the 3-D model is 8.0 mm. The length also same as the previous model which is 40.2 mm which divided into two parts namely as unburned gas region and burned gas region by a stainless steel wire mesh but have double wire mesh into the combustor that shows in Figure 3.4. The location of the wire mesh A is 30.0 mm from inlet and the location of the wire mesh B is 20.0 mm from the inlet of the combustor, which is measured from the centre of the combustor inlet to the left side of the wire mesh. This value is chosen to ensure that the flow will be fully developed before passing through the wire mesh. The wall thickness is modelled as a solid phase. Figure 3.5 shows computational domains double wire mesh of the counter current (dimensions in mm) with the thickness diameter is 8.0 mm.

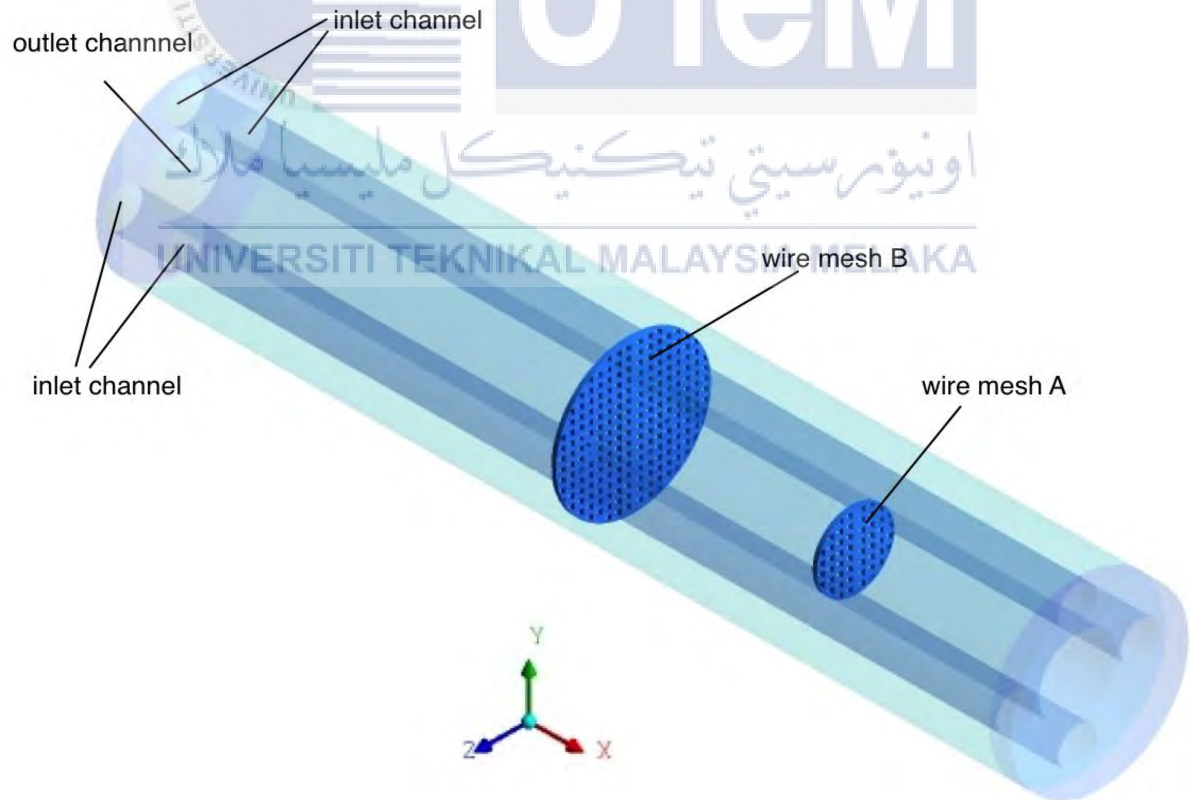

Figure 3.4: The 3-D Geometry of Counter Current Double Wire Mesh (Single Piece). The Inlet Velocity, U is 35.0 cm/s and Equivalent Ratio, Φ is 1.0.

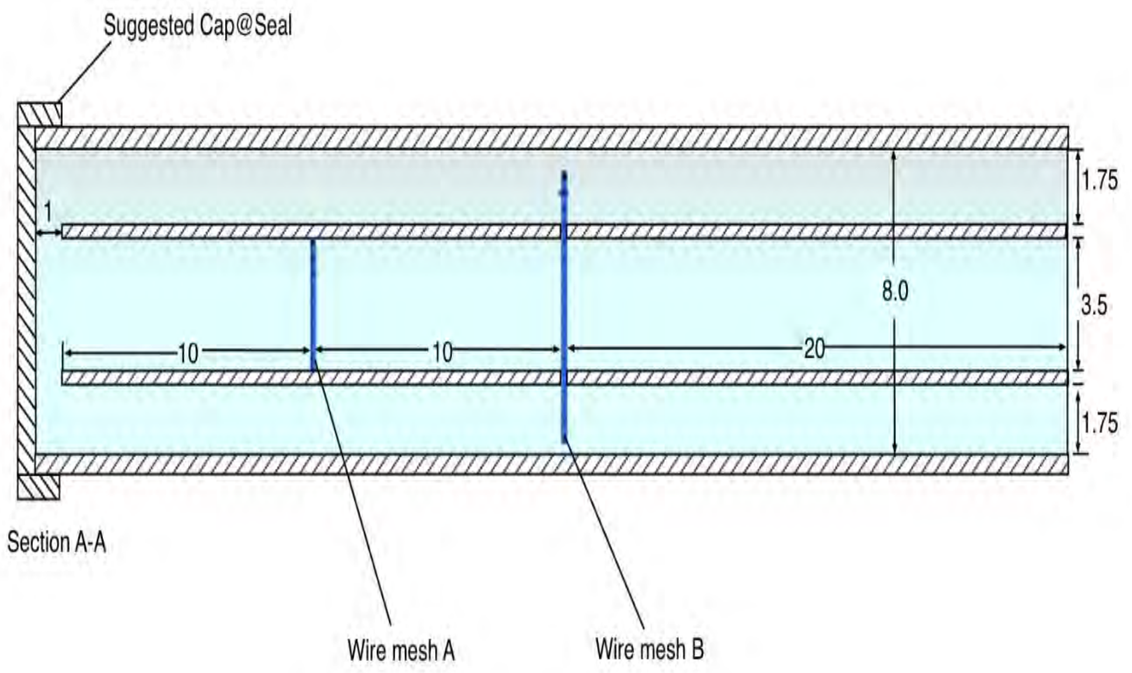

Figure 3.5: Computational Domains Double Wire Mesh (Single Piece) (Dimensions In mm).

3.6 DISCRETIZATION OF COUNTER CURRENT MICRO COMBUSTORS MODEL

3.6.1 Single Tube with Single Wire Mesh

After design has been completed, the next step is to design and calculate the meshing of the each combustor model. The minimum meshing sizing design for single tube with single wire mesh is 3.1672e – 002 mm and the maximum sizing mesh is 4. 0540 mm. In addition, the minimum edge length is 0.20 mm. The size function is curvature and the relevance centre is coarse. On the smoothing sizing mesh is medium. Figure 3.6 shows the meshing geometry of the single tube with single wire mesh combustor. Table 3.2 shows the sizing meshing single tube with single wire mesh model. The inlet velocity, *U* is 35.0 cm/s and the equivalent ratio of the combustors is 1.0.

Figure 3.6: The Meshing Geometry of the Single Tube with Single Wire Mesh Combustor. The Inlet Velocity, U is 35.0 cm/s and Equivalent Ratio, Φ is 1.0.

Table 3.2: The Sizing Meshing Single Tube with Single Wire Mesh Model

Sizing Meshing	
Size Function	Curvature
Relevance Center	Coarse
Smoothing	Medium
Curvature Normal Angle	Default (18.0º)
Min Size	Default (3.1672e002 mm)
Max Tet Size	Default (4.0540 mm)
Growth Rate	Default (1.20)
Max Dual Layers In Thin Regions	No
Minimum Edge Length	0.20 mm

3.6.2 Double Tube with Single Wire Mesh

For this design, the next step is to design and calculate the meshing of the combustor model. The minimum meshing sizing design for single tube with single wire mesh is 0. 10 mm and the maximum sizing mesh is 3. 20 mm. In addition, the minimum edge length is 4. 127e -003 mm. The size function is curvature and the relevance centre is coarse. On the smoothing sizing mesh is medium. Figure 3.7 shows the meshing geometry of the double tube with single wire mesh combustor. Table 3.3 shows the sizing meshing double tube with single wire mesh model. The inlet velocity, *U* is 35.0 cm/s and the equivalent ratio of the combustors is 1.0.

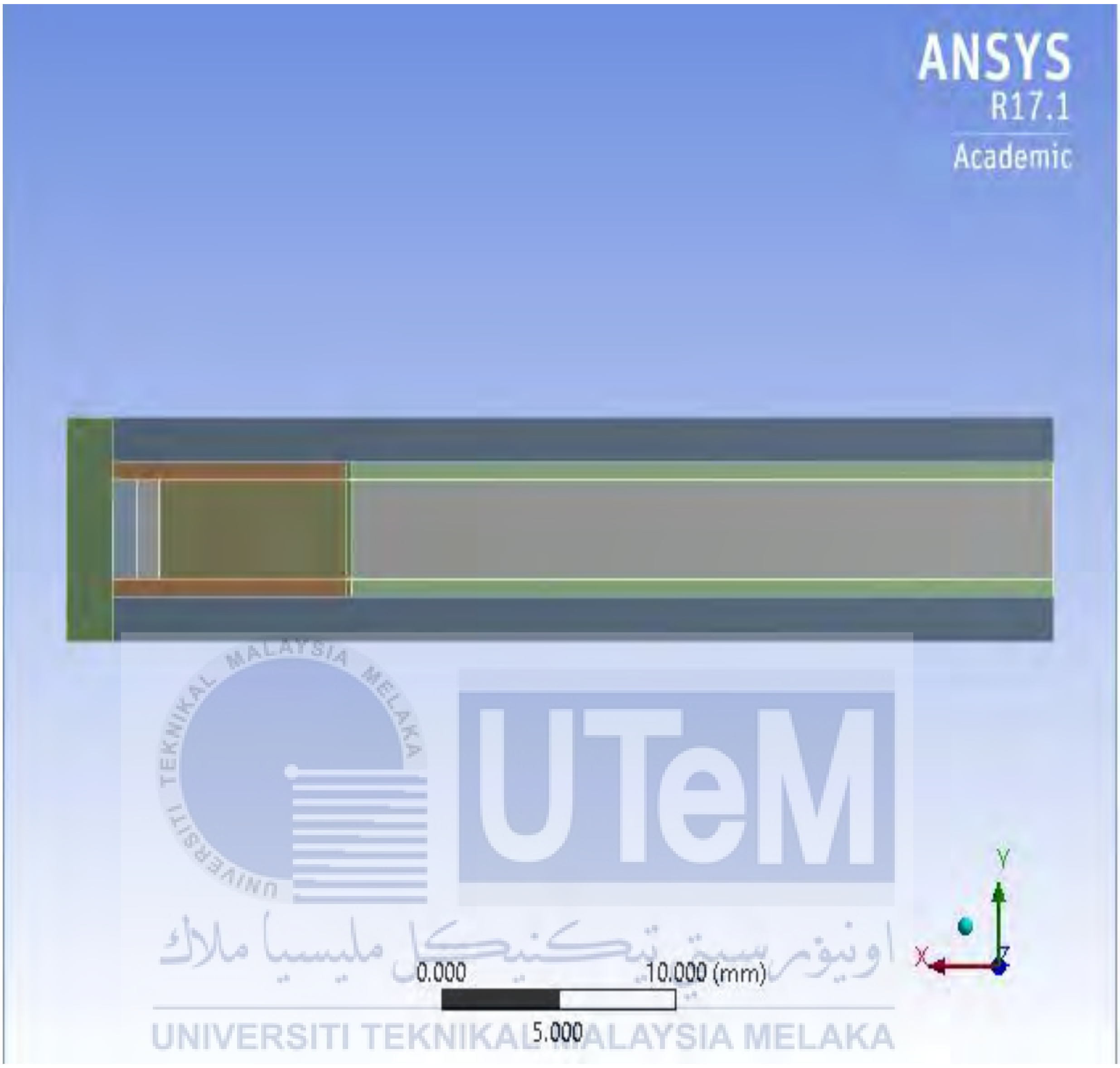

Figure 3.7: The Meshing Geometry of Double Tube with Single Wire Mesh Combustor. The Inlet Velocity, *U* is 35.0 cm/s and Equivalent Ratio, *Φ* is 1.0.

Table 3.3: The Sizing Meshing Double Tube with Single Wire Mesh Model

Sizing Meshing	
Size Function	Curvature
Relevance Center	Coarse
Smoothing	Medium
Curvature Normal Angle	Default (18.0^{o})
Min Size	0.10 mm
Max Tet Size	3.20 mm
Growth Rate	Default (1.20)
Max Dual Layers In Thin Regions	No
Minimum Edge Length	4.127e-003 mm

3.6.3 Double Wire Mesh (Single Piece)

For this design, the next step is to design and calculate the meshing of the combustor model. The minimum meshing sizing design for single tube with single wire mesh is 0. 10 mm and the maximum sizing mesh is 3. 20 mm. In addition, the minimum edge length is 2. 3112e -002 mm. The size function is curvature and the relevance centre is coarse. On the smoothing sizing mesh is medium. Figure 3.8 shows the meshing geometry of the double wire mesh combustor (single piece). Table 3.4 shows the sizing meshing double wire mesh combustor model (single piece). The inlet velocity, *U* is 35.0 cm/s and the equivalent ratio of the combustors is 1.0.

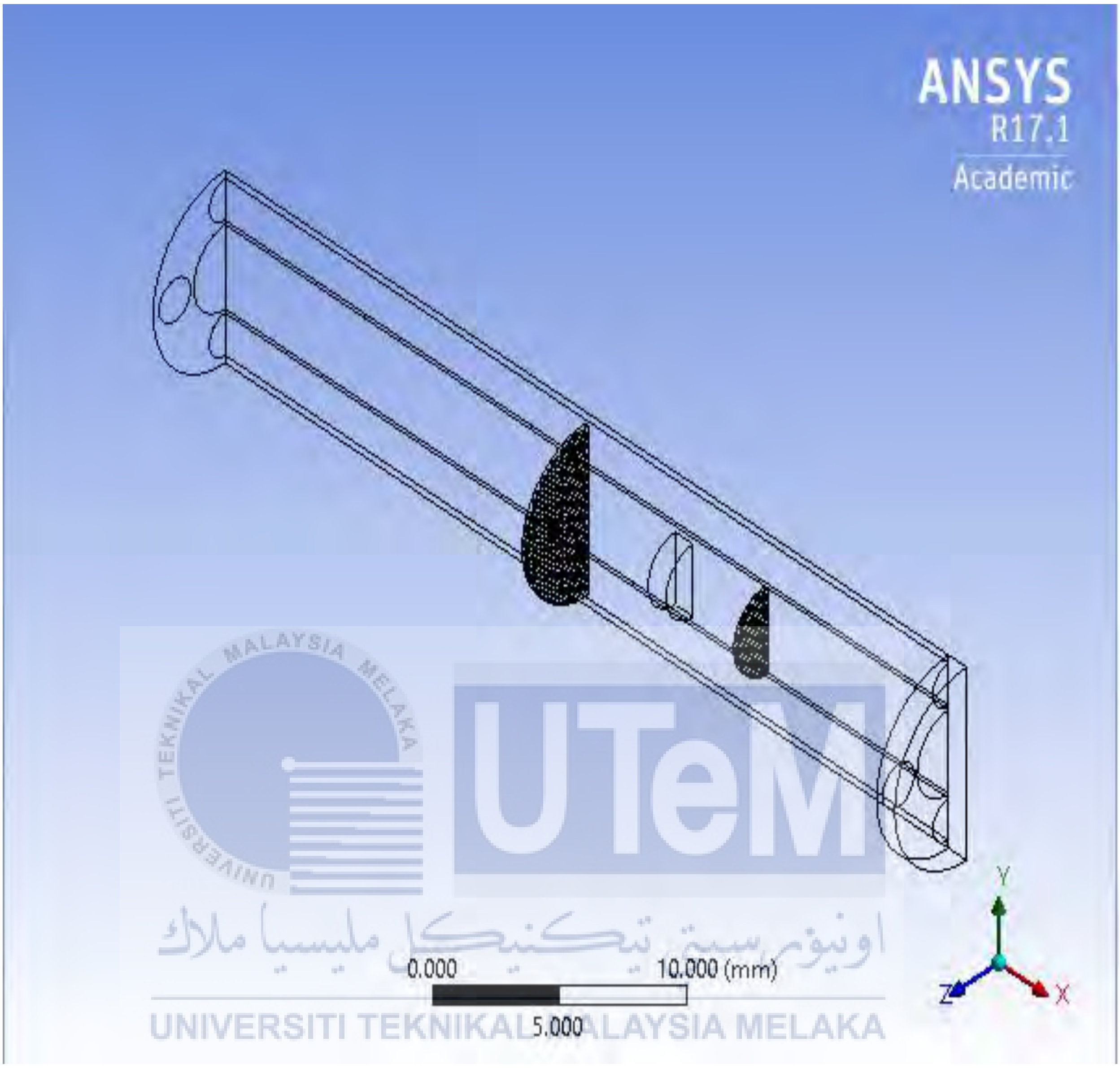

Figure 3.8: The Meshing Geometry of Double Wire Mesh Combustor (Single Piece). The Inlet Velocity, U is 35.0 cm/s and Equivalent Ratio, Φ is 1.0.

Table 3.4: The Sizing Meshing Double Wire Mesh Model (Single Piece)

Sizing Meshing	
Size Function	Curvature
Relevance Center	Coarse
Smoothing	Medium
Curvature Normal Angle	Default (18.0°)
Min Size	0.10 mm
Max Tet Size	3.20 mm
Growth Rate	Default (1.20)
Max Dual Layers In Thin Regions	No
Minimum Edge Length	2.3112e-002 mm

3.7 CALCULATION OF MASS FRACTION FOR EACH EQUIVALENCE RATIO

The type governing equations utilized are the typical fluid motion combined with reacting flows. The mass conservation equation (continuity) is given by:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho u_x) + \frac{\partial}{\partial y}(\rho u_y) + \frac{\partial}{\partial z}(\rho u_z) = S_m \qquad (3.1)$$

The symbol of S_m is the source term. The example of this term is vaporization of fluid or any user – defined source. This numerical model, $S_m = 0$. For a steady state condition $\frac{\partial p}{\partial t} = 0$. The above Equation 3.2 has already included the pressure work and kinetic energy terms. However, the numerical model is assumed to be incompressible flows and neglects these types of works. Moreover, the selected pressure-based solver by default does not include the pressure work or kinetic energy.

$$\nabla.[\underset{u}{\rightarrow}(\rho E + p)] = \nabla.[k\nabla T - \Sigma_i h_i \underset{J_i}{\rightarrow} + (\bar{\bar{\tau}}.\underset{u}{\rightarrow})] + S_h \qquad (3.2)$$

No-slip boundary type condition is applied at the interface between the fluid and the solid wall. The heat flux at this interface is calculated using Fourier's law. Heat transfer per unit area by means of convection at the outer surface of the combustor wall is given by:

$$q_{loss} = h_{conv} (T_{wall} - T_{amb}) + \varepsilon\sigma (T_{wall}^4 - T_{amb}^4) \tag{3.3}$$

Where h_{conv} is the convective heat transfer, T_{wall} is the wall temperature of the combustor and T_{amb} is defined as the ambient temperature. The value of T_{amb} is initialized to 295 K. The value of h_{conv} is fixed to be at 5 W/m^{2}K, which represent a weak natural convection (Bahadori et al. 1995). The external emissivity (ε) for the outer wall of the combustor and the wire mesh is set to 0.90 and 0.70 respectively. The value of Stefan-Boltzmann constant (σ) used is 5.67×10^{-8}W/m^{2}K^4. A thermal insulation (zero heat flux boundary) is applied at both left and right wall edge of the combustor. The value of k for the tube combustor is set to 1.6 W/mK, which represents the typical value of k for a quartz tube. For the outlet boundary condition, a fixed pressure inlet is applied. A laminar flow of U is 35.0 cm/s with a flat velocity profile is applied at the inlet while the inlet feed temperature is initialized at 295 K. No swirl flow of velocity is applied. To ignite the propane-air mixture in the combustor, the value of U is first set to 20.0 cm/s and the equivalence ratio (ϕ) is fixed to 1.0. A technique that is called as "cold flow" is employed where the momentum and continuity equation is first solved. Then, by patching a high temperature around an area that can be defined as patch zone, the energy and species equations are then solved. This patch zone is located at 2.5 mm from the outlet and should not be placed too close to the outlet since it can result to a reverse gas flow that negatively affects the ignition process. A sufficiently high temperature of 1600 K is applied in the patch zone to ensure that the fuel- air mixture can be ignited. Once ignited, the flame propagated to the upstream and eventually stabilized near the wire mesh. To obtain the blowout limits, the U value is gradually stepped up with 5.0 cm/s interval. If the new value of U causes the flame to propagate to the outlet, then the process is started again with the previous U value. The increment is then reduced to 1.0 cm/s interval until the flame is blown out of tube. The maximum value of U before the flame is blown out is considered as the blowout limit. As for determining the extinction limit, the value of U is gradually reduced with 1.0 cm/s interval. The lowest value of U before the flame extinct is defined as the extinction limit. For this case study, the laminar speed, *U* is constant for all 3-D combustor which is 35.0 cm/s.

For the mass diffusion in laminar flows, ANSYS Fluent employs the dilute approximation which also known as Fick's law to model the mass diffusion due to the concentration gradients:

$$j_i = -\rho D_{i,m} \nabla Y_i - D_{T,i} \frac{\nabla T}{T} \tag{3.4}$$

$D_{i,m}$ = Mass Diffusion Coefficient for Species i,

$D_{T,i}$ = Thermal Diffusion Coefficient

The sample calculation of mass fraction at equivalence ratio (Φ = 0.90) for the input of the equation above. It is assumed that air is assumed to be a mixture of 21.0 mol % of oxygen and 79.0 mol % of nitrogen. By using the chemical reaction of one – step propane combustion:

$$C_x H_y + a\,(O_2 + 3.76N_2) \rightarrow xCO_2 + \frac{y}{2} H_2O + 3.76aN_2 \tag{3.5}$$

$$C_3 H_8 + a\,(O_2 + 3.76N_2) \rightarrow 3CO_2 + 4\, H_2O + 3.76aN_2 \tag{3.6}$$

$$a = \frac{x + \frac{y}{4}}{\Phi} = \frac{3+2}{0.90} = 5.5556$$

$$C_3 H_8 + 5.5556\,(O_2 + 3.76N_2) \rightarrow 3CO_2 + 4\, H_2O + 3.76(5.5556)\, N_2 \tag{3.7}$$

Next, finding the molar fraction (*X*) of each species:

$$N_{C_3H_8} = 1;\ \chi_{C_3H_8} = \frac{N_{C_3H_8}}{N_{Total}} = \frac{1}{1+5.5556+20.8891} = \frac{1}{27.444656} = 0.03644 \tag{3.8}$$

$$N_{O_2} = 5.5556;\ \chi_{O_2} = \frac{N_{O_2}}{N_{Total}} = \frac{5.5556}{1+5.5556+20.8891} = \frac{5.5556}{27.444656} = 0.2024 \tag{3.9}$$

$$N_{N_2} = 20.8891;\ \chi_{N_2} = \frac{N_{N_2}}{N_{Total}} = \frac{20.8891}{1+5.5556+20.8891} = \frac{20.8891}{27.444656} = 0.7611 \tag{3.10}$$

The calculation the mixture molecular weight (MW_{mix})

$$MW_{mix} = \sum \chi_i \, MW_i \tag{3.11}$$

$$MW_{mix} = \chi_{C_3H_8} M\,W_{C_3H_8} + \chi_{O_2} MW_{O_2} + \chi_{N_2} MW_{N_2}; \tag{3.12}$$

$$MW_{mix} = 0.03644(44.06) + 0.2024(32) + 0.7611(28.013);$$

$$MW_{mix} = 29.4048 \frac{kg}{kmole};$$

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

$$Y_{C_3H_8} = \frac{\chi_{C_3H_8} M\,W_{C_3H_8}}{MW_{mix}} = \frac{0.03644(44.06)}{29.4048} = 0.05460 \tag{3.13}$$

$$Y_{O_2} = \frac{\chi_{O_2} MW_{O_2}}{MW_{mix}} = \frac{0.2024(32)}{29.4048} = 0.2203 \tag{3.14}$$

Thus, the value of the species of mass fraction are then being the input to the Fluent.

3.8 Computational Domain

For the set up under computational domain by using three – dimensional (3-D) simulation model, the numerical equations of the fluid flow are solved by CFD. The computational domain in this case study covered only by 3-D on which boundary conditions. The boundary condition for the simulation on the ambient temperature, equivalent ratio (*Φ*), the flow rate of air propane, velocity inlet, *U* (laminar speed) and others. For the model boundary only energy and the species model are on. The reaction for all model is volumetric with chemistry solver of stiff chemistry solver. It is also run with condition of inlet diffusion, diffusion of energy source and thermal source. The chemical reaction was used is propane – air mixture which consist of propane C_3H_8, water vapour, carbon dioxide, oxygen and also nitrogen.

The starting velocity, *U* (laminar speed) was set up from 20.0 cm/s that to find the blowout limit. After find the blowout limit which is 35.0 cm/s, the value was constant for all model numerical simulation of the combustors. The equivalent ratio (*Φ*) also fix which is 1.0 and also assume that the combustor is made of quartz with *k* is 1.6 W/mk. The mass fraction has been set up for propane mass fraction is 0.05460 and the oxygen is 0.2203.

The starting temperature was set up to 295 K for the boundary condition outlet combustor. 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. The reference value, default area is 1 m^2, the density is 1. 225 kg / m^3, the length is 1000 mm, the velocity is 1 m/s, the temperature is 288.16 K, the viscosity is 1. 789e – 05 kg / ms.

3.9 FACTORS INFLUENCING FLAME VELOCITY AND THICKNESS

3.9.1 Temperature

The temperature dependencies of S_L and δ can be inferred from Eq. (3.17) and Eq. (3.18), recognizing the following approximate temperature scaling's. The pressure dependencies are also indicated.

$$\alpha \propto \bar{T}^{\,0.75}\, T_u\, P^{-1} \qquad (3.15)$$

$$\frac{\bar{\dot{m}}'''_F}{\rho_u} \propto T_u T_b^{\,-n} P^{\,n-1} \exp\left(-E_A / R_u T_b\right) \qquad (3.16)$$

$$S_L = \left[-2\alpha\,(\nu + 1)\,\frac{\bar{\dot{m}}'''_F}{\rho_u}\right]^{1/2} \qquad (3.17)$$

$$\delta = 2\alpha / S_L \qquad (3.18)$$

Where the exponent n is the overall reaction order, and $\bar{T} = 0.5\,(T_b + T_\alpha)$. The combining the above Eq. (3.15) and Eq. (3.16) scaling's yields

$$S_L \propto \bar{T}^{\,0.375}\, T_u T_u^{\,-n/2} \exp\left(-E_A / 2R_u T_b\right) P^{(n-2)/2} \qquad (3.19)$$

and

$$SL \propto \bar{T}^{\,0.375}\, T_b^{\,n/2} \exp\left(+E_A / 2R_u T_b\right) P^{-n/2} \qquad (3.20)$$

We see that the laminar flame speed has a strong temperature dependence, since global reaction orders for hydrocarbons are about 2, and apparent activation energies are approximately 1.67 x 10^8 J/kmol (40 kcal/gmol). For example Eq. (3.19) predicts the flame speed to increase by a factor of 3.64 when the unburned gas temperature is increased from 300 K to 600 K. The increasing the unburned gas temperature will also increase the burned gas temperature by about the same amount, if we neglect dissociation and temperature dependent specific heats.

3.9.2 Pressure

Equation 3.20 shown that $S_L \propto P^{(n-2)/2}$. If, we assume a global reaction order of 2, flame speed should be independent of pressure. Experimental measurements generally show a negative dependence of pressure. (Andrews and Bradley, 1972) found that,

$$S_L\ (cm/s) = 43[P\ (atm)]^{-0.5} \tag{3.21}$$

Fits their data for P > 5 atm for methane – air – flames. The law (Laws, 1993) provides a summary of the flames speed data for a range of pressure which are up to 5 atm or less for the following fuels: H_2, CH_4, C_2H_2, C_2H_4, C_2H_6, and C_2H_8. The previously cited work by (Metghalchi and Keck, 1982) also provide flame speed – pressure correlations for selected fuels. The effect of reduced pressure on the combustion efficiency of lean H_2/air flames in a micro – combustor was investigated and also found that the combustion efficiency increase as the pressure is reduced, and then decrease when the pressure is further reduced from 0.8 to 0.5 atm as the sample (Wei et al. 2016).

3.9.3 Equivalent Ratio

Except for very rich mixtures, the primary effect of equivalent ratio on flame speed for similar fuels is a result of bow this parameter affects flame temperatures. Thus, we would expect flame speed to be a maximum at a slightly rich mixture and fall off on either side. Flame thickness shows the inverse trend, having a minimum near stoichiometric.

3.9.4 Fuel Type

For C_2 – C_2 alkanes is a single bond, alkenes is a double bond and alkynes is a triples bond. Also shown are CH_4 and H_2. The flame velocity of propane is used as a references. Roughly the C_3-C_6 hydrocarbons all follow the same trend as a function of flame temperature. Ethylene (C_2H_4) and acetylene (C_2H_2) have velocities greater than the C_3-C_6 group, whereas methane lies somewhat below. Hydrocarbon's maximum flame speed is many times greater than that of propane. Several factors combine to give H_2 its high flame speed. The first thermal diffusivity of pure H_2 is many times greater than the hydrocarbon fuels. The second, the mass diffusivity of hydrogen likewise is much greater than the hydrocarbon and the third is the reaction kinetics for H_2 are very rapid since the relatively slow CO – CO_2 step that is a major factor in hydrocarbon combustion is absent.

3.10 SUMMARY

Figure 3.9 illustrated the work flow for the project PSM. The project begin with the literature review on the previous project which cover various topic such as geometry of combustors, method of stabilization of flame and etc. This helps in gaining a better understanding on what be done throughout the process as well as developing for the report writing later. The designing numerical model of counter current micro combustors by using ANSYS software. Next, generated numerical model by parameter such as inlet velocity, equivalent ratio that used to stable the flame of the combustors. The simulation process takes places and this is where the whole process needs to starts again if there are problems arise to stable the flame of the combustors and numerical models. The numerical model was stimulated by using ANSYS Fluent software and the results was proposed. Next, writing the full report.

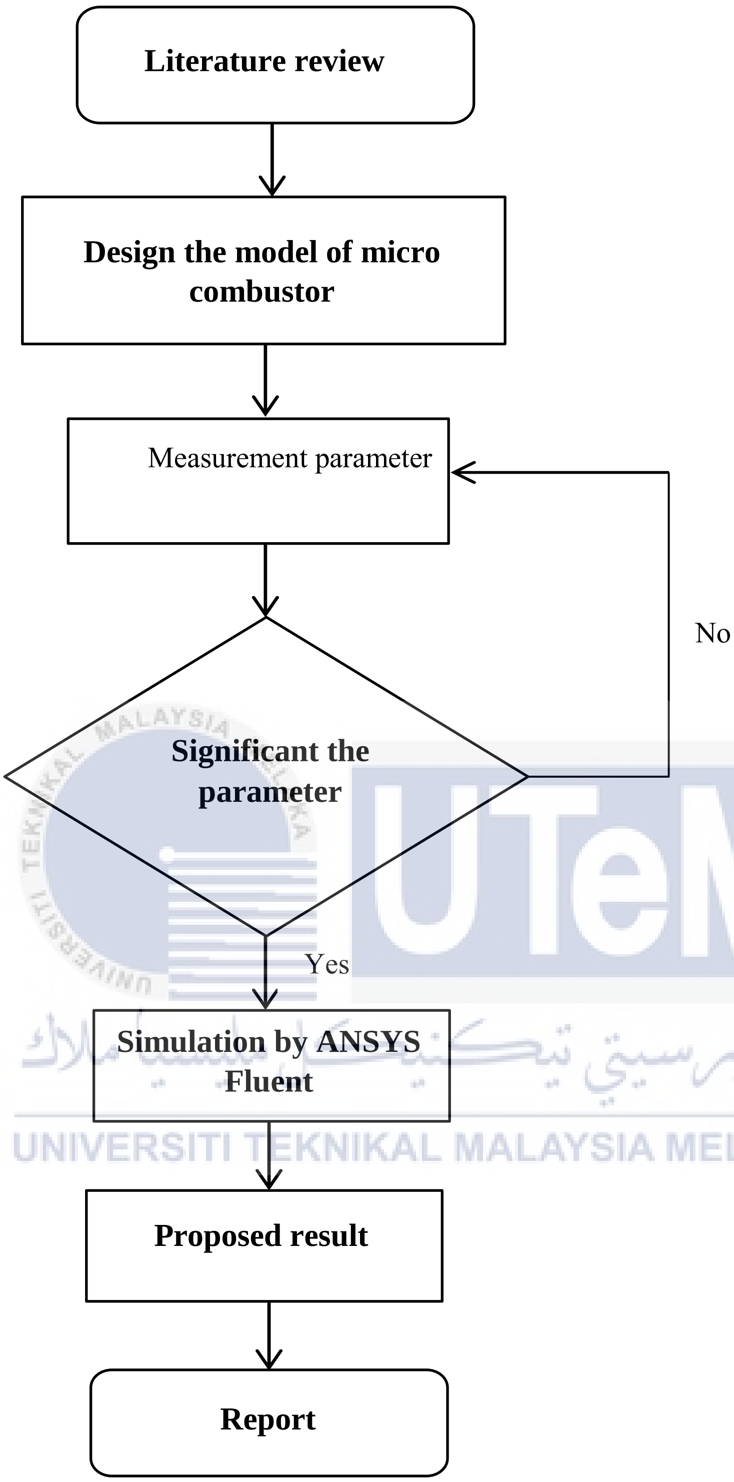

Figure 3.9: Flow chart of the project for PSM

CHAPTER 4

RESULT & DISCUSSION

4.1 OVERVIEW

This chapter shows the result design of the project which is counter current micro combustor for all type of model combustors. The result was designed and will be evaluate and stimulate by using ANSYS Fluent Software. In micro combustors, the parts which are flame, inner and also outer wall temperature are interdependent to each other. These features are essentially important in a micro power generation research.

For the analysis of the simulation case study, the wall thermal conductivity values for both the unburned *(k_u)* and burned *(k_b)* gas region were constant at 1.6 W/mk. The effect of wall thermal conductivity on the temperature contours of the combustors are shown in Figure 4.1 is single tube with single wire mesh, Figure 4.2 is double tube with single wire mesh and Figure 4.3 is double wire mesh with (single piece). The flame temperature can be defined as the highest gas temperature recorded along the simulation. The process of the transferring the heat from the hot burned gas to the unburned gas reactants in various type of the combustors is by the wall conduction.

In addition, the uniform temperature can be achieved by using a high wall thermal conductivity in the unburned *(k_u)* and burned gas region *(k_b)*. A lower temperature that means a reduction a reduction of the combustor efficiency in converting heat to electrical energy and a proper consideration was necessary in order to balance between the need of a high performance combustors. The efficiency of a micro combustors in converting heat produced from combustion to electrical is significantly affected by the temperature. The surge of flame temperature that results to a greater wall surface temperature distribution.

4.2 The speed velocity on the flame stabilization

In micro scale combustors, the wall thermal conductivity plays a significant role in determining the stabilization of the flame combustors. The heat conduction from the burned gas region promotes the pre – heating of the unburned gas that eventually enhances the flame stability. For all cases, a stable flame can be achieved with the inlet velocity, (*U*) of 20.0 cm/s regardless of the equivalent ratio value. The value of *U* is gradually stepped up with 1.0 cm/s interval and further calculation is conducted until a converged solution is achieved. For this case study, the inlet velocity, *U* is constant which is 35.0 cm/s.

4.3 Wall surface temperature in the burned region

For this cases, the wall temperature is an important criteria for all model micro scale counter current combustors. A uniform and stable temperature is required for a good combustor. This numerical model simulation, the combustor with wire mesh, flame stabilizes in the burned gas region. Thus, a temperature is recorded on the wall surface in this region. The relationship in designing a micro counter current combustor is important for this case study. In Figure 4.1, the temperature at the burned region is low compare in Figure 4.2 which is temperature along the tube combustor is higher than it. Because the combustor was designed with double tube that the gas out from the outlet tube in combustor will pre heated the tube again. This elevation of the temperature is mainly because there is no straight thermal path from the wire mesh to the ambient air. In other words, there is high thermal stress occurs on the combustor and the outer wall. In conclusion, the temperature in Figure 4.2 is higher than Figure 4.1. The similarity between two figures which is a wire mesh.

The comparison between Figures 4.2 with Figure 4.3 is the temperature along the tube. The temperature in Figure 4.2 is higher than Figure 4.1 but lower in Figure 4.3. The designing of the numerical model simulation of double wire mesh (single piece) is meant the wire mesh can transfer a lot of heat from the burned gas region to the unburned gas region. It is shows that high temperature, transverse heat transfer across the burner wall is likely to be more dominant than the axial heat transfer to the upstream. In conclusion, the temperature along the tube combustors in Figure 4.3 is higher than Figure 4.2 and Figure 4.1.

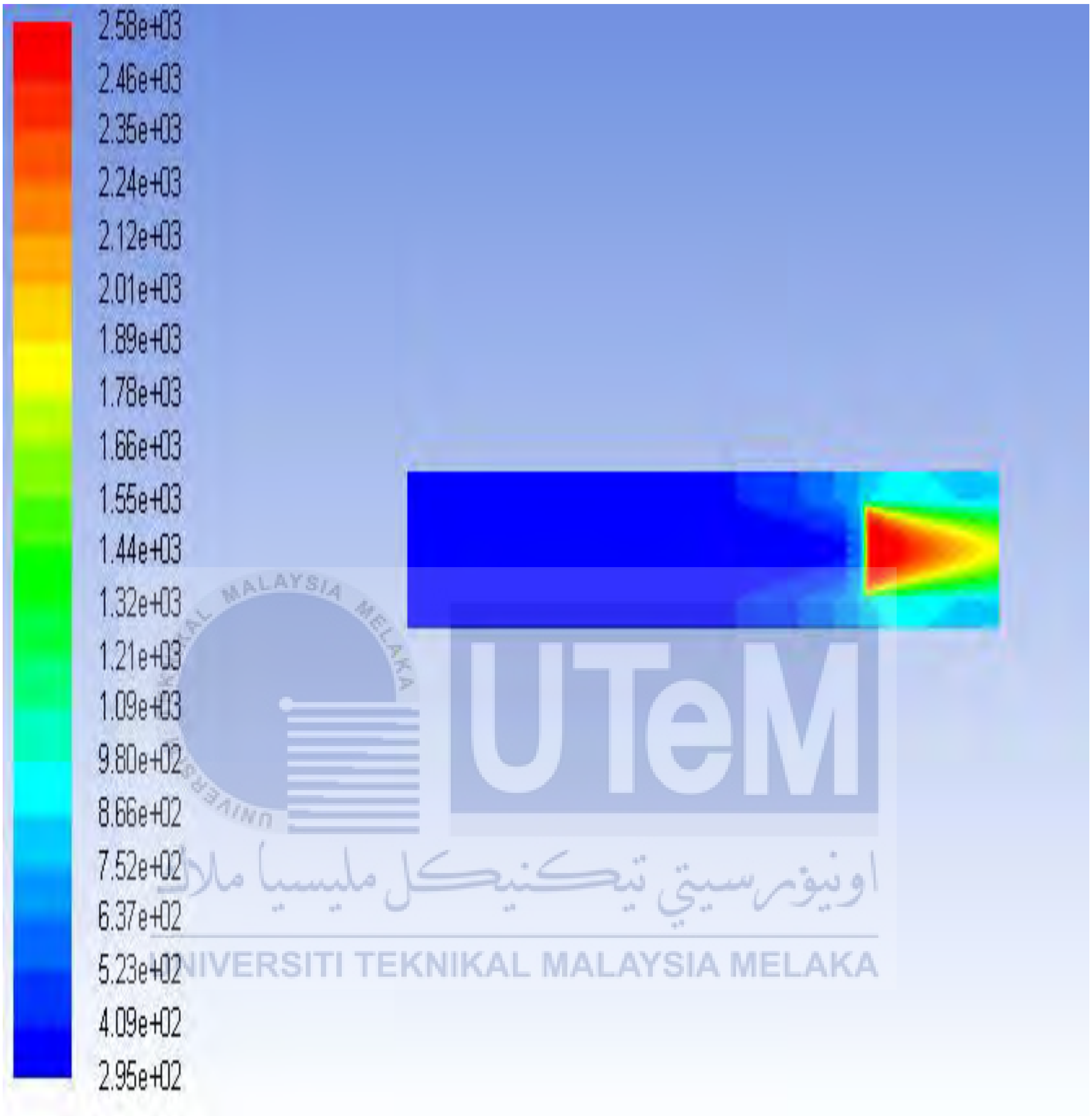

Figure 4.1: The Temperature of Single Wire Mesh. The Inlet Velocity, *U* is 35.0 cm/s and Equivalent Ratio, *Φ* is 1.0.

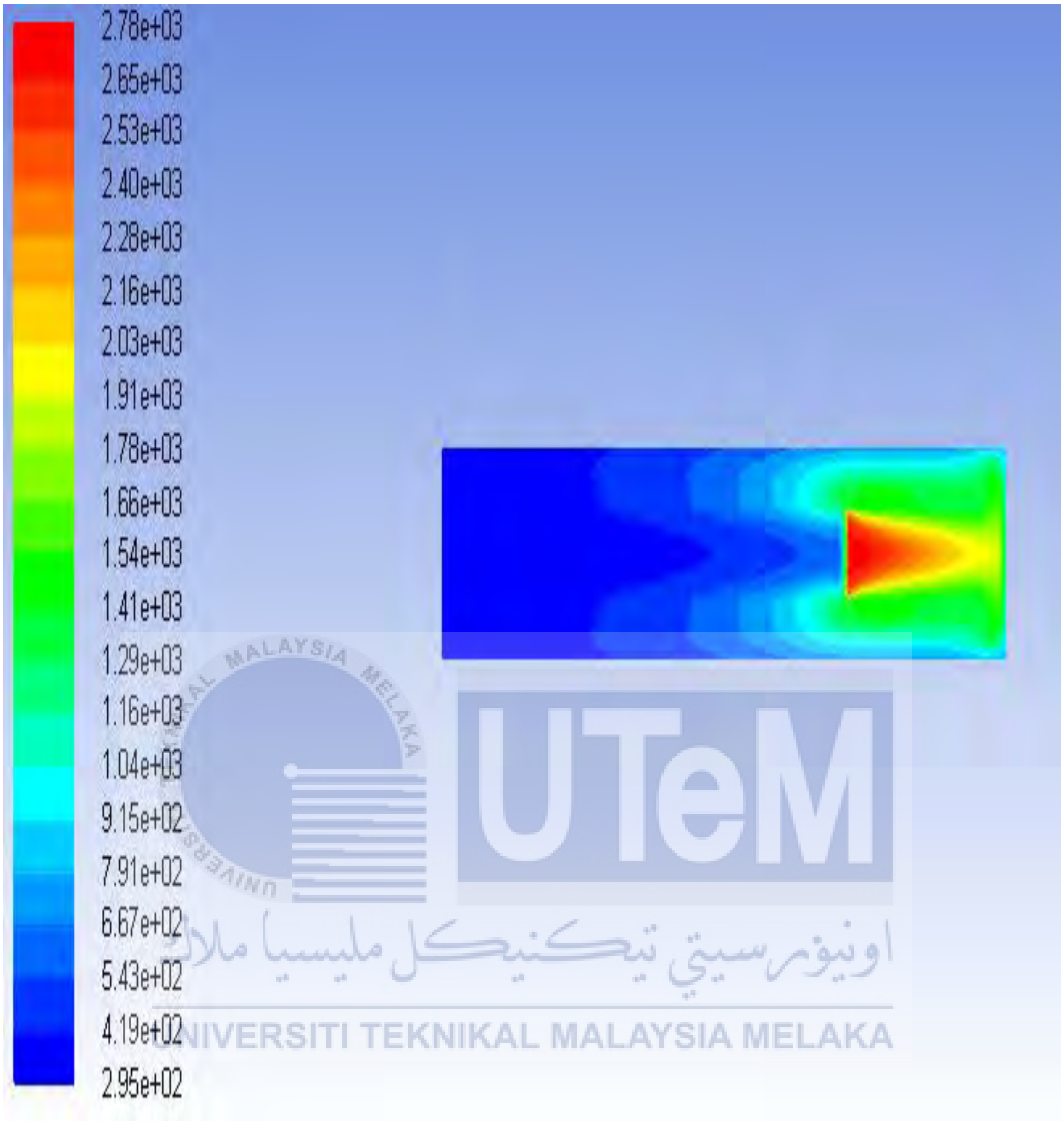

Figure 4.2: The Temperature of Double Tube with Single Wire Mesh. The Inlet Velocity, *U* is 35 cm/s and Equivalent Ratio, *Φ* is 1.0.

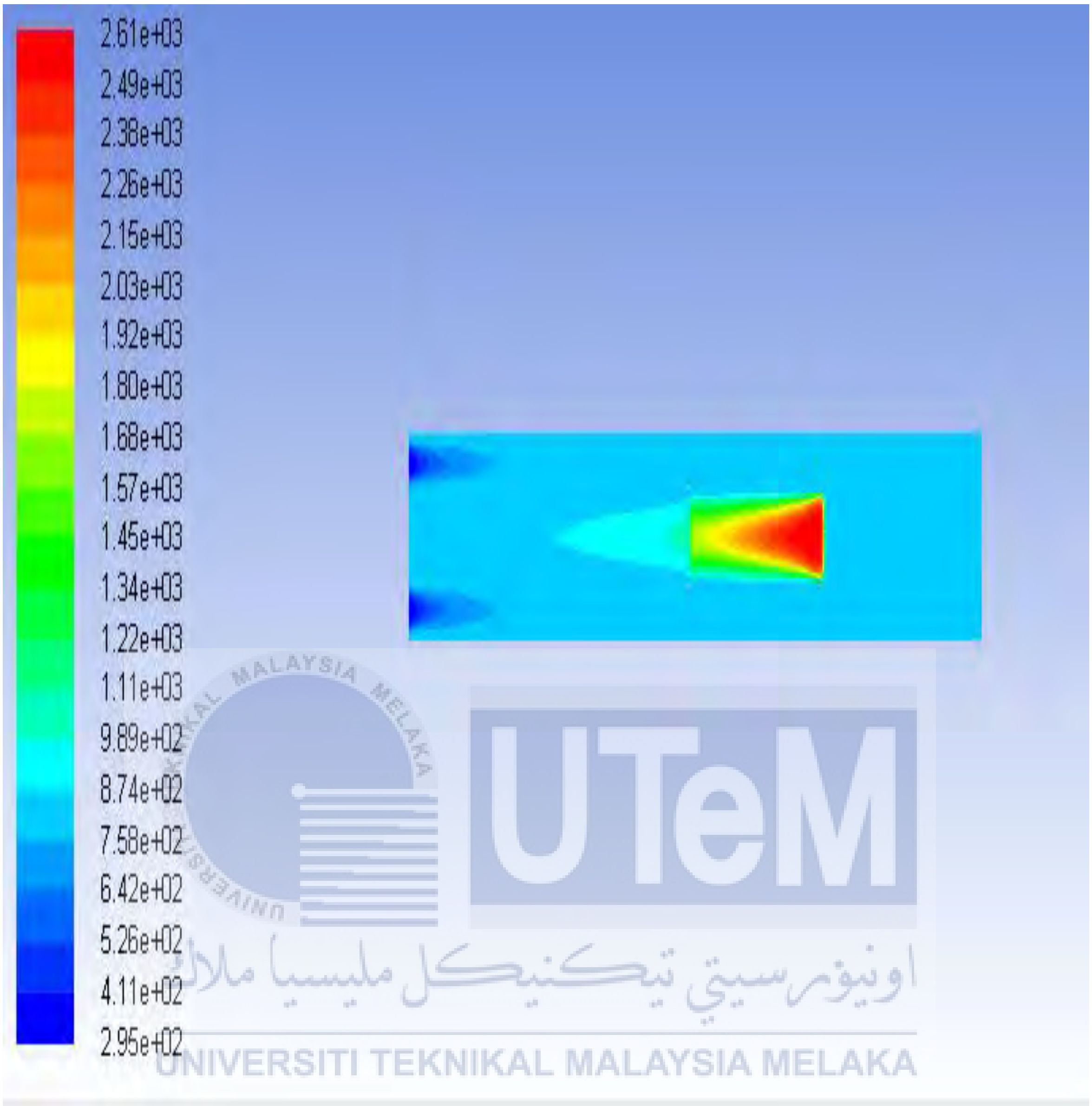

Figure 4.3: The Temperature of Single Tube with Double Wire Mesh (Single Piece). The Inlet Velocity, U is 35.0 cm/s and Equivalent Ratio, Φ is 1.0.

The improvement of the flame stabilization limits for all model simulation due to the existence of the wire mesh and designing tube combustors, which plays in transferring heat from the burned to unburned gas region. However, the model simulation results show that double wire mesh (single piece) combustor has a high temperature along the wall of the unburned gas region. It is increase the combustor performance. The higher temperature, it will increase the flame stabilization that contributed the effective of combustors.

In addition, the number of the wire mesh for the double wire mesh (single piece) is effect the flow of the streamlines. A steady – state cold flow simulation with inlet velocity, U is 35.0 cm/s becomes faster compare to the other combustor with single wire mesh which is single tube with single wire mesh and double tube with single wire mesh.

4.4 SUMMARY

In this chapter, numerical simulations to investigate the temperature of the combustor model on the flame stabilization were performed. Apart from that, credible three dimensional (3-D) numerical model for counter current combustor has also been established. The results show that double wire mesh (single piece) has higher gas temperature, which can potentially generate more useful electrical energy. If the laminar speed is higher, the temperature also higher because the laminar speed, S_L is directly proportional to the temperature. The changes in the model simulation in these critical parameters that help to explain the case study of the flame stabilization. By conducting 3-D numerical simulation, it is known that the main reason of the improved blowout limits is due to be significant increase of the unburned gas temperature near to the wire mesh.

CHAPTER 5

CONCLUSION

The literature study to the simulation of counter current micro combustor for micro power generation. The ANSYS Fluent Software were used to stimulate and analyses method. The preliminary result have been obtained by using the ANSYS Fluent Software. For this PSM 1, the report only prepared the drawing of the counter current and find some information about the methodology of the stimulation analysis. Therefore, the next work is stimulate and analysis the design by using the ANSYS Fluent Software. This software will helps to analysis the ambient air temperature and examine the parameters that contribute to the changes of the experiment.

The three dimensional (3-D) numerical simulations of the combustion of propane – air mixture in micro counter current tube combustors with wire mesh has been successfully demonstrated. The presented of the numerical simulations can sufficiently represented the propane – air mixture combustion in this of the model simulation of the combustors. In addition, the preheated zone of the combustors which is the flame already in contact with the wire mesh. From the situation, the heat transfer from the hot burned gas to the combustors walls and ambient air is intensified.

The inlet velocity of the combustors was determine the blowout limit to stable flame near to wire mesh. The double wire mesh (single piece) is the model numerical simulation that have a larger temperature condition in the counter current tube combustors. This heat recirculation enhances the flames stabilization in the micro counter current of the combustors.

From the objectives of the case study, the design of the counter current was achieved and also stimulated at the ambient air temperature at 295 K on the flame stabilization of the counter current. The numerical model simulation of the counter current was analyse the effect of the exhaust gas heat recirculation of the flame stabilization and also examine the important parameters such as inlet velocity and equivalent ratio that contributed to the flame stabilization. Thus, the objectives of the case study was achieved.

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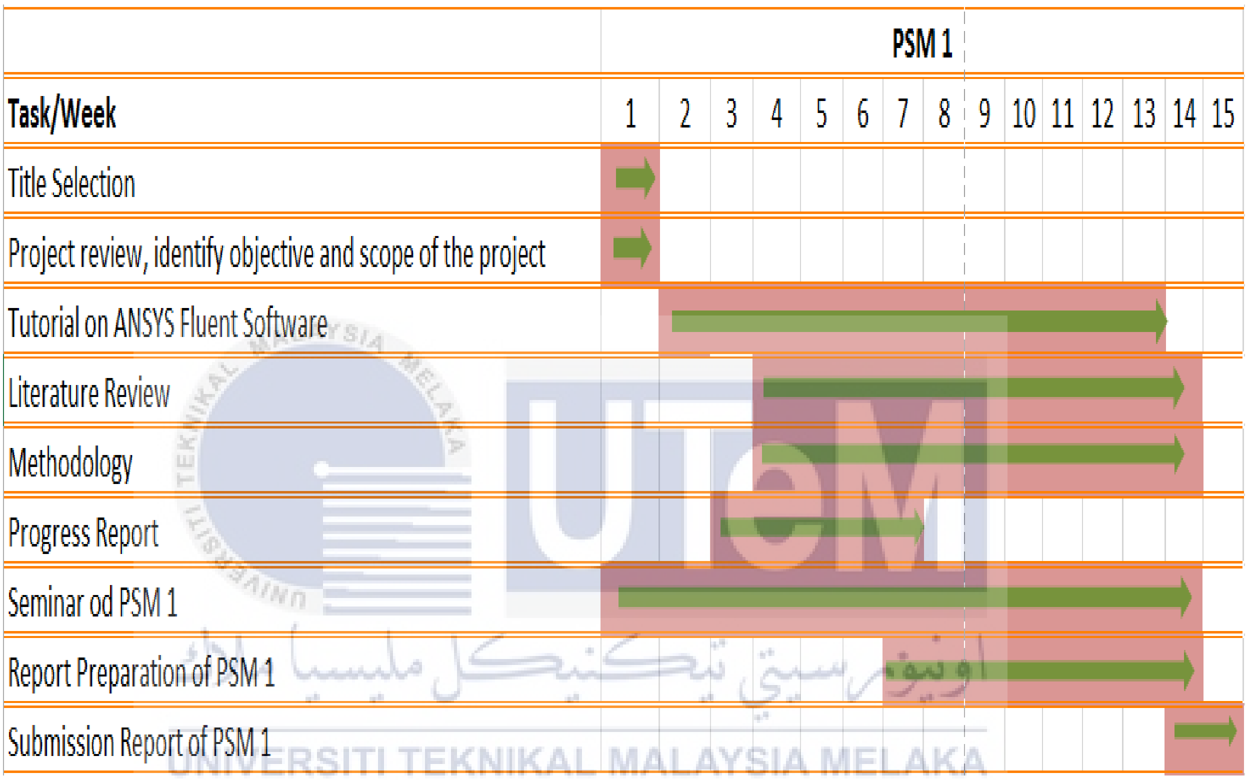
APPENDICES

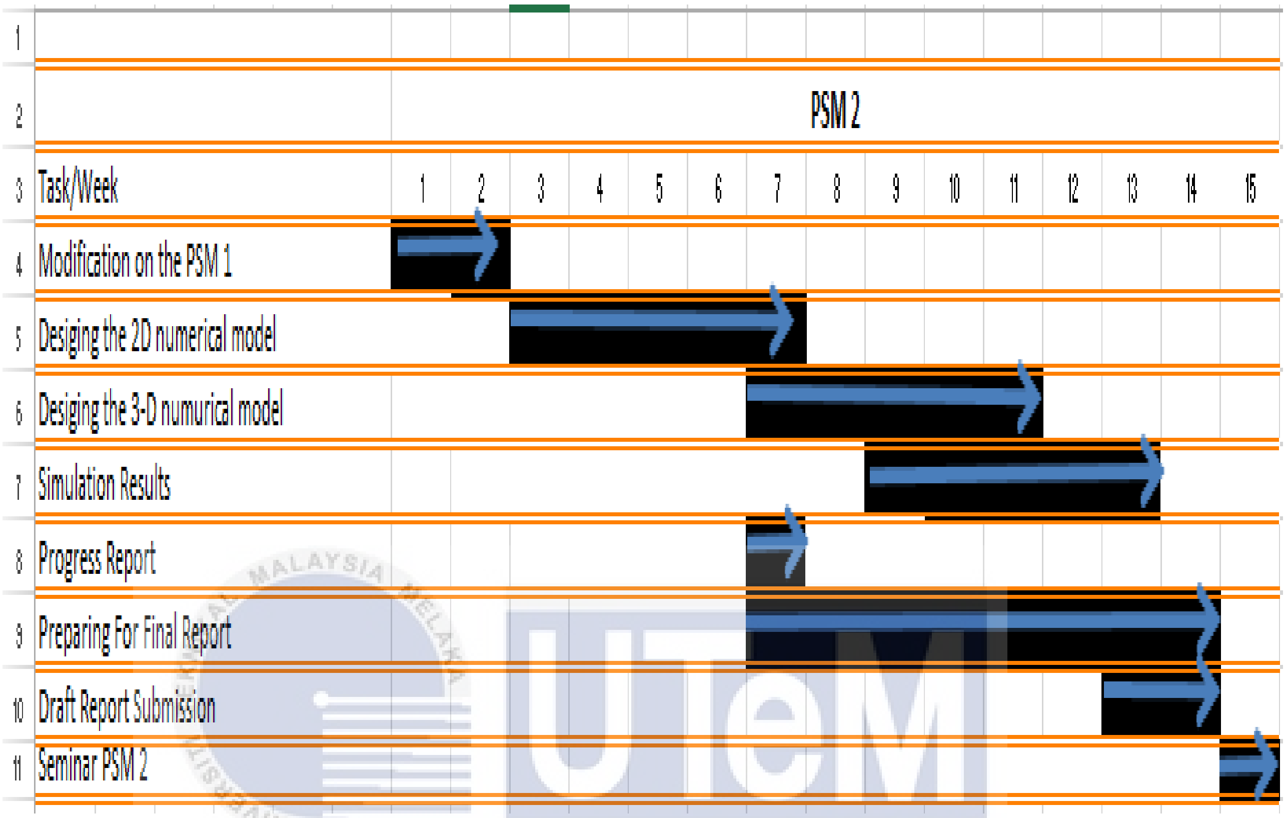
APPENDIX A

GANTT CHART PSM 1



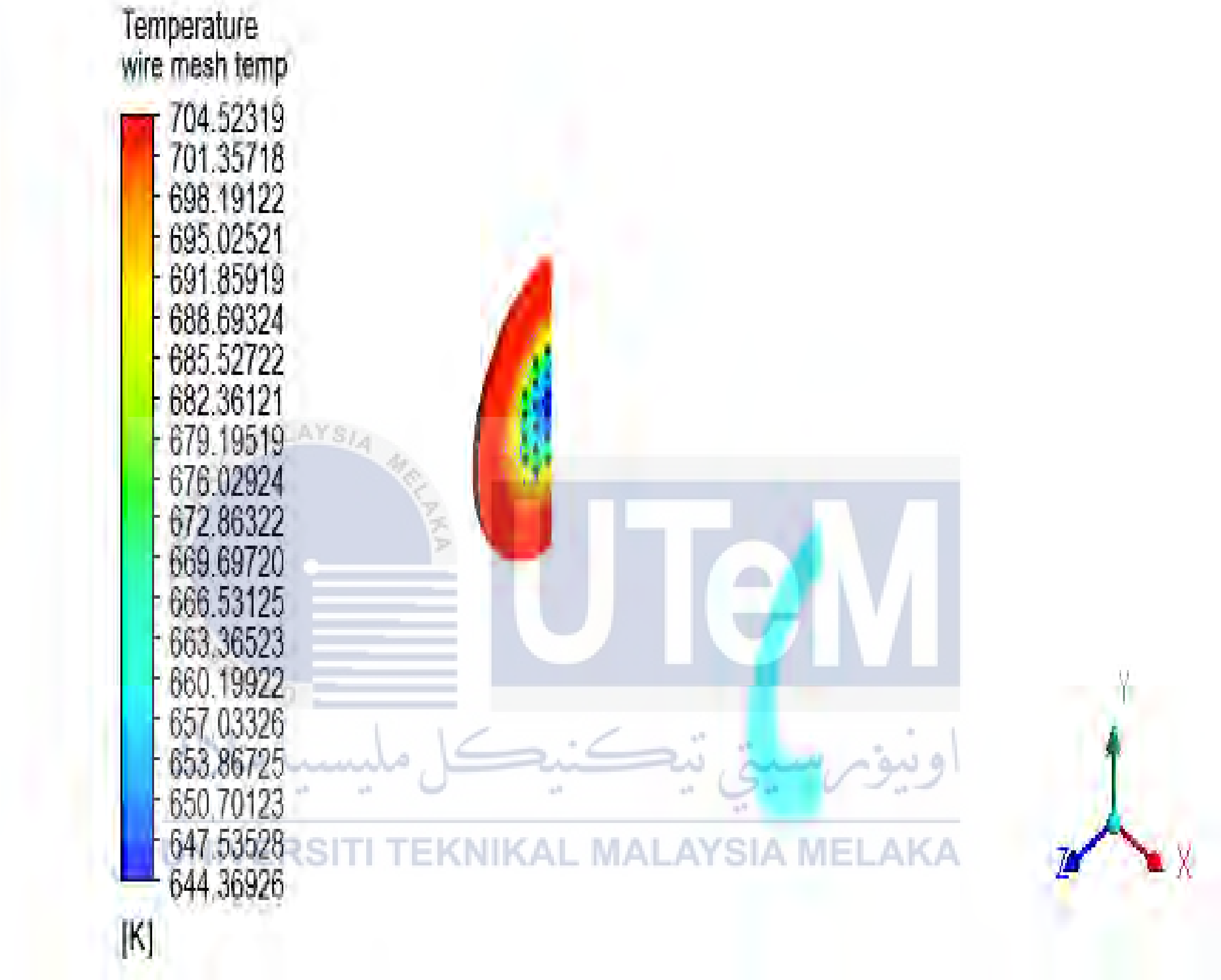
APPENDIX B

GANTT CHART PSM 2



APPENDIX C

Temperature of the wire mesh single tube



APPENDIX D

Temperature of the double wire mesh