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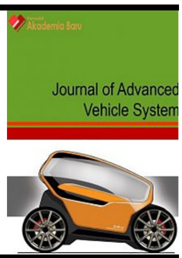

Flame stabilization in multiple inlet channel meso-scale tube combustors with wire mesh

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ABSTRACT

Micro combustion system is one of potential solutions that provides better energy requirement for small-scale devices as compared to conventional batteries. Very recently, quite a number of works have been performed to enhance the combustion stability of meso and micro-scale combustors. Researchers and engineers are diligently experimenting various design of micro combustors with the ultimate objective of having reliable burner. In this study, a meso-scale tube combustor with multiple inlet channel is proposed. Stainless steel wire mesh is utilized as the flame holder, which is located between the unburned and burned gas region. The combustion take place in a channel with 3.5 mm diameter. Aluminium is selected as the material of the combustor considering the limitation of fabrication technology. A three dimensional (3-D) model is utilized to demonstrate the combustion of propane-air mixture in the designed combustor. The results in terms of streamline velocity pattern, heat of reaction, wire mesh and outer wall temperature are established. It is shown in this paper that flame can be stabilized in the tube combustor. Nevertheless, the proposed combustor is only at a preliminary design where there are quite a number of important parameters that need to be obtained before going into fabrication stage. One of the important examples is flame blow out limits.

1. Introduction

The invention of high performing electronics devices has sparked the research interest in micro power generation. The limited energy resources and the highly desired alternatives to conventional batteries have become the prime catalyst to the renewed research interest in micro power generation [1]. With the invention of highly sophisticated electronic devices, the demand for

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batteries with the capability of greater energy capacity, shorter charging period and lightweight design are skyrocketing. The recent progress in micro power generation systems in which hydrocarbon fuels are utilized might become the viable solution of having a better power source as compared to batteries [2].

One of the key components in micro power generation is the narrow channel combustor. It is fundamentally important to understand micro combustion phenomena so that a reliable micro combustor can be designed [3]. Even though flame stabilization in a confined space is reported to be achievable, it is considerably a great challenge to sustain a stable flame such narrow channel. The main reason that contribute to this predicament is mainly due to the high surface to volume ratio [4] that causes a large portion of heat loss from the flame to the wall. As a result, flame quenching occurs within a matter of seconds [5].

Researchers have shown that there are many ways to stabilize flame in a micro combustor. One of the most popular methods is by utilizing the heat produced from the combusted products to pre-heat the unburned reactants. This method is also defined as heat recirculation method. Generally, there are two types of pre-heating method [3]. The first method is called as the direct method where the heat is transferred from the hot burned gas to the unburned gas region through conduction and radiation. Single channel micro combustor (SC) mainly utilizes this type of heat recirculation mechanism in which the heat from the burned gas region is axially transferred to the unburned gas region via the combustor wall [6]. As such, the combustion stability can be significantly enhanced. On the other hand, indirect pre-heating method is an approach where the flow of the burned gas is reversed to pre-heat the unburned reactants. Swiss-roll combustor utilizes this concept resulting to a huge improvement of flame stabilization limits as compared to SC combustors. Nevertheless, the geometry of a Swiss-roll combustor is relatively complicated making it difficult to be numerically and experimentally investigated [7]. Thus, a combustor with simpler geometry is preferred.

Mikami et al. [8] had proposed the use of flame holder in a single channel quartz tube combustor. In their experimental work, a stainless steel wire mesh is placed between the burned and unburned gas region and the experimental results show that the flame can be stabilized without external heating. Combustion stability in meso and micro-scale combustors is greatly influenced by a few factors such as the wall thickness and materials [9,10]. The effects of wall thermal conductivity on the combustion stability in meso and micro-scale combustors with gaseous hydrocarbon fuels have been thoroughly examined [11,12]. However, these studies are limited to combustors without a flame holder. Recently, [13] numerically investigated the effect of wall thermal conductivity in a combustor with concentric rings. A two-dimensional (2-D) model is proposed and their results suggest that changing the combustor wall thermal conductivity in both the unburned and burned gas region significantly affects the combustion stability. Nevertheless, there is a limitation of the a 2-D numerical model, where it could not effectively simulate the role of stainless wire mesh in enhancing flame stabilization limits as shown in experiment. Thus, a three-dimensional (3-D) numerical model is proposed [14].

This research investigated flame stabilization in a possible design concept of meso-scale tube combustor with stainless steel wire mesh. The proposed design of the combustor can also be utilized for liquid hydrocarbon fuels, which ultimately solves the main problem of micro power generation system that is mobility. Numerical model is utilized owing to the scale of the combustor, which make it difficult to establish experimental data.

2. Research methodology

2.1. Design concept

The design concept of the four channels meso-scale tube combustor with stainless wire mesh is proposed and shown in Fig.1. The unburned gas is being pre-heated by the exhaust gas via the wire mesh B. This unburned mixture is also being heated up since the supply channel passes in between the combustion channel. The unburned gas region in all four supply channels are being heated up before being combusted as illustrated in Fig 2. It is important to note that the the exhaust gas is not being recirculated back into the supply channel. The exhaust gas flows out of the combustor through the outlet. This concept is different than the combustor with Exhaust Gas Recirculation (EGR). The selection of material to be used for the combustor is performed using CES EduPack 2013[15]. Table 1 presents the design requirement for the tube combustor. There are four possible materials to be selected that conform to the design requirement. These potential material are aluminium, coated steel, commercial iron and zinc-copper. Aluminium is selected to be material for the tube combustor considering the manufacturing capability,

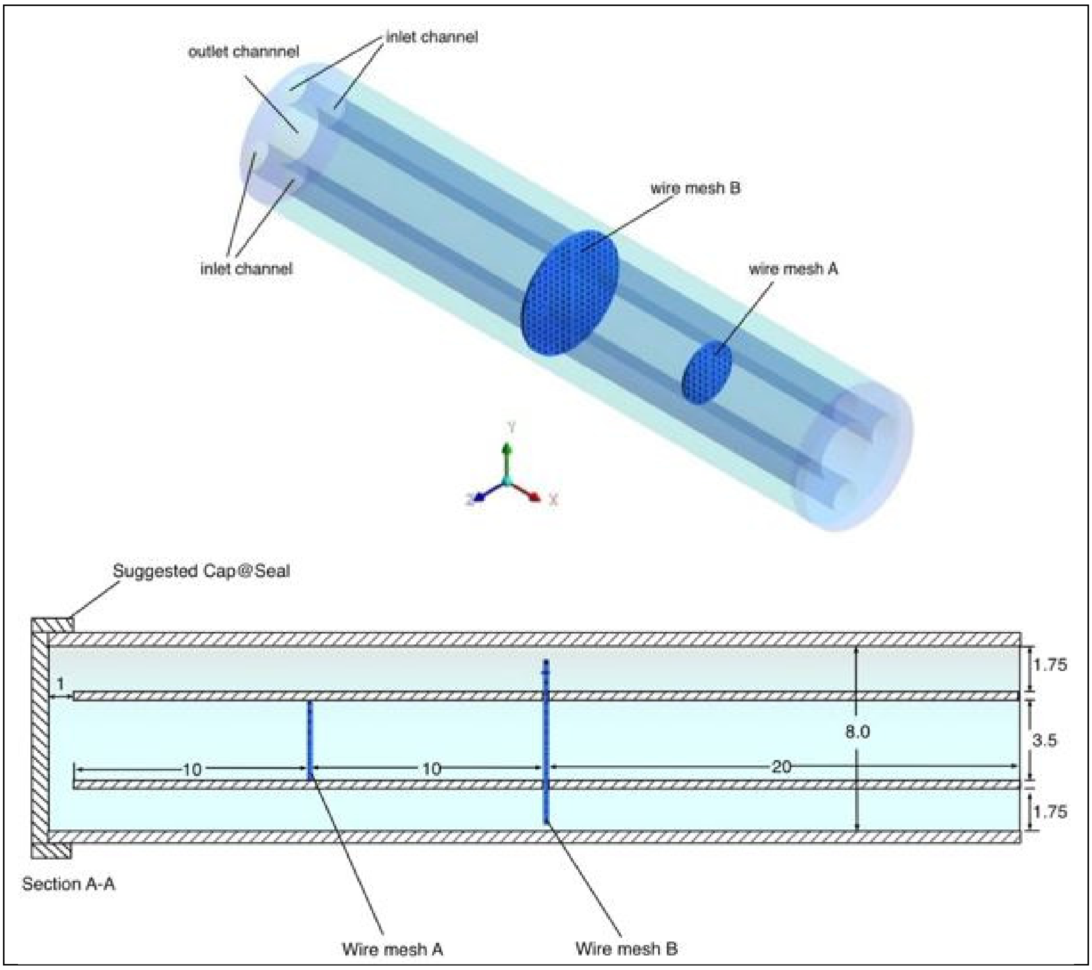


Fig. 1. Proposed Design of Meso-scale Tube Combustor with Four Inlet Channels

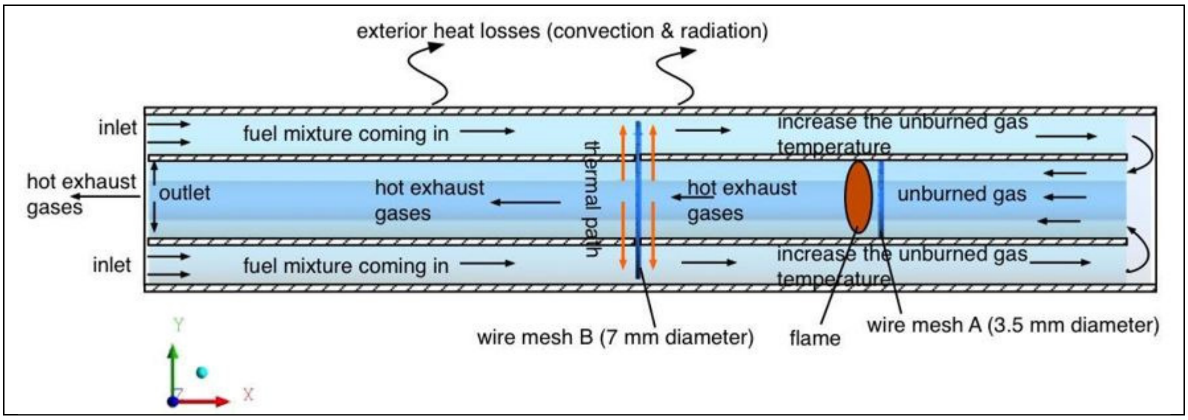


Fig. 2. Schematic diagram indicating the location of the combustion channel

Table 1
Design requirement for the multiple channel tube combustor

Properties	Requirements
Price range	Between RM 1 to RM 10 per kg
Thermal conductivity	Between 20 W/m/K to 100 W/m/K
Melting point	Minimum of 700K
Durability: flammability	Non-flammable
Durability: Oxidation at 773K	Unacceptable

2.2. Numerical setup

The type of fuel used is propane-air mixture while one-step global reaction chemistry is employed. The governing equations utilized for the numerical model are the typical fluid motion combined with reacting flows [15]. The mass conservation equation (continuity) is given by;

$$\frac{\partial\rho}{\partial t}+\frac{\partial}{\partial x}(\rho u_x)+\frac{\partial}{\partial y}(\rho u_y)+\frac{\partial}{\partial z}(\rho u_z)=S_m \quad (2)$$

S_m is the source term. An example of this term is vaporization of liquid or any user-defined source. Nevertheless, in this numerical model the value of S_m is fixed to 0. For a steady state condition, $\frac{\partial\rho}{\partial t}=0$. The momentum conservation equation in x-direction;

$$\frac{\partial\rho u_x}{\partial t}+\frac{\partial(\rho u_x u_x)}{\partial x}+\frac{\partial(\rho u_y u_x)}{\partial y}+\frac{\partial(\rho u_z u_x)}{\partial z}=-\frac{\partial p}{\partial x}-\frac{\partial}{\partial x}\left(\frac{2}{3}\mu(\nabla\cdot\vec{u})+2\mu\frac{\partial u_x}{\partial x}\right)+\frac{\partial}{\partial y}\left[\mu\left(\frac{\partial u_y}{\partial x}+\frac{\partial u_x}{\partial y}\right)\right]+\frac{\partial}{\partial z}\left[\mu\left(\frac{\partial u_x}{\partial z}+\frac{\partial u_z}{\partial x}\right)\right]+\rho f_x \quad (3)$$

Momentum equation in y-direction;

$$\frac{\partial(\rho u_x u_y)}{\partial x}+\frac{\partial(\rho u_y u_y)}{\partial y}+\frac{\partial(\rho u_z u_y)}{\partial z}=-\frac{\partial p}{\partial y}-\frac{\partial}{\partial x}\left[\mu\left(\frac{\partial u_y}{\partial x}+\frac{\partial u_x}{\partial y}\right)\right]+\frac{\partial}{\partial y}\left(\frac{2}{3}\mu(\nabla\cdot\vec{u})+2\mu\frac{\partial u_y}{\partial y}\right)+\frac{\partial}{\partial z}\left[\mu\left(\frac{\partial u_z}{\partial y}+\frac{\partial u_y}{\partial z}\right)\right]+\rho f_y \quad (4)$$

Momentum equation in z-direction;

$$\frac{\partial(\rho u_x u_z)}{\partial x}+\frac{\partial(\rho u_y u_z)}{\partial y}+\frac{\partial(\rho u_z u_z)}{\partial z}=-\frac{\partial p}{\partial z}-\frac{\partial}{\partial x}\left[\mu\left(\frac{\partial u_x}{\partial z}+\frac{\partial u_z}{\partial x}\right)\right]+\frac{\partial}{\partial y}\left[\mu\left(\frac{\partial u_z}{\partial y}+\frac{\partial u_y}{\partial z}\right)\right]+\frac{\partial}{\partial z}\left(\frac{2}{3}\mu(\nabla\cdot\vec{u})+2\mu\frac{\partial u_y}{\partial z}\right)+\rho f_z \tag{5}$$

where;

$$\nabla\cdot\vec{u}=\frac{\partial u_x}{\partial x}+\frac{\partial u_y}{\partial y}+\frac{\partial u_z}{\partial z} \tag{6}$$

The energy transfers due to conduction, species diffusion and viscous dissipation is represented by the Eq. (7) and (8) respectively.

$$\nabla\cdot(\vec{u}(\rho E+p))=\nabla\cdot\left(k\nabla\mathrm{T}-\sum_i h_i\vec{J}_i+(\bar{\bar{\tau}}\cdot\vec{u})\right)+S_h \tag{7}$$

$$\nabla\cdot(\vec{u}\rho h)=\nabla\cdot(k\nabla\mathrm{T})+S_h \tag{8}$$

where S_h is heat of chemical reaction or any other volumetric heat sources added by the user.

Eq. (7) and Eq. (8) 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.
For the species transport equation is defined as:

$$\nabla\cdot(\rho\vec{u}Y_i)=-\nabla\cdot\vec{J}_i+R_i+S_i \tag{9}$$

where R_i and S_i is the net rate of production of species *i* by chemical reaction and rate of creation by addition from the dispersed phase plus any user-defined sources.

For the mass diffusion in laminar flows, Fluent employs the dilute approximation, which is also known as Fick's law to model the mass diffusion due to the concentration gradients. The equation for the mass diffusion is given as;

$$\vec{J}_i=-\rho D_{i,m}\nabla Y_i-D_{T,i}\frac{\nabla T}{T} \tag{10}$$

The boundary treatment at the interface between the fluid and solid wall is assumed to be no-slip boundary type. The heat flux at this interface is calculated using Fourier's law. Heat transfer per unit area by means of convection and radiation at the outer surface of the combustor wall is given as:

$$q_{loss}=h_{conv}(T_{wall}-T_{amb})+\varepsilon\sigma(T_{wall}^4-T_{amb}^4) \tag{11}$$

where h_{conv} is the convective heat transfer coefficient, 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 constant 5 W/m^{2}K. Since the combustor is assumed to be made of aluminum, the external emissivity (ε) for the outer wall is fixed to 0.31 while value of ε for the wire mesh is set 0.70. The value of Stefan-Boltzmann constant (σ) used is $5.67\times10^{-8}\mathrm{W/m^2K^4}$. A thermal insulation (zero heat flux boundary) is applied at both left and right wall edge of the combustor. For the outlet boundary condition, a fixed pressure inlet is applied. A symmetrical boundary condition is established at the origin of z-plane so that the calculation can be performed only in half of the domain. The material thermal properties and the gas transport data are obtained from Fluent internal database [15,16]. Initially, the momentum and continuity equation is solved. Then, the energy and species equations are solved by applying a sufficiently high temperature of 1600 K to the patching zone, which is defined 1 mm from the outlet. Once ignited, the flame propagates to the upstream and eventually stabilizes near the wire mesh. With a fixed equivalence ratio (ϕ), both blowout and extinction limits are obtained by gradually changing the inlet flow velocity (U).

3. Results and discussion

The simulations start with cold flow assumption where only continuity and momentum equations are first solved. The results in terms of streamline pattern with inlet velocity U of 0.35 m/s is depicted in Fig.3. As depicted in the figure, high flow velocity is achieved in the small confined area far from the inlet. Such high-speed flow might affect the flame stabilization in the tube combustor.

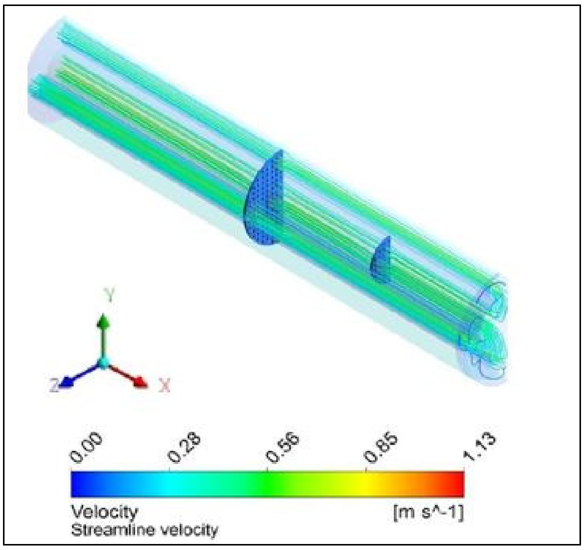


Fig. 3. Cold flow streamline velocity for *U*=0.35 m/s

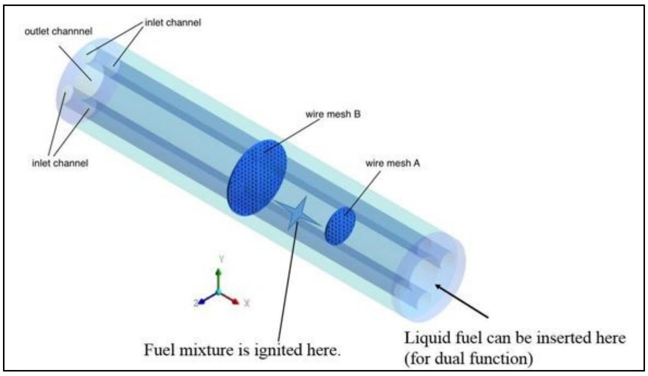
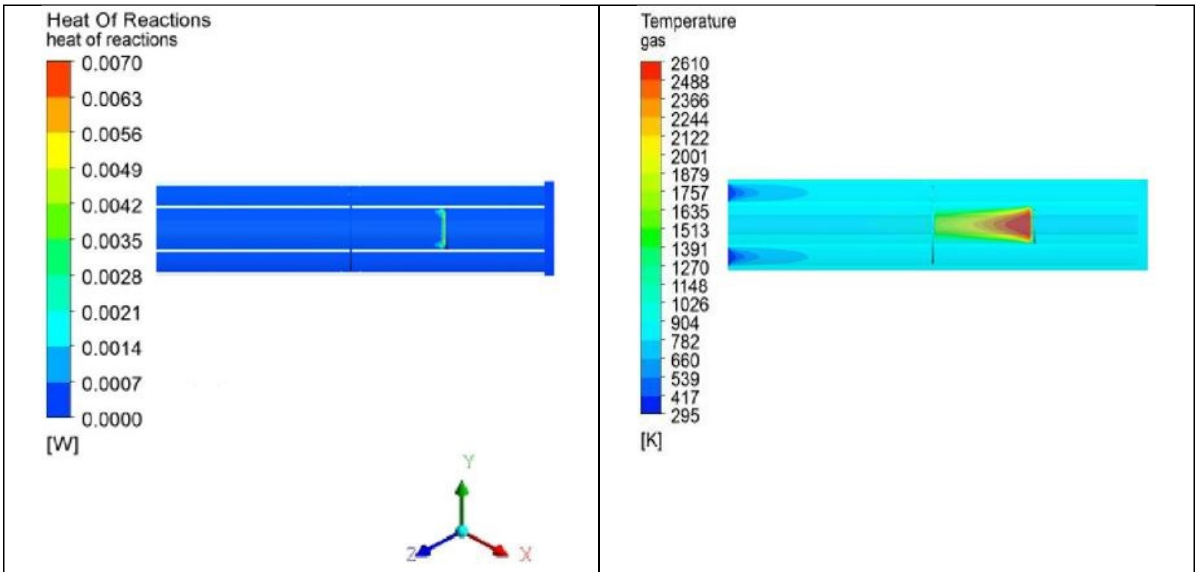


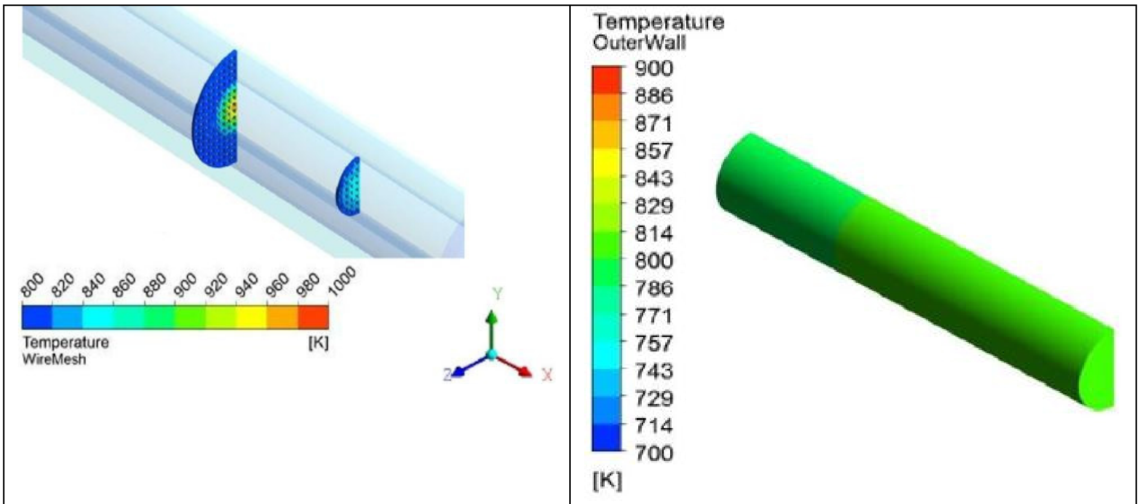
Fig. 4. The location of the patch zone

Next, the mixture of propane and air inside the combustor is ignited. In numerical simulations, this ignition can be done by solving the energy and species equation. A sufficiently high temperature is given to a patch zone where the ignition starts to occur as illustrated in Fig.4. The results of the simulations are shown in Fig. 5 and Fig. 6 respectively.



(a) Heat of reaction indicating the flame position (b) Gas temperature with *U*=0.35 m/s and *ϕ*=1.0

Fig. 5. Flame position and gas temperature



(a) Wire mesh temperature (b) Outer wall temperature

Fig. 6. Wire mesh and combustor outer wall temperature (For *U*=0.35 m/s and *ϕ*=1.0)

Figure 5 indicates that the flame stabilizes near wire mesh A. The flame nearly attaches to the wire mesh. This behavior suggests that the local flow mixture velocity is lower than the flame burning velocity. As a results, the flame is nearly attached to the mesh. The gas temperature is considerably high that is likely due to the use of single step combustion chemistry. Meanwhile, Fig.6 depicts the wire mesh and outer wall temperature. A uniform outer wall temperature of 820 K is obtained for this type of combustor. It desirable for a combustor to have a uniform wall temperature since the material lifespan can be enhanced.

4. Conclusion

Numerical simulations of combustion in meso-scale tube combustor with multiple channel have been successfully demonstrated. The numerical results show that the flame can be stabilized near the stainless steel wire mesh. Apart from that, the proposed design of combustor is one of the solutions to problem of mobility problem of micro power generation system. Liquid hydrocarbon fuels can utilize with minor modification to the combustor. It is important to note that the combustor is at a preliminary design stage. Hence, there are numerous parameters that need to be first established before entering the fabrication stage.

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