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Combustion Characteristic inside Micro Channel Combustor

(Ciri Pembakaran di dalam Pembakar Mikro)

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ABSTRACT

Small-scale electronic devices require long hours' operation and fast charging time. Potential technology to support requirement of small-scale electronic device is micro scale combustor. Unfortunately, micro scale combustion is prone to combustion instability. Therefore, objective of this study is to investigate the combustion characteristics, mechanism that stabilize the flame and combustor performance of the 2-D microchannel combustor with bluff body having various slit percentages gap. Two-dimensional computational domain with the height and length of the channel H = 1 mm and L = 16 mm is used respectively. The height of the bluff body is 0.5 mm and located at 2 mm from the inlet. The slit gap percentage varied in this study is 0% to 70%. The results show that the combustion characteristic such as stable flame, wavy flame, blow-off, and flame split into two parts is significantly influenced by the slit gap percentage. Flame is moving downstream and blow-off at the slit percentage of 10% to 25%. At the slit percentage of 30%, the flame zone moves towards the upstream due to the secondary vortex that exists behind the bluff body as slit gap increases and pushes the flame upstream. The reaction zone is split into two parts at 60% and 70% slit gap percentage. It is due to the incoming fresh mixture of CH4/air mixture flows through the slit and cuts the flame zone. It is also found that by increasing inlet velocity beyond 2.0 m/s, the flame becomes unstable and leads to blow-off as increase in equivalence ratio up to 1.0.

Keywords: Micro combustor; bluff body; slit gap; combustion instability; micro channel

ABSTRAK

Alatan elektronik mudah alih memerlukan penggunaan untuk jangka masa lama dan masa pengecasan yang cepat. Teknologi yang berpotensi untuk memenuhi keperluan alat elektronik ini adalah ruang pembakaran mikro. Malangnya, pembakaran mikro terdedah kepada ketidakstabilan pembakaran. Kajian ini bertujuan untuk mengkaji ruang pembakaran mikro bersama bluff body yang mempunyai belahan. Oleh itu, objektif kajian ini adalah untuk melaksanakan kajian terhadap karakter pembakaran, mekanisma yang menyebabkan api stabil dan keupayaan ruang pembakaran mikro dalam dua dimensi bersama bluff body yang mempunyai belahan di tengah. Ruang pembakaran secara 2 dimensi yang mempunyai ketinggian H = 1 mm dan panjang L = 16 mm telah digunakan. Ketinggian bluff body adalah sebanyak 0.5 mm yang ditempatkan 2 mm dari bahagian masuk ruang pembakaran. Peratusan bukaan bluff body yang digunakan adalah dari 0% sehingga 70%. Keputusan kajian mendapati sifat pembakaran seperti api yang stabil, api yang berombak, api yang tertolak keluar, dan api terpisah kepada dua bahagian adalah hasil dari kesan peratusan bukaan pada bluff body tersebut. Didapati juga bagi bukaan 40%, keberkesanan pemancar adalah yang tertinggi. Selain itu, didapati setelah ditambah peratusan bukaan melebihi 10%, pembakaran akan bergerak kearah belakang ruang pembakaran dan terpadam. Apabila peratusan bukaan ditambah sebanyak 30%, pembakaran akan bergerak ke bahagian hadapan ruang pembakaran disebabkan kehadiran vortex kedua di belakang bluff body yang menarik *pembakaran ke hadapan. Selain itu, pada bahagian tengah pembakaran telah terpecah kepada dua disebabkan kehadiran bahan bakar methane dan udara CH4/air baharu yang telah menembusi pembakaran tersebut dan seterusnya memotong zon pembakaran menjadi dua bahagian. Didapati juga dengan peningkatan kelajuan masuk melebihi 2.0 m/s, api tersebut menjadi tidak stabil dan akhirnya mengakibatkan api terpadam apabila nisbah bahan bakar ditingkatkan sehingga 1.0.*

Kata kunci: Pembakar mikro; bluff body; ruang slit; ketidakstabilan pembakaran; mikro canal

INTRODUCTION

The United States Energy Information Administration (US EIA) had published the latest amendment of its International Energy Outlook 2017 (IEO2017), which is a research for world energy markets and reported that fossil fuel sources are the main usage for energy consumption and have been increased year by year. Fast growing energy source is expected by renewable and nuclear power but the world is still dependent on fossil fuels as its primary principle energy source well into the future. Microelectromechanical System (MEMS) technology required a power source that have high energy density. A good candidate is a micro combustor. The idea of micro combustor started by Epstein & Senturia (1997) due to the rapid development of MEMS and portable devices and also to cater weakness of the batteries. Moreover, unlike batteries suffering from vital drawbacks of long recharging but short operating time, micro combustor-based devices take advantage of instant rechargeability just by replacing the fuel cartridge (Ju & Maruta 2011; Kaisare & Vlachos 2012). In combination with these benefits, other strong points for micro combustor are constant voltage during operation, no memory effect, better chemical stability, and longer lifetime that makes it quite attractive and promising for providing power in various small-scale applications (Chia & Feng 2007). Every new finding comes with the challenges; micro combustion researchers were faced with a huge surface to volume ratio and resulted in higher heat loss to walls of combustor and the flame might quench. Several researches have been conducted to solve the issue related to the micro combustor. Pan. et al. (2017) study on the rectangular channel micro combustor and found that at constant inlet velocity, the centerline heat of outer wall rises with the expanding of the channel height. The reason is that the energy imported to the channel rises with the expansion of channel height at the same time, and more fuel can participate in the reaction, which conducts to a corresponding increase in heat discharge, thus the centerline heat of the outer wall rises gradually. Akhtar et al. (2017) used curved micro combustor tube. The tube was bent according to certain radius of 30o, 45o, 60o, and 75o. The types of fuel used is hydrogen/air mixture where chemical mechanism consists of nine species and 19 reactants. It was found that curved tube micro combustor is more efficient in combustion which is 7.84% better than straight tube micro combustor. An interesting fact about micro combustor geometry was proposed by Zuo et al. (2017) is micro elliptical tube combustor type. There is one circular micro combustor and four different sizes of micro elliptical tube combustors that had been tested. The innovation of micro combustor with cavity was made by Zhang et al. (2017) by making convex cavity structure. The configuration of micro combustor is it has length (L) of 10 mm, wall thickness of 0.2 mm, channel diameter (c) is 1 mm, the length (w) and depth (d) of convex cavity are 1.5 mm and 0.2 mm, respectively. The consequences of normalized cavity length, the normalized cavity diameter, position, and the number of convex cavities in the micro combustor with premixed methane/air combustion were analyzed. They had revealed that by increasing the normalized cavity length, methane conversion ratio may increase up to 89.7% and enhance the extinction limit to 17.1 m/s. Other than that, by increasing normalized cavity diameter, it may improve combustion stability and enhance the extinction limit to 18.9 m/s at $\theta = 0.3$. However, there are several issues related to the micro combustor, which are the stability of the flame internally due to short flow residence time, and high surface-to-volume ratio that contributes to increasing heat losses from the combustor walls (Kang et al. 2017). There are many methods to stabilize the flame inside micro combustor and one of it is by using bluff body inside micro combustor. Yan et al. (2018) had studied combustion characteristics of methane/air in a micro combustor with a regular triangular pyramid bluff body and found that blow-off limit was extended 2.4 times more than micro combustor without bluff body. In addition, by increasing blockage ratio of the bluff body, the temperature behind bluff body increased. Liu et al. (2014) had investigated the blowout in slit bluff-body stabilized flames for macro scale and found out that blowout limit can be improved by optimal slit ratio. The idea of bluff body with a slit was proposed by few researchers including Tong et al. (2017) studied about the effects of central air jet on bluff body stabilized premixed methane-air flame. They designed a conical bluff body with air injector in the middle of the bluff body. The results are as follow; the air injector effects are it releases heat load that may be helpful for the problem of high heat load in real application but the negative side is the air injector makes the flame unstable compared to without air injector in the middle of bluff body. Slit gap was also studied in tubular reactor in microchannel by Wu & Li (2016). The configuration of micro combustor consists of two platinum tubes with 1 mm gap each. The tubes were placed coaxially in a quartz tube where the gap location is 5.5 mm from the tube inlet. The reactant used was hydrogen/air and inlet temperature is 300 K with constant ambient temperature of 101 kPa. They had found that the gap had induced flame stabilization in microchannel by reducing the velocity of reactants, heat source and providing ideal number of chemical radicals such as H, O, and OH. From previous studies of micro combustor, it was identified that no study was found for a trapezoidal bluff body with a slit in the middle inside microchannel combustor. Thus, the opportunity was taken to study the combustion characteristic of CH4/air in a 2-D micro combustor with the bluff body having varies slit size to elucidate the mechanisms that stabilize the flame inside the microchannel combustor.

METHODOLOGY

Figure 1 shows the computational domain of the coordinate system simultaneously with boundary conditions.

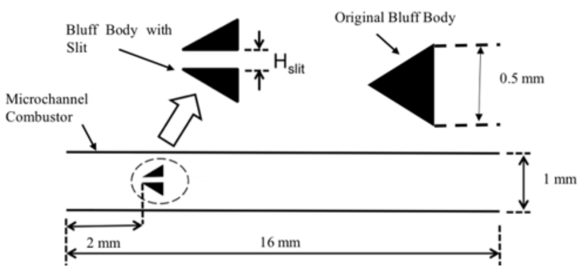

FIGURE 1. Computational domain

The height and length of the channel are H = 1 mm and L = 16 mm. It was designed based on experimental and numerical investigation on micro combustor with a bluff-body carried out by Wan et al. (2012). Although the quenching distance of methane is from 2.0 – 2.5 mm, the geometry of micro combustor has length of 16 mm and thus the flame will exist at the direction of length instead of height. The bluff body height is Hbluff = 0.5 mm height and located at x = 2 mm from the inlet. Slit gap percentages of 0% to 70% have been selected in this study. Percentage of the slit gap is defined by the ratio between the height of slit, Hslit and height of the bluff body, Hbluff. Kinetic theory was used to estimate transport properties. For instance, the heat conductivity and viscosity for particular species and ideal gas mixing law is used to calculate the mixture of the transport properties. Besides that, an ideal gas assumption was also utilized and piece-wise-polynomial approximation was used to calculate the specific heat. The analysis was performed in a steady case two-dimensional configuration. CH4/air mixture is issued from the inlet at temperature 300 K. The outlet of the combustor is assumed to be a fully developed flow. In the present study, air is assumed to be a mixture of O2 and N2 with 21 mol% and 79 mol%, respectively. By default, the CH4/air combustion elements are very complicated which involve hundreds of interaction particles among gas species and thus required long computation time. In this case, only one-step reaction mechanism of CH4/air was used because it is good enough to analyze the flame dynamics according to Westbrook & Dryer (1981) and therefore detailed chemical reaction is not required. The model was simulated as methane single-step oxidation with oxygen where the products are water vapor and carbon dioxide. The equivalence equation is in (1):

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \tag{1}$$

The reaction rate used is the global one-step methane oxidation reaction rate or the Arrhenius type reaction rate model introduced by Westbrook & Dryer (1981). The Arrhenius type reaction rate model equation is as below:

$$r_{CH4} = 1.3 \times 10^8 exp(-2.027 \times 10^8/RT) \times [CH_4]^{0.2}[O_2]^{1.3} \tag{2}$$

A uniform size of a grid with a size of 1×10^{-5} m × 1×10^{-5} m was used. Note that grid test was not carried out due to the fine grid size is smaller than flame thickness (1 mm). Therefore, it is enough to analyze the combustion. A laminar steady state model was used following the suggestion from Kuo & Ronney (2007) by reason that it could be much more applicable to observe the features of flow and combustion when the Reynolds number, Re < 500. Moreover, several researchers who investigated micro combustor also utilized laminar flow model (Zhang et al. 2018; Liou et al. 2018; Niu et al. 2016; Wan et al. 2015; Baigmohammadi et al. 2013). Quartz was used as a material for both the bluff body and channel. The discrete ordinates (DO) radiation model was used for the surface-to-surface radiation between the inner surfaces of the microchannel. A non-slip and impermeable wall surfaces boundary condition is applied to the combustor walls. Both natural convection and thermal radiation heat transfer have been assigned at the outer surface of the combustor walls. The solid surface emissivity and heat transfer coefficient of 0.65 and 17 W/(m^2·K) were used respectively (Su et al. 2015). Initially, an isothermal flow was solved. Artificial ignition was set at the ignition zone for higher auto-ignition temperature of methane (873K) (Robinson & Smith 1984), which is 2500 K. After the reaction started and the flame existed, the artificial ignition temperature was turned off. The convergence criterion was set for energy residual less than 10-6. The simulations were conducted on Intel(R) Core(TM) i5-7200U processor with 12.0 GB RAM. Blockage ratio is one of the elements to analyze the behavior of flame that passes through any bluff body. The blockage ratio is defined as the bluff body height, Hbluff, which is divided by the height of slit, Hslit (Niu et al. 2016). Therefore, the equation will be:

$$\zeta = \frac{H_{bluff}}{H_{slit}} \tag{3}$$

where
ζ is the blockage ratio
H_{bluff} is the bluff body height (mm)
H_{slit} is the height of slit (mm)

RESULTS AND DISCUSSIONS

Figure 2 shows the difference of heat of reaction between inlet velocity of 1 m/s and 2 m/s for equivalence ratio 0.8. Justification of this sample were taken because at equivalence ratio 0.8 and inlet velocity 2 m/s, overall highest combustor efficiency was attained for slit percentage of 40% and to compare the effect of inlet velocity, the same equivalence ratio with lower inlet velocity was taken. In large velocities for example 4.5 m/s and 5 m/s, the flame front is no longer able to be extended due to the low heat recirculation at vicinity of the bluff body and as a result, the flame blew off. Figure 3 obviously illustrates that the different flame front for heat of reaction contour of different inlet velocity. For inlet velocity 1 m/s, the preheating zone is smaller than inlet velocity 2 m/s.

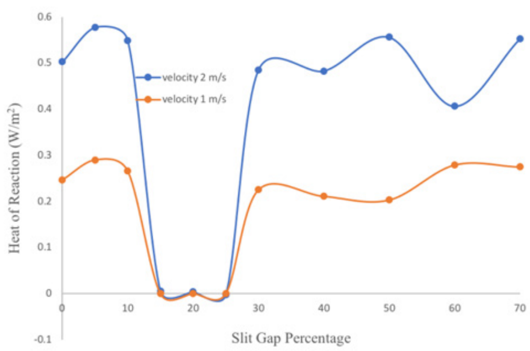

FIGURE 2. Heat reaction at various slit gap

This is because of the bluff body with slit gap effect and higher velocity produced stronger secondary vortex which assist the combustion by retracting the preheating region to the upstream and thus the incoming fresh reactants is able to preheat and burn. This result is similar with Ansari & Amani (2018) who found that baffle can move the flame front towards upstream to enhance the burning mixture time inside the combustor. It also can improve the efficiency of micro-combustor.

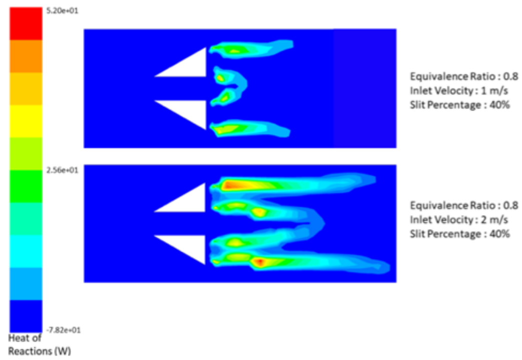

FIGURE 3. Contour heat of reaction at inlet velocity 1 m/s and 2 m/s

Referring to Figure 4, it is seen that for 15% slit gap where velocity contour indicates the local flow speed at around 2.65 m/s which exceeded the flame velocity at around 0.35 m/s. When local flow speed is too high and cannot match with flame speed, it will push the flame downstream and result of blow-off. The local flow speed at three narrow path between bluff body prevent the formation of recirculation zone and thus blow-off happens. The highest local flow velocity is at slit gap 25%, as seen in Figure 4.

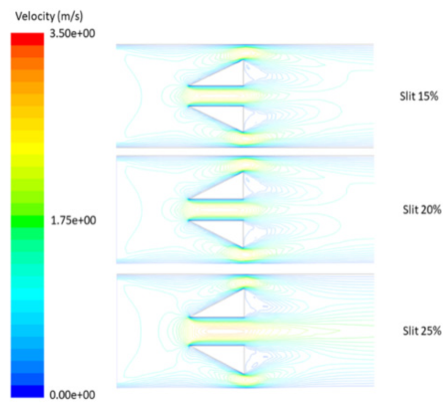

FIGURE 4. Velocity contour at slit gap 15%, 20% and 25%

Thus, the blow-off phenomenon is definitely characterized by large-scale disruptions with vortices transporting recirculation zones away from the flames. This result is similar with Briones & Sekar (2012) who studied the effect of Von Kármán vortex shedding on regular and open-slit V-gutter stabilized turbulent premixed flames. At the equivalence ratio 1.0, it was seen that for 50%, 60% and 70% slit gap, velocity flow field fluctuate and the recirculation zones began to shrink (Figure 5).

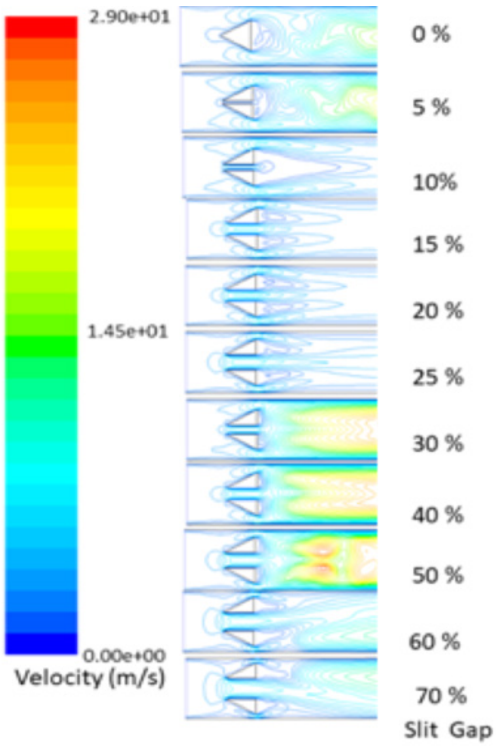

FIGURE 5. Velocity contour at various slit gap

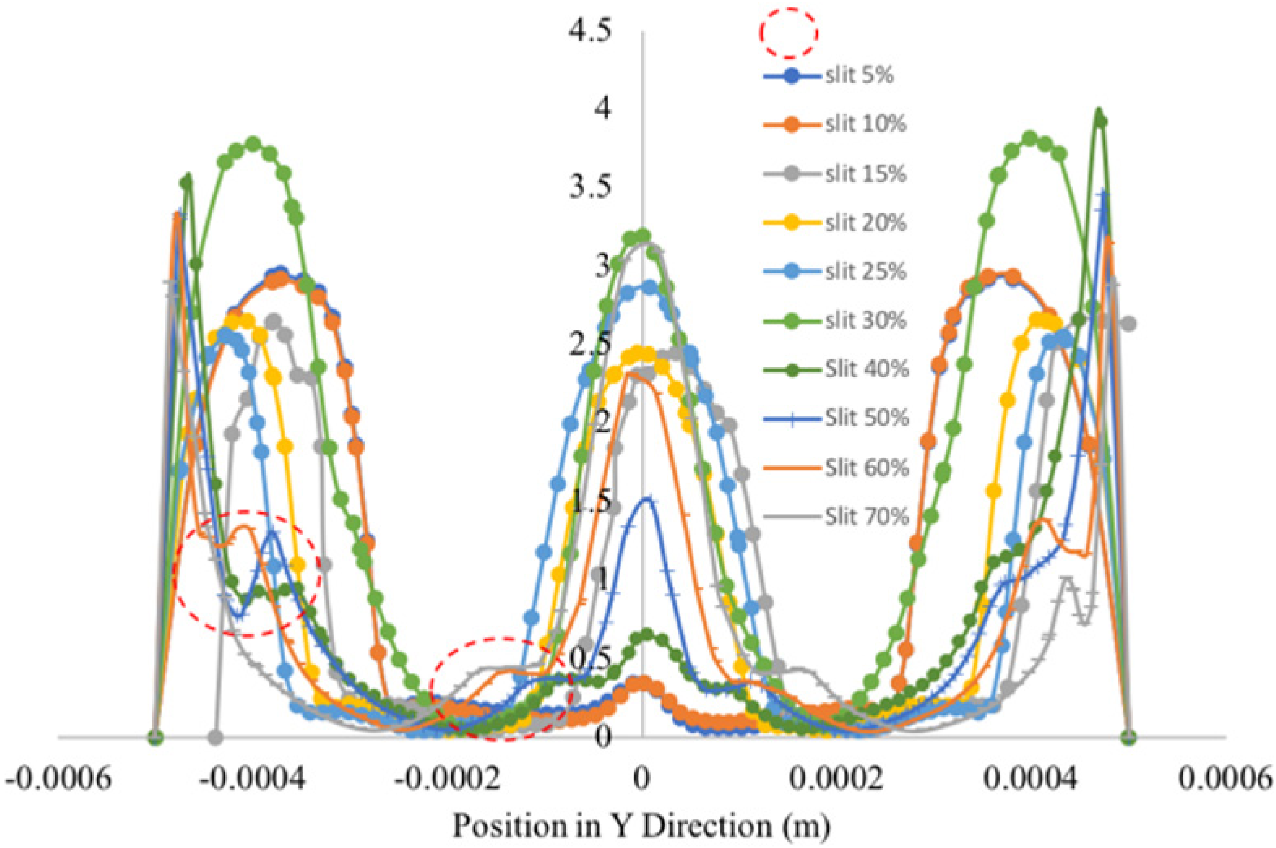

FIGURE 6. Velocity magnitude in y-direction

This was due to the huge slit gap that allowed more incoming fresh reactants in high equivalence ratio to pass through and push the recirculation zone downstream. This result is similar with Briones & Sekar (2012), where by increasing equivalence ratio, turbulence fluctuations increase. In addition, this result also agrees with Briones & Sekar (2012), who found that for bluff body with open slit gap in the middle, turbulence pulsation gets higher at locations where huge interruptions are present and getting lower at places that the combustion is occurring. These findings are also similar with Lieuwen & Shanbhogue (2007) who found that sustainability of flames will exist as long as hot products have recirculation, which act as a "torch" to sustain the combustion at the anchoring point. In a number of situations, the recirculation zone is too powerful, which makes the reactants to pull back before passing through the flame. When the vortex is shed, it makes up a passage for reactants on one location to drill to the other side. As combustion locally extinguishes, it will form a passage for cold reactants to attack straight to the stabilization point of the combustion branch on the opposite location, which makes another point for cold reactants to enter and then dilute the temperature. As a result, it erases the "torch" that ignites the incoming fuel/air mixture and starts to move downstream where blow-off happens. On the other hand, the vortex produced is related to flame speed. A flame absolute speed is able to remain constant through the flame front, where the flame is not being thickened or thinned by the flow. In this case, the effect of bluff body and the slit gap had thinned the flame and made the speed higher at empty narrow path at the bluff body. This situational condition is illustrated in Figure 6. Figure 6 shows the graph of velocity magnitude at a certain position in y-direction, which is very near of trailing edge of bluff body for equivalence ratio 0.8 and inlet velocity or flame absolute speed of 1.0 m/s. In Figure 6, it is shown that at location -0.0005 m until -0.000264 m, -0.000125 m until 0.000126 m, and 0.000264 m until 0.0005 m, the velocity is high except for slit gap 5%, 10%, 40%, and 50%. The high-speed region is at empty narrow path of bluff body. This is because as the volume of space shrink, the reactants particles are compressed and moved rapidly until they collide with each other. According to Poinsot & Veynante (2005), the flame speed changes due to flow speed up through the flame front and is dependent on the position of the measurement. In this case, as the flow speeds up, but in a different direction, which is to the inner wall of combustor and bluff body edge and those walls reflect the speed to other directions. As this situation keeps on repeating, vortices are produced at aft of bluff body and preventing the reactants to continue burning. As a result, the flame blows off. The direction of displacement speed is dependent of how strong the vortex is being produced as stated by Im & Chen (2001), where when the vortex strength is weak, flame displacement speed becomes positive and penetrates into the channel between the vortices. However, a negative displacement speed is from the intense compressive strain field induced by the vortex pair and quench the flame leading edge for stronger vortex cases, such as at 25% slit gap. Interestingly, although 30% slit gap and beyond, the reactants speed are still high for example for 30%, 60%, and 70% slit gap at narrow path near to the bluff body but due to existence of secondary vortices evidently by vortex signature in Figure 6, the recirculation zone can be pulled back at vicinity of the bluff body trailing edge and thus flame can be anchored. For the case of 5%, 10%, 40%, and 50% slit gap, the vortex had decreased the local reactants speed to be matched with flame speed as to allow the burning of incoming fuel/air mixture. This is agreeing with Turns (2012) who stated that the existence of a strong recirculation zone of hot products ignites the unburned gases and provides a region where the local flames speed can match the local flow velocity.

CONCLUSION

Combustion characteristics are influenced by slit gap percentage, inlet velocity, and equivalence ratio. With the expansion of inlet speed, the range of recirculation zone is expanding. Unfortunately, with the increment of slit gap from 10% until 25%, the flow fields move downstream and then blow-off. Interestingly, as the slit percentage increases to 30%, the flow field returns and attaches to the bluff body. Mechanism that stabilize the flame are strong recirculation zone, local flame speed matching with local reactants velocity and assistance of vortex to slow down reactant speed or to pull the recirculation zone upstream.

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DECLARATION OF COMPETING INTEREST

None

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