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DEVELOPMENT OF PLANAR MESO-SCALE COMBUSTOR WITH DOUBLE NARROW SLIT FLAME HOLDER AND VARIOUS ASPECT RATIOS FOR MICROPOWER GENERATOR

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Досліджено вплив співвідношення сторін прямокутної мезомасштабної камери згоряння з вузькощільовим стабілізатором полум'я на межу стійкості полум'я, поведінку полум'я і рівномірність температури стінок камери згоряння. Камера згоряння виготовлена з міді з площею поперечного перерізу 6 мм2. Співвідношення сторін камери згоряння (AR) варіювалося в межах 1, 1,5, 2,67 і 6. ЗВГ і чистий кисень попередньо змішувалися, і експеримент проводився при обмеженій швидкості потоку. В якості окислювача обраний чистий кисень з метою детально показати діапазон стійкості полум'я в межах дуже вузької відстані загасання. Все спостережуване полум'я знаходилося всередині камери згоряння, а не зовні каналу. В даному дослідженні використовувався стабілізатор полум'я нового типу, а саме подвійний вузькощільовий стабілізатор полум'я. Стабілізатор полум'я з подвійною щілиною і свого роду погано обтічним тілом в центрі допомагає рециркулювати потік і продовжити час перебування, щоб зробити полум'я більш стабільним. Використання подвійного вузькощільового стабілізатора полум'я успішно розширило карту стійкості до дуже низького коефіцієнту надлишку повітря (ϕ)*. Однак через дуже високу швидкість поширення полум'я була присутня мертва зона близько до стехіометричного стану. Співвідношення сторін зіграло важливу роль для круглої камери згоряння. Співвідношення сторін дало великий ефект у визначенні межі карти стійкості, який може бути досягнутий при збагаченій суміші. Камера згоряння з AR=1.5 мала найширший діапазон межі займистості, в той час як AR=6 мала найвужчі межі стійкості полум'я. Однак в останній досягнута найбільш рівномірна температура стінок, що має велике значення для високоефективного перетворення теплової енергії в електричну. Результати даного дослідження можуть бути використані при визначенні підходящої паливної суміші для мезомасштабної камери згоряння в якості джерела тепла малопотужного генератора/теплової електричної системи*

Ключові слова: межа стійкості полум'я, температура стінок, співвідношення сторін, подвійний вузькощільовий стабілізатор полум'я, плоска мезомасштабна камера згоряння

1. Introduction

A remarkable development in portable electronic equipment is currently encouraging research on energy provision. The power source widely used for portable electronic equipment at the moment is the battery. Pb-acid batteries or even Li-ion batteries have a lower energy density than the energy of the combustion reaction of hydrocarbon fuel, especially when compared to nuclear energy [1]. The high energy density of hydrocarbon fuels creates a great opportunity to develop combustion based micro-power generation systems to meet increasing demands for portable power devices [2]. Utilization of direct combustion power through a micro power generator (MPG) or thermo-electric system (TES) has been extensively investigated. The main component of the MPG/TES is combustor as a heat generator and thermophotovoltaic (TPV) or thermoelectric (TE) as an energy converter module. The heat generator for MPG/TES is microscale or mesoscale combustors.

The high energy density in the MPEG/TES is produced from the high heat generation on combustor and high efficiency of thermal to electric energy converter. High heat generation on combustor could only be achieved if the flame is able to be stabilized and has a uniform combustor wall temperature. Flame stability in the micro or mesoscale combustor is strongly influenced by heat loss. The ratio of the heat loss to the heat generation is inversely proportional to the combustor characteristic length. The smaller the size of the combustor, the greater the heat loss from the flame zone, which leads to thermal quenching.

Therefore, studies are devoted to reaching wider flame stability limit using double narrow slit flame holder and reaching uniformity of combustor wall temperature that meets the requirements of a micro power generation or thermo-electric system by varying aspect ratio of the planar mesoscale combustor. This paper will provide a better understanding of heat accumulation and heat loss in the combustor wall which determines flame stabilization and temperature distribution on the combustor wall.

2. Literature review and problem statement

The high conversion efficiency of thermal energy into electricity of a micro power generation or thermo-electric system is reached when the combustor wall temperature is high and uniform. This can be reached by controlling the heat transfer from the flame to the combustor wall as much as possible and heat loss together with the products of combustion as little as possible. The heat transfer can be controlled either by changing the shape and size of the combustor, which will also affect the flame stability. In addition to the high and uniform wall temperature, the position of the surface of the combustor in a PV/TE cell has a great influence in improving the efficiency of the system. The study of combustor geometry concluded that compared with the cylinder combustor, rectangular combustor offers radiation flux perpendicular to the PV cell that will increase the electricity generated and system efficiency [3]. It has been investigated that formation of the planar flames in mesoscale channels and flame stabilized with the preheated mixture at high temperature is quite promising [4].

Researches to improve flame stability by reducing heat loss at the micro or mesoscale combustor have been carried out using electric heating [5]. Another method used to reduce heat loss is by generating heat recirculation in the combustor such as on swiss roll combustor [6]. The flame holder is also used to improve flame stability. There are several studies related to efforts to stabilize flame using flame holders, such as research using porous media, wire mesh backward facing steps or wall cavity. It has been observed that porous media combustion of premixed H_2-air in a planar micro-combustor indicate that the wall temperature increases with increasing mixture rate, and higher emitter efficiency was achieved for mixtures with $\phi \approx 0.8$ [7]. It is also pointed out that a micro-diffusion flame of n-heptane with the porous media in the tube, the flame could be stabilized close to the porous media and it effectively increase flame stability at low Reynolds number and hence more radiation heat is transferred through the outer tube at high Reynold number [8]. Another research used porous media and swirling combustor with a heat-regeneration reverse tube indicate that could improve the intensity and uniformity of the combustion chamber (emitter) illumination and could increase the surface temperature of the chamber wall [9].

Another type of flame holder is wire mesh [10, 11]. The mesh enhances heat transfer from the heated wall to the unburned gas and the flame can be stabilized near the mesh. Therefore, the mesh can act as a combustion inhibitor or an enhancer. Flame holder using backward facing step used a methane-oxygen mixture in non-adiabatic cylindrical and it concluded that adding carbon dioxide could extend RERI (Repetitive Extinction and Re-Ignition) flame regimes in the mesoscale reactors that could lead to more uniform temperature distribution on the outer surface of the lengthy mesoscale reactors as compared to the stationary flame regimes [12]. In a numerical study carried out in [13], it is concluded that the presence of backward facing step leads to an increase in the blowout limit and mean wall temperature. The combustor with lower step height had higher (mean) wall temperature. Research on the wall cavity for flame stabilizers in [14] showed that the behaviors of premixed CH_4/air flame in mesoscale channels with and without cavities were experimentally investigated. No stable symmetric flame was observed in the channel without cavities and flame is prone to inclining and pulsating. In contrast, the flame can be effectively anchored in the presence of cavities.

Studies that examined the flame stability limits and wall temperatures have been examined, but the observed area still tends to be in the area of large equivalence ratio. The flame phenomenon of the circular mesoscale combustor (d=4 mm) has been studied using a methane-oxygen mixture [15]. The study produced a map of flame stability limits and divided into 5 flame modes. The stable region inside the combustor is small in both the quartz and stainless in the Re above 50 and the $\phi>2$.

It has been revealed from previous studies [15] that the use of pure oxygen produces a very high flame propagation speed, consequently the flame stability limit shifts to a rich mixture, this is due to the fact that the flame had a flashback at a low equivalent ratio. Improvement effort has been made to delay the occurrence of flashback by using a double narrow slit flame holder [16] which results showed that the flame stability limit can extend to the low equivalent ratio (lean mixture). However, the experiment was only carried out on the combustor with a single aspect ratio. In this study, experiments were carried out on various aspect ratios to obtain the best performance of the mesoscale combustor in combustion with pure oxygen. This is important because the aspect ratio determines the balance between heat accumulation and heat loss on the combustor wall for the application of micro power generators that establish the flame stability and temperature distribution of the combustor wall. There must be a compromise between heat loss and flame stability, aspect ratios that will take part in compromising these two things. The results to be achieved get a combustion chamber that has a stable flame and a more uniform wall temperature. Thus, development of planar mesoscale combustor which has a stable flame and uniform wall temperature is a promising aspect of the implementation of micro power generator.

3. The aim and objectives of the study

The aim of the present study is to investigate how the narrow slit flame holder and aspect ratio influence the flame stability and uniformity of the combustor wall temperature.

To achieve the set aim, the following objectives have been accomplished:

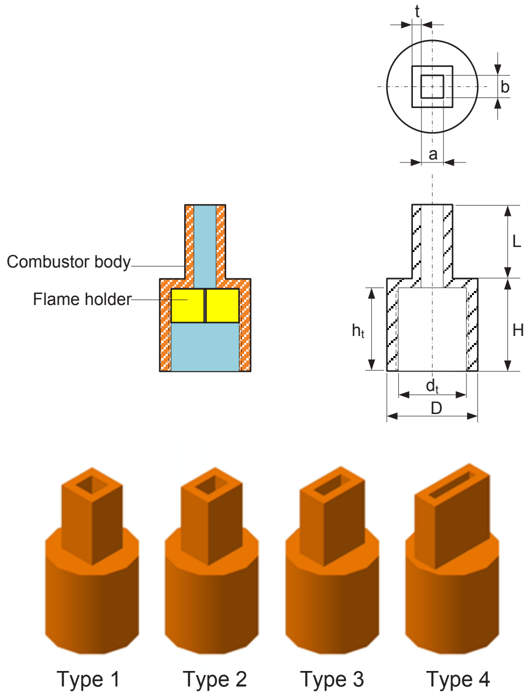
– study on the flame stability limit at various equivalence ratios and reactant flows on planar mesoscale combustor;

– study on the influence of the front flame shape and colors on combustor axis temperature;

– study on the influence of aspect ratio on the combustor wall temperature, uniformity, and illumination.

4. Materials and methods of research

The premixed combustion characteristics of liquefied petroleum gas (LPG) with pure oxygen were observed in the planar type combustor with different aspect ratios (Fig. 1). The combustor was made from copper, consisted of a combustor body and flame holder. Combustor geometry specification is shown in Table 1. Flame holder shape was a cylinder with double narrow slits sized 8×4×0.2 mm as shown in Fig. 2. The channel length and combustor thickness effects have been eliminated by making it the same for each combustor.



Type 1 Type 2 Type 3 Type 4

Fig. 1. Combustor geometry and dimensions

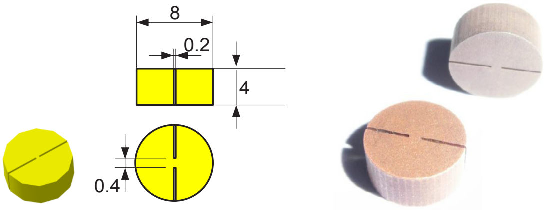


Fig. 2. Double narrow slit flame holder geometry and dimensions

Aspect ratio is the ratio of length to the width of the combustor cross section. The area of the cross-section was fixed, while the aspect ratio was varied. Fuel was premixed with pure oxygen to perform stabilized flame in the very narrow quenching distance so that various kinds of stability in the mesoscale combustor could be observed. Experimental setup for this study is shown in Fig. 3. Each flow rate of the fuel and the oxidizer was measured by Kofloc flow meter with a measurement range of 2–20 mL/min for fuel and of 50–500 mL/min for oxygen. The fuel and oxidizer were mixed in the mixer before being burned in the combustor. The composition of LPG used in this study is shown in Table 2, while the purity level of oxygen was 99.99 %. Premixed combustion was performed in the combustor positioned horizontally.

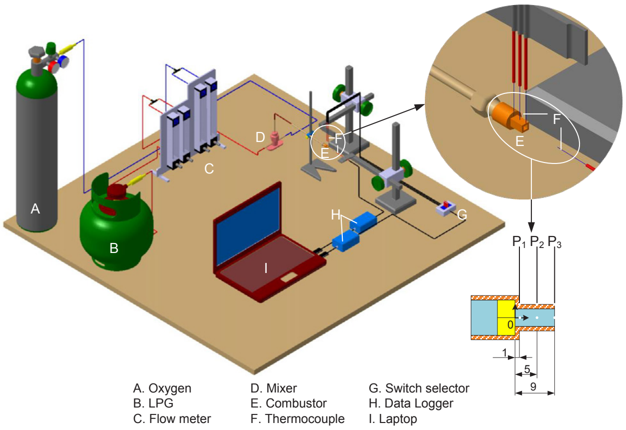


Fig. 3. Experimental setup and temperature measurement points

Table 2

LPG composition

Composition	% Volume
Propane	48.86
N-butane	31.64
Iso-butane	18.91
Ethane	0.42
Neo-pentane	0.10
Iso-pentane	0.07

The temperature measurement was performed in the wall and combustor axis. The combustor axis temperature was measured by using R (Pt-13%Rh/Pt) type thermocouples while the combustor wall temperature was measured by K (Nickel-Chromium) type thermocouple. A thermocouple was connected to the NI USB-TC01 data logger for data acquisition. Temperatures were measured at a distance of P_1=1 mm, P_2=5 mm, and P_3=9 mm from the entrance as shown in Fig 2. The origin of the axis was at the surface of the flame holder. Retrieving temperature data is conducted after getting a flame stability map. Temperature measurement was carried out on the reactant flow rate U=50, 75, and 100 cm/s at equivalence ratio ϕ=0.3, 0.8, 1, and 1.2. Measurements in the combustor axis are done to measure the flame temperature and its influence of flammability limit. Wall temperature measurements were used to compare the uniformity of the combustor wall temperature.

Table 1

Combustor geometry specifications

Combustor Type	a (mm)	b (mm)	t (mm)	L (mm)	H (mm)	h_t (mm)	D (mm)	d_t (mm)	D_h (mm)	A_c (mm^2)	Vol (mm^3)	A_R
1	2.45	2.45	1	8	10	9	10	8	2.45	6	48	1
2	2	3	1	8	10	9	10	8	2.4	6	48	1.5
3	1.5	4	1	8	10	9	10	8	2.18	6	48	2.67
4	1	6	1	8	10	9	10	8	1.71	6	48	6

Besides flow rate and temperature data, visual data were also recorded, which includes front flame visualization and combustor walls visualization. The flame and combustor wall visualizations used Canon EOS 60 D camera. Flammability limit map was obtained by keeping constant the oxygen mass flow rate while varying the fuel mass flow rate and vice versa. To maintain the existence of the flame in the combustor, measurements were taken in a high flow rate area at a low equivalence ratio and low flow rate at high equivalence ratio. The number of data recorded to each combustor was over 3,000 points. The data points that were inside the stability area were removed, leaving the outermost point as the boundary of each region. The flame is considered to be stable when it is able to establish on the flame holder in the same state for 10 minutes. Temperature data were recorded when they were reached steady.

5. The result of an investigation of the role of aspect ratio on flame stability and wall temperature uniformity

5. 1. Effect of aspect ratio on flame stability limit

The flame stability limits for combustion of LPG-oxygen in the planar mesoscale combustor with different aspect ratio are shown in Fig. 4–7. Flame stabilization modes were classified based on the observation. There are six flame stability regions inside the boundary; i. e. region of stable without noise, stable with noise, transition zone, the dead zone, the pseudo-stable and blow off limit. The dashed line is the measurement limit due to limitation of the experiment apparatus that can't measure very high flow rate; however, the data of stability limit in the applicable range had been obtained. Stable without noise is the region where the flame can be maintained and was stable in one position for more than 10 minutes without any sounds. Stable with noise is the region where the flame can be maintained for more than 10 minutes with sounds. The transition is the region where the flame can be maintained for more than 10 minutes which was sometimes without and with noise. The dead zone is the region within the flammability limit area in which flame could not be stabilized. The flame tends to flash back then quenching (extinct), sometimes with an explosion. Pseudo Stable is the region where the flame can be maintained for more than 3 minutes but in the additional time will extinct. Blow off limit is the limit where if the equivalence ratio is shifted to the left of the line, the flame will blow off.

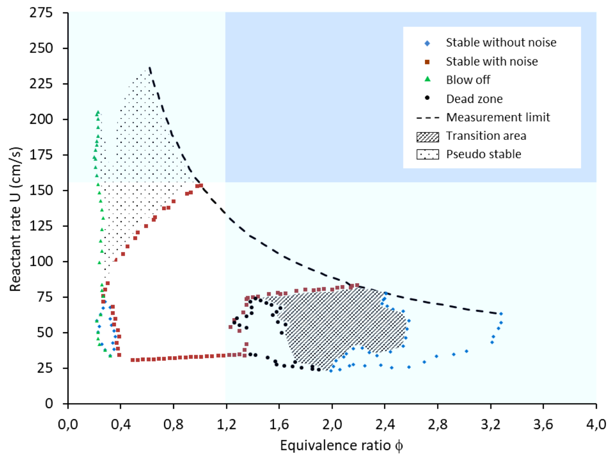


Fig. 4. Flame stability limits for combustor with A_R=1

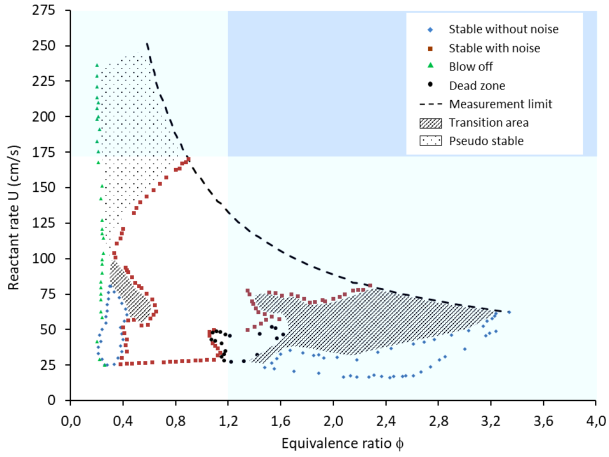


Fig. 5. Flame stability limits for combustor with A_R=1.5

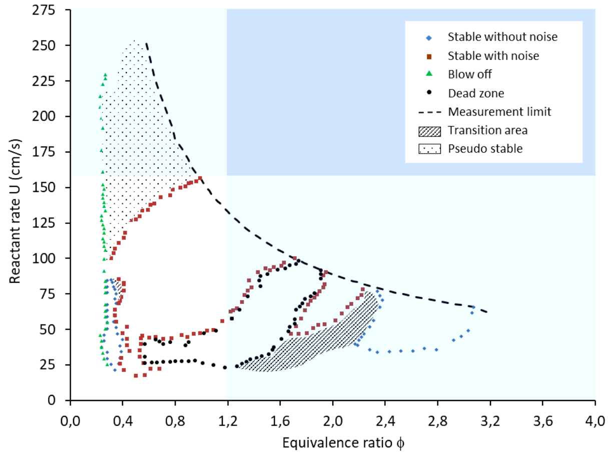


Fig. 6. Flame stability limits for combustor with A_R=2.67

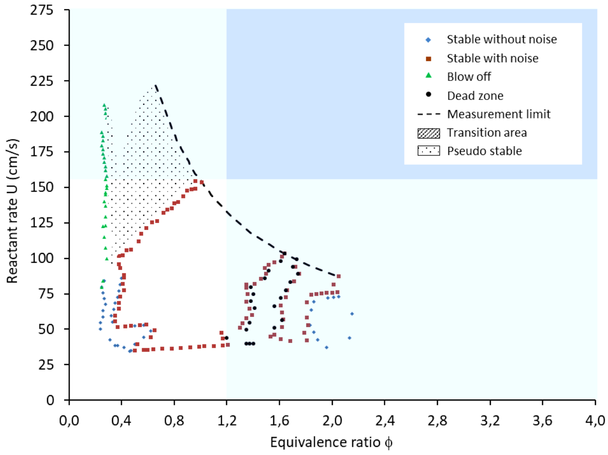


Fig. 7. Flame stability limits for combustor with A_R=6

Stable without noise region occurs at a low flow rate and very lean or very rich mixtures. At the very low equivalence ratio, combustor with A_R=1 has the smallest area. The increase in aspect ratio results in downsizing of the hydraulic diameter so that heat losses rise. The increase in reactant rate still produced a low temperature to compensate for a large heat absorbed by the wall. Instead of a very rich mixture, the increase of the aspect ratio causes maximum reactant rate decrease. After passing through stoichiometric, the increase of equivalence ratio produces lower temperatures.

This is due to heat generation absorbed by unburned fuel. More rise of aspect ratio, the heat loss due to absorbed wall grew. Both of these things which cause the maximum reactant rate decrease and maximum equivalence ratio is shifted to the left (decrease).

The second region is stable with noise. This region is located in the middle between the stable without the noise region. The noise is caused by flame oscillation [17]. Stable with noise region occurs over a range of equivalence ratios which produces high temperatures. At high temperatures, the flame speed is high and tends to move towards the flame holder in the upstream region. As the flame reaches the flame holder it is quenched by the holder and the combustion reaction rates drop so that the flame is converted to the downstream. At the downstream, heat loss decreases so that the flame speed is recovered and moves again to the upstream and so on the flame oscillates creating noise. The flame is actually unstable, but it can be maintained forever. The widest stable with noise region is obtained in the combustor with A_R=1.5. Noise intensity is very high on the stoichiometric and decreases in the rich and lean mixture.

The third region is the transition zone. The transition zone is located between the stable limit without and with noise. The transition zone is the region where possible stable both with and without noise. Except for combustor with A_R=6, combustors with A_R=1, A_R=1.5, and A_R=2.67 have a transition zone. The transition zone is not found in A_R=6. It is interesting to look carefully at the transition region in the lean mixture. At A_R=1.5 and A_R=2.67 there is a transition zone in a lean mixture. Transition zone in the lean mixture is present in high reactant velocities due to a more reactant to be burned to produce higher temperatures. In a combustor with A_R=6, although stable zones without noise can reach a high flow rate transition zone does not occur. The product temperature is not high enough to trigger the transition zone due to the heat loss to the walls.

The fourth region is the dead zone. In this region, the flame had a flashback then extinguished. Dead zone occurs in regions with a high temperature in combustor axis where the speed of combustion reaction becomes very high. Dead zone also occurs at a low flow rate of reactants. Dead zone with the smallest area occurs at the combustor with A_R=1.5. Combustor with A_R=2.67 has the largest dead zone area and lower average wall temperature. Wall temperature will be discussed in the next sub-chapter.

The fifth region is the pseudo-stable which is characterized like stable with noise region, and it is unable to sustain a flame for 10 minutes. During the time, the wall temperature starts to increase from the ignition and after reaching a peak temperature is not constant but declining and the flame eventually extinguished. It is not found in another region where the wall temperature is steady at the time. For that reason, this area is called pseudo-stable. Wall temperature increase is an indicator of the increasing temperature inside the combustor. The smallest pseudo stable region takes place at AR=6 and the largest does at A_R=1.5.

The last is the line of blow off. On the right side of the line of the blow off, the flame can exist inside the combustor, whereas at the start blow off to the left, the flame will be blown and extinguished. Blow off slightly shifted to the higher equivalence ratio with increasing aspect ratio. A lower aspect ratio was able to maintain a flame on a small equivalence ratio because it had a smaller heat loss.

5. 2. Effect of the flame front colors and shape on combustor axis temperature

Fig. 8 shows a visualization of the flame front in the mesoscale combustor at the reactant rate of U=100 cm/s. The greater equivalence ratio makes the brighter flame. The greater equivalence ratio means the more fuel is burned. It makes the flame temperature rise. An increase in temperature is what causes the colors of the flame look even brighter. The greater equivalence ratio also makes the flame shape wider. The shape of a flame holder in the form of a narrow slit which has two sides greatly influences the flame shape. Except in the combustor with A_R=1.5 and ϕ=0.8–1.2, the flame separates on each slit flame holder. It is separated by a clear boundary. In the combustor with A_R=1.5, there is no visible flame separation. The flame holder with a double slit is most suited to the combustor with A_R=1.5. Solid flame is able to reach a high heat generation with minimal losses. It is proved that combustor with A_R=1.5 has higher inlet temperatures at all equivalence ratios and wider flammability limit.

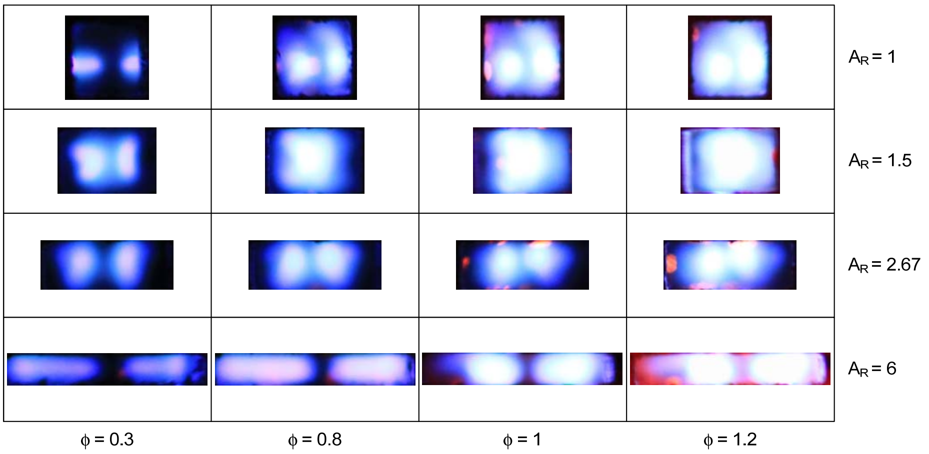


Fig. 8. Flame front at U=100 cm/s

Fig. 9 shows the temperature distribution along the combustor axis at various equivalence ratios and reactant rates of U=100 cm/s. Combustor with A_R=1.5 has a relatively uniform temperature over a range of equivalence ratios ϕ=0.3–1.2 and reached the highest temperature of 1,790 ^{o}C at ϕ=1.2. The distance of narrow slit flame holder with the combustor walls most ideal seems to be achieved by the aspect ratio of 1.5. Combustor with A_R=1.5 generates great heat with minimal losses. This combustor has the highest combustor axis temperature and widest flammability limit.

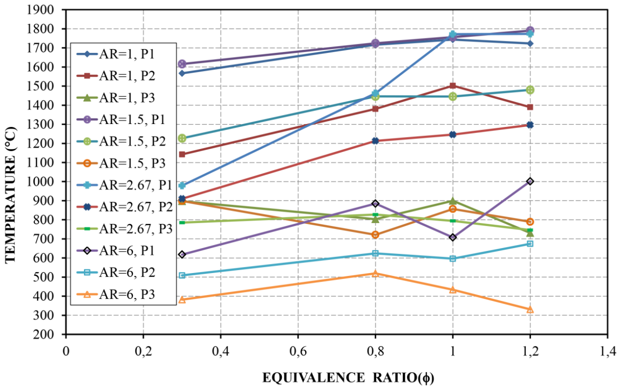


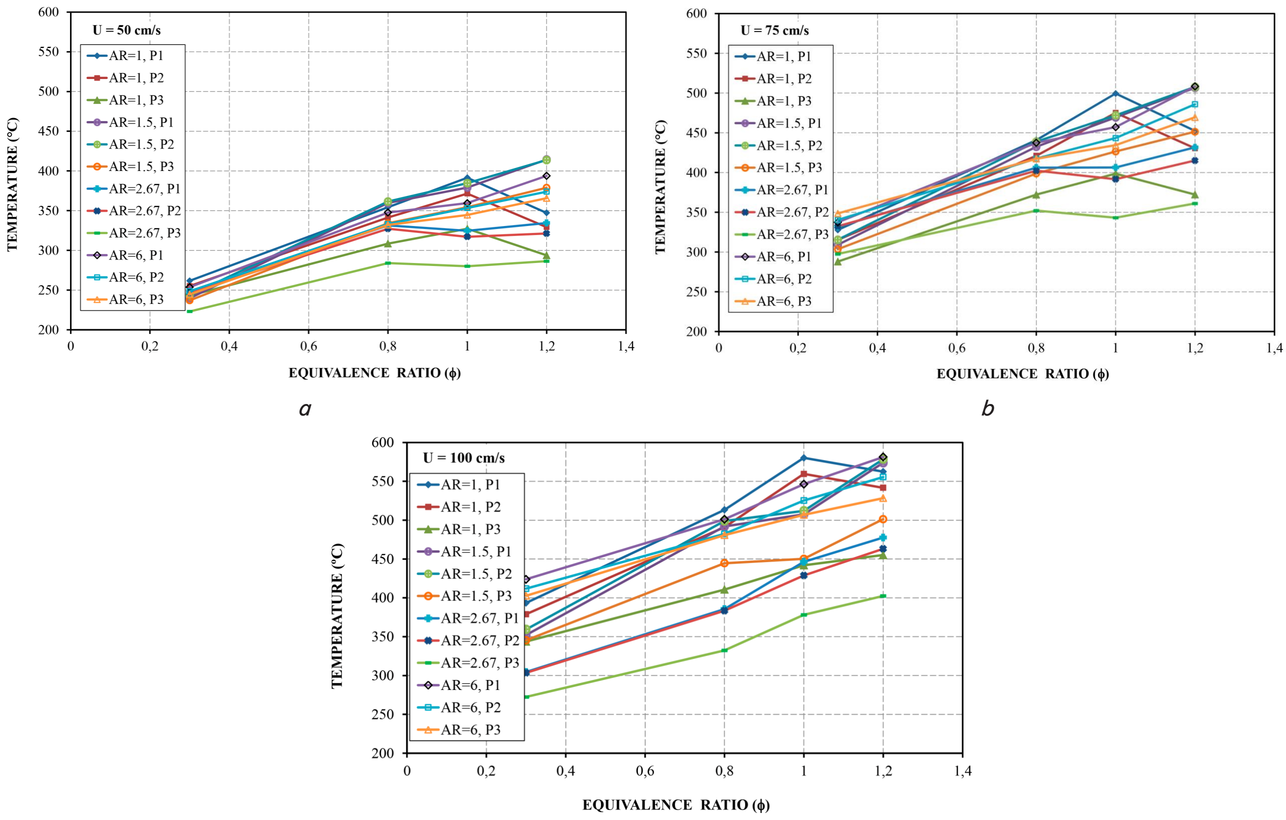
Fig. 9. Combustor axis temperatures at various equivalence ratios and U=100 cm/s

5. 3. Effect of aspect ratio on the combustor wall temperature, uniformity, and illumination

Wall temperature measurement is shown in Fig. 10. It shows the temperature distribution along the combustor walls at various equivalence ratios and flow rates of U=50–100 cm/s. When it was getting closer to the entrance, the combustor wall temperature increased. The temperature at the combustor wall changes sharply with the equivalence ratio than that on the combustor axis. High temperatures in the combustor wall occurred at an equivalence ratio ϕ=0.8 to 1.2. The highest combustor wall temperature, T=581 °C is achieved at the combustor with A_R=6 at P_1, at the equivalence ratio ϕ=1.2. Combustor with A_R=6 has the smallest hydraulic diameter. It makes the closest distance of the flame to the wall so that more heat was absorbed by the combustor wall.

Fig. 11 shows a comparison of combustor axis temperature (C.A.T) and the combustor wall temperature (C.W.T) at various aspect ratios at a reactant flow rate of U=100 cm/s. At all equivalence ratios and aspect ratios, the highest combustor axis temperature is achieved at P_1 and the lowest is at P_3. At the entire equivalence ratio, the highest temperature of the combustor axis is achieved by combustor with A_R=1.5, giving the largest range of stability. At P_1, the combustor wall temperatures are the highest almost at all aspect ratios. The highest temperature of the walls takes place at A_R=6 in P_1 with the equivalence ratio of ϕ=1.2. Although in the combustor axis temperature is lower than another aspect ratio, combustor with A_R=6 indicates a higher and more uniform wall temperature, where the temperatures of P_2 and P_3 were very close to P_1. Fig 11 more clearly shows that the conduction heat loss in the wall at the entrance section is much larger than the convection heat loss together with combustion products at ϕ=1 and ϕ=1.2. The lowest wall temperature is generated by the combustor with A_R=2.67 at all equivalence ratios. This explains why the combustor with A_R=2.67 has the most extensive dead zone.

Fig. 12–14 shows the combustor wall temperature (C.W.T) at various aspect ratios at a reactant flow rate of U=50, 75 and 100 cm/s. At all equivalence ratios and aspect ratios, the highest combustor axis temperature is achieved at P_1 and the lowest is at P_3. At P_1, the combustor wall temperatures are the highest almost at all aspect ratios. The highest temperature of the walls takes place at A_R=6 at P_1 with the equivalence ratio of ϕ=1.2. Although in the combustor axis temperature is lower than another aspect ratio, combustor with A_R=6 indicates a higher and more uniform wall temperature.



a

b

c

Fig. 10. Combustor wall temperatures at various equivalence ratios and reactant rates: *a* – U=50 cm/s; *b* – U=75 cm/s; *c* – U=100 cm/s

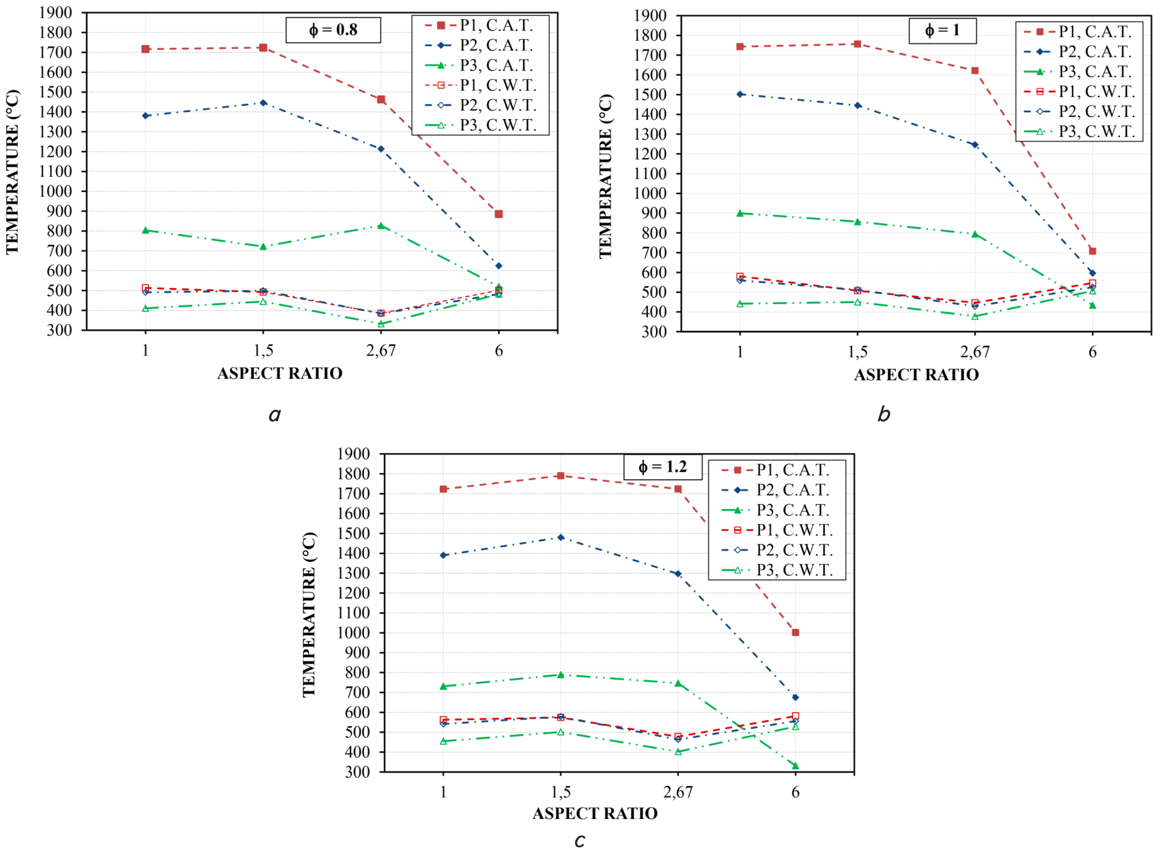


Fig. 11. Combustor axis and wall temperature at various aspect ratios and *U*=100 cm/s: *a* – ϕ=0.8; *b* – ϕ=1; *c* – ϕ=1.2

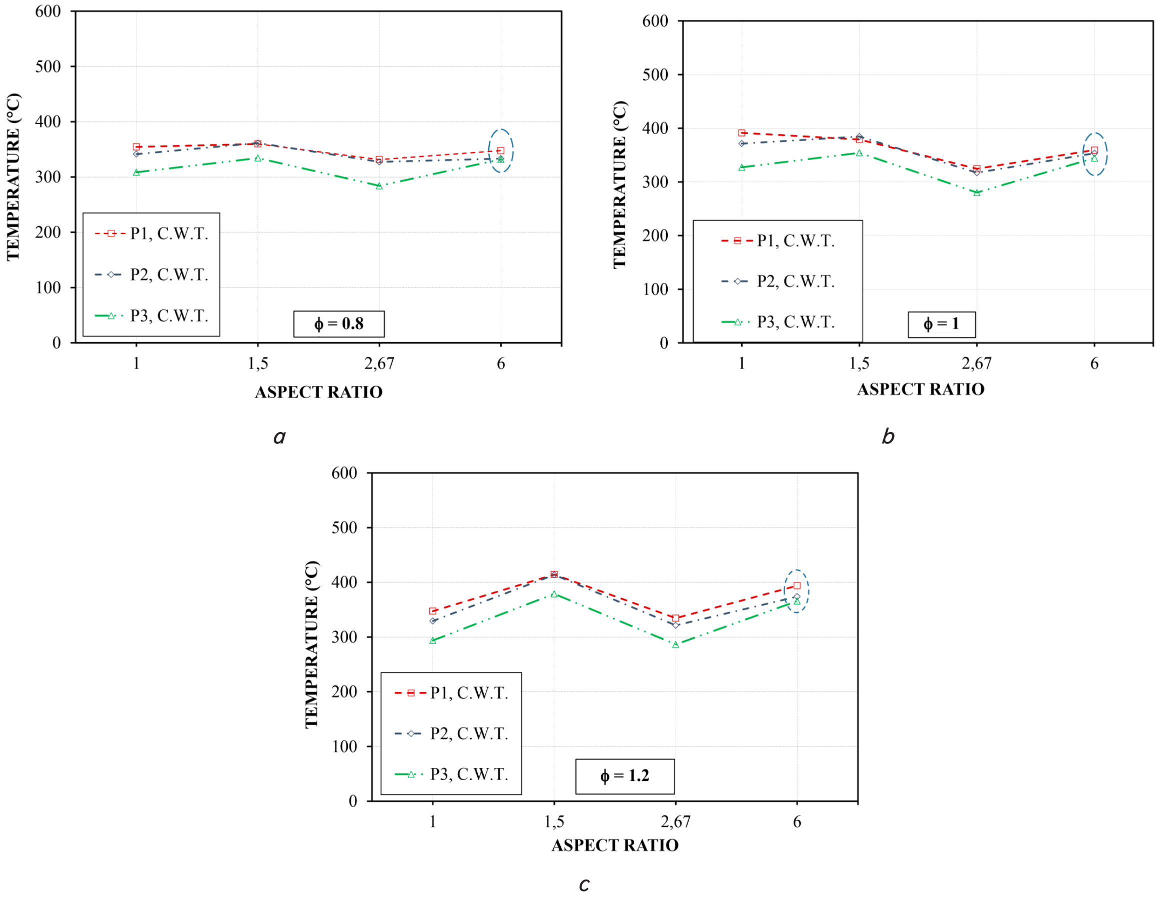
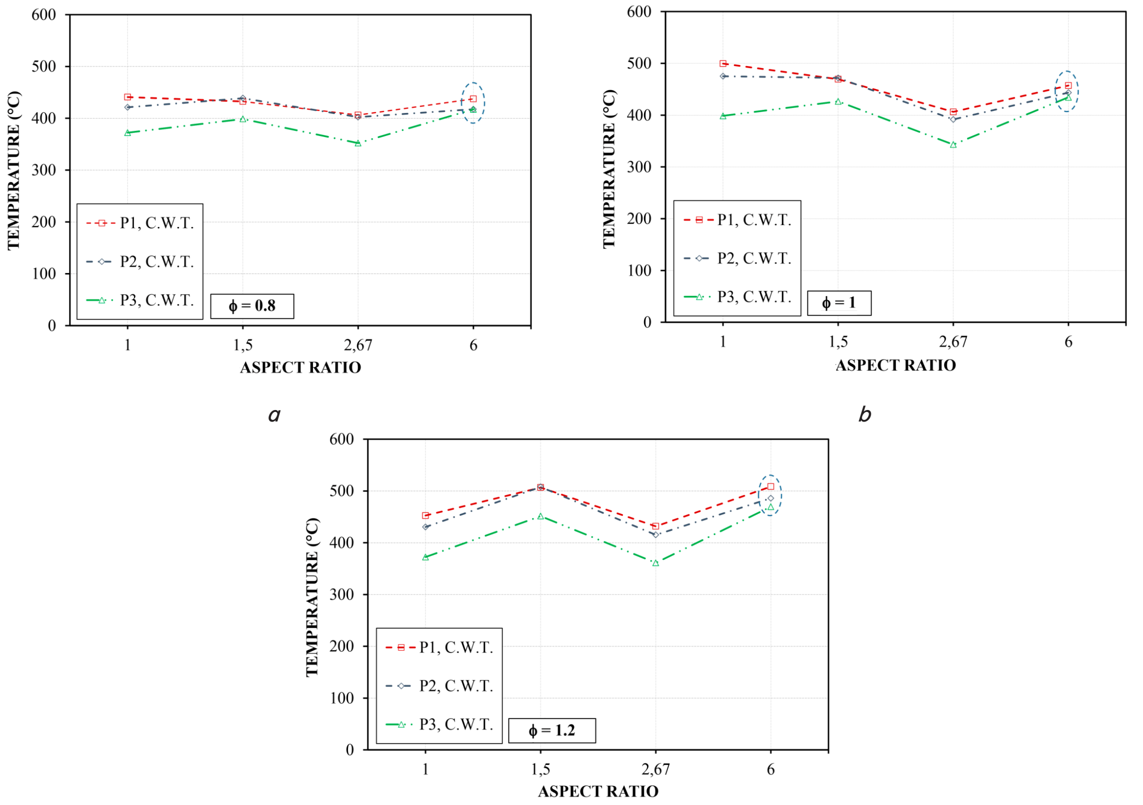
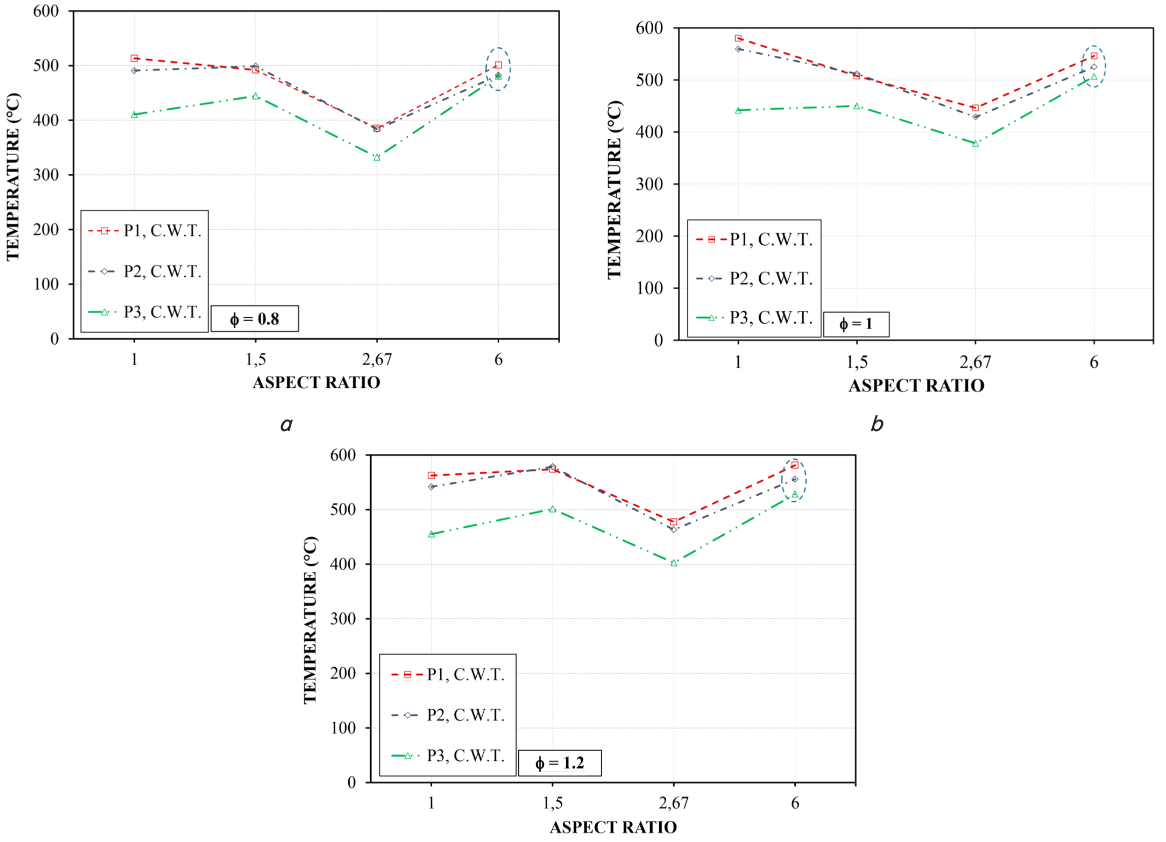


Fig. 12. The most uniform combustor wall temperatures (oval dash line) at various aspect ratios and *U*=50 cm/s: *a* – ϕ=0.8; *b* – ϕ=1; *c* – ϕ=1.2



a *b* *c*

Fig. 13. The most uniform combustor wall temperatures (oval dash line) at various aspect ratios and U=75 cm/s: *a* – ϕ=0.8; *b* – ϕ=1; *c* – ϕ=1.2



a *b* *c*

Fig. 14. The most uniform combustor wall temperatures (oval dash line) at various aspect ratios and U=100 cm/s: *a* – ϕ=0.8; *b* – ϕ=1; *c* – ϕ=1.2

Fig. 15 shows illumination behaviors of the combustor wall. The most illuminate combustor wall is generated by the combustor with A_R=6 at ϕ=1.2 due to the highest wall temperature (Fig. 15). This fact shows that heat transfer from the flame to the combustor wall was the biggest on the combustor with A_R=6, even though the heat generated by the combustion process in this combustor is the smallest, as indicated by the lowest flame temperature measured at the combustor axis. It was the reason why the combustor with A_R=6 has the narrowest stable flame zone, without or with noise.

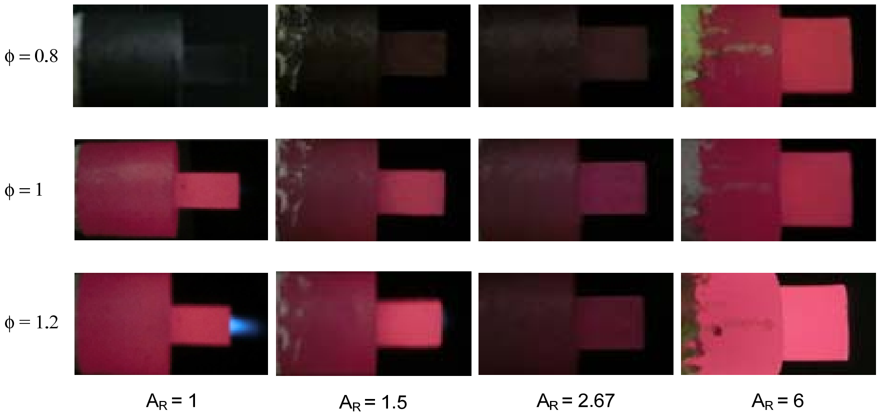


Fig. 15. Illumination behaviors of combustor wall at U=100 cm/s

6. Discussion of the results of studying the role of aspect ratio, flame stability and wall temperature uniformity of the planar mesoscale combustor with double narrow slit flame holder

The use of double narrow slit has successfully shifted the upper limit of the flame to very lean regions, and produced areas such as in Fig. 4–7. This design provides satisfactory results that are able to shift the flame stability limit in super poor regions at the lowest equivalence ratio of 0.2. The use of a double slit flame holder increases turbulence for better mixing and increases reactant residence time at high flow rates. The double narrow slit also increases the local reactant rate which is able to restore flashback at a low reactant rate. It also helps the combustion process through the initial heating of reactant at the flame holder wall.

The use of double narrow slit flame holders produces interesting new areas that are observed. The greater the aspect ratio, the narrower the flame stability map. The rich mixture shifts to the left (tends to stoichiometry), while the lean is relatively constant. The existence of a stable area in the area of a very lean mixture opens up the opportunity to use combustor as a source of heat energy in a highly efficient with less fuel. Stable with noise has the most extensive area of the entire map. The most interesting new area observed is the dead zone. In this region, the flame had a flashback then extinguished. The flashback speed sometimes was very fast so the flame had enough energy to pass through a narrow slit of flame holder and the flame hits the bottom wall of the combustor and then extinguishes. Dead zone occurred in regions with a high temperature in combustor axis where the speed of combustion reaction becomes very high. The dead zone also occurred at a low flow rate of reactants. Unlike the stable with noise, where flashback flame can recover, in dead zone flame is unable to recover. The greater of the aspect ratio, the dead zone region increases. Large aspect ratio increases heat loss. When the flame propagation speed increases and flashback, so much heat is absorbed by the wall so that the flame is unable to recover. The pseudo stable region is also interesting to discuss. Pseudo stable occurred at high reactant rate that makes the temperatures inside the combustor increased. An increasing temperature inside the combustor causes an increase in Lewis Number. Lewis Number magnitude depends on the thermal conductivity (k), heat capacity (C_p) and mass diffusivity. The thermal conductivity of nonmetals (reactant mixture) is approximately constant at high temperatures. High temperatures cause density to drop, while heat capacity (C_P) and mass diffusivity increase. The decrease in density is more significant than the increase in C_P and D_{AB}, so that Lewis number increases with increasing temperature. The greater Lewis Number means thermal diffusivity more than mass diffusivity that makes the flame tend to flashback and caused quenching.

In general, the axis temperature will decrease with increasing aspect ratio, but Fig. 9 shows that the combustor with A_R=1.5 has higher temperature along the combustor axis in each equivalence ratio than the other combustors. This is what causes the stability map of the combustor with A_R=1.5 most extensive. Combustor A_R=6 has the lowest axis temperature but has a high average wall temperature. Fig. 11 also shows the heat loss due to conduction mechanism in the wall in the entrance area (P_1) of combustor A_R=6 is much greater than the heat loss due to convection mechanism together with the combustion products. A high aspect ratio produces a more uniform wall temperature.

The scope of this combustor application can be used as a power source on micro generators with either using thermal electricity even at a low equivalence ratio (0.3) or using TPV at the equivalence ratio of 0.8–1.2. The combustor with A_R=1.5 shows the widest flame stability limit while combustor with A_R=6 shows the most uniform wall temperature. Referring to the results of the flame stability map and uniformity and also the illumination, combustor with the aspect ratio of 6 is highly recommended for both applications.

Even though they have obtained a wide stability map and uniform wall temperatures, this research work still has limitations in terms of the presence of dead zones in stochiometric regions and reducing noise. Prospects for further research are related to search how to eliminate or to shift the dead zone to the richer mixture, the region that is not in the efficient operating range. The second is the research can be the minimization of noise.

7. Conclusions

1. This research successfully compares flammability limit for planar mesoscale combustor at various aspect ratios using double narrow slit flame holder. The range of equivalence ratios for LPG-oxygen premixed combustion is very wide from the very lean mixture (ϕ=0.20) until a very rich

mixture (ϕ=3.34). Double narrow slit flame holder has succeeded in shifting the stability limit to very lean mixture. The aspect ratio gave a great effect to determine the limit of the stability map that can be achieved at the rich mixture. The most extensive range is obtained on combustor with the aspect ratio of 1.5 and the narrowest range is found on combustor with the aspect ratio of 6. The range of flame stability limit of the combustor with the aspect ratio of 1.5 is even wider than that of the combustor with the aspect ratio of 1, which has a larger hydraulic diameter. It indicates that the aspect ratio is an important factor for a non-circular combustor in addition to the hydraulic diameter. It also corresponds well with the flame holder shape.

2. The flame holder with a double narrow slit is most suited to the combustor with A_R=1.5. Solid flame is able to reach a high heat generation with minimal losses. It is proved that combustor with A_R=1.5 has higher inlet temperatures at all equivalence ratios and wider flammability limit.

3. The highest and the most uniform wall temperatures are reached at combustor with the aspect ratio of 6. The combustor with the aspect ratio of 6 is highly recommended for both applications of the thermo-electric or TPV system.

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