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FLAME BEHAVIOR INSIDE CONSTANT DIAMETER CYLINDRICAL MESO-SCALE COMBUSTOR WITH DIFFERENT BACKWARD FACING STEP SIZE

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У даній роботі розглядається поведінка стійкості полум'я в циліндричній мезомасштабній камері згоряння при різних розмірах оберненого назад уступу. Обернений назад уступ змінювали шляхом зміни розміру вхідного діаметра камери згоряння, в той час як розмір вихідного діаметра камери згоряння залишався постійним, зберігаючи постійну площу контакту. В якості палива використовувався бутан (C_4H_{10}), в якості окислювача – повітря. Результати показують, що, як правило, режим полум'я і карту режиму полум'я отримують для умов стійкого полум'я на ободі камери згоряння, стійкого полум'я в камері згоряння, стійкого полум'я поблизу уступу, пульсуючого полум'я, пульсуючого обертового полум'я, обертового полум'я, проскоку і відсутності займання. Розподіл режиму полум'я і карти режиму полум'я залежить від поведінки швидкості потоку реагенту, струменевого потоку, що генерує напругу зсуву, вихрового потоку, що регулює теплову взаємодію зі стінками, і середнього потоку, що створюється шляхом зміни розміру оберненого назад уступу при різному співвідношенні компонентів і швидкості реагенту в випробувальному діапазоні. Струменевий потік руйнує стійкість полум'я до згасання через сильну напруги зсуву. Вихровий потік обертає полум'я, в той час як перехід від струменевого до вихрового потоку викликає коливання обертового полум'я. Слабкий вихор при середньому потоці грає важливу роль в тепловій взаємодії зі стінками, що підтримує високу стійкість полум'я. Зменшення розміру оберненого назад уступу сприяє розширенню області стійкості полум'я, однак процес згоряння призводить до проскоку полум'я. Задаючи швидкість реагенту при невеликому розмірі оберненого назад уступу до умови існування слабкого вихрового потоку можна уникнути проскоку, зберігаючи високу стійкість полум'я. Стійке полум'я відбувається при суміші від стехіометричної до збідненої і зі швидкістю потоку реагенту від низької до середньої. При високих швидкостях потоку реагенту полум'я схильне до нестійкості. Однак при низькій і середній швидкості потоку реагенту полум'я в камері згоряння має тенденцію до стійкості

Ключові слова: циліндрична мезомасштабна камера згоряння, обернений назад уступ, поведінка полум'я, режим полум'я, карта режиму полум'я

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1. Introduction

Flame stabilization on a micro-/meso-scale combustor requires a deep understanding of the flame stabilization mechanism and behavior. This condition encourages the study of flame behavior in micro-/meso-scale combustor [1]. Micro- and meso-scale combustor is an important component of Micro Power Generator (MPG). In the Micro Power Generator, the chemical energy of hydrocarbon fuel is converted to thermal energy through combustion in micro- and meso-scale combustor. Then, it is converted to electrical energy using Thermophotovoltaic (TPV), Thermoelectric or Conventional Micro Power Generator such as a Micro Gas Turbine, etc. To achieve the highest efficiency of the Micro Power, Thermophotovoltaic or Thermoelectric Generator requires a stable flame on micro- and meso-scale combustor to achieve a uniform and high temperature of the combustor wall.

2. Literature review and problem statement

The results of previous studies show that it is challenging to stabilize combustion in micro-/meso-scale combustors [2, 3]. The reduction of the combustor size scale increases the ratio of heat loss to heat generation related to high surface to volume ratio on micro- and meso-combustor. These conditions lead to unstable flame due to thermal quenching around the combustor wall [4] and an increase of heat loss on the combustor wall, triggering flame extinction [5]. This condition is strengthened by a short residence time and inadequate reaction time [6].

Many researches were conducted on flame behavior and its effect on the flame stability in the micro-/meso-scale combustor. Some unstable flame behaviors were observed in micro- and meso-scale combustion [1, 7, 8–11]. The pulsating flames and flames with repetitive extinction and ignition (FREI) at a moderate flow rate that occur in the combustion characteristics of the premixed methane-air mixture in a narrow tube with temperature gradient treatment were observed by [7] experimentally. Modes of self-extinguished flame, stabilized planar flame, and spinning flame in the combustion of a mixture of premixed methane-air and propane-air in a mesoscale divergent channel was observed by [1]. Observations of the combustion mode of the premixed methane-air mixture on the meso-scale diverging combustor were carried out by [8] and obtained planar flame, negatively stretched, and positively stretched. Furthermore, spinning flame with high frequency was investigated by [9] on a meso-scale tube combustor with two/three steps, and it was found that the characteristics of the spinning flame were significantly influenced by flow rate and equivalence ratio. The combustion characteristics of the premixed methane-air mixture in the micro channel with external heating treatment for variations in the flow velocity and equivalence ratio were observed by [10] experimentally, where stable flames, flames with repetitive extinction and ignition (FREI), and weak flame are obtained. The characteristics of flame with repetitive extinction and ignition (FREI) dynamics in the combustion of premixed hydrogen-air mixtures in a heated micro channel were investigated by [11] numerically. It can be concluded that the unstable flame modes preclude considerable application of combustors with different geometric structures as a component of the Micro Power Generator.

Many researchers have developed particular treatment in micro combustors to increase flame stability, based on the effects of heat recirculation, flow recirculation, materials, media, geometry, and so on. Several methods were used to stabilize the flame in a micro- or meso-combustor such as the use of wire mesh [4], external heating [10], heat recirculation [12], porous media [13], catalyst material [14], enlargement of the combustor diameter [15], and the use of backward facing step [6, 16, 17]. Investigation of the use of the backward facing step to stabilize combustion in micro combustors was carried out by [6]. The backward facing step on the micro-/meso-scale combustor could increase the combustion stability at high reactant velocity with a broader range of equivalence ratios. It is caused by the increase of fuel and air reactants mixing by recirculation flow around the backward facing step and increased reactant residence time in the combustor, which perfects and stabilizes the combustion [6]. Research on the use of backward facing step in micro- or meso-scale combustor was continued by [16], which applies a micro combustor with a backward facing step as a component in the Micro-Thermophotovoltaics Power System. In the research by [17] regarding the use of backward facing step in the meso-scale combustor, it showed that the increasing size of the backward facing step (increasing the diameter of the reactor) could increase the stability of the flame. In this research, various flame regimes occur due to the influence of geometry variations (length and diameter of the reactor), Reynolds number, and equivalence ratio, which results in groups of flame regimes, namely blow-out, the marginal, the stationary (stable), the repetitive extinction and re-ignition (RERI), the stationary (stable)-flashback, and the RERI-flashback.

However, in studies of the micro-/meso-scale combustor with the implementation of the backward facing step above, flame stability is carried out by increasing the diameter of the combustion reaction zone, while the diameter of the inlet is kept constant. Increasing the diameter of the combustion reaction zone will increase flame stability, related to an increase in surface to volume ratio and a decrease in heat loss to heat generation ratio, not only because of the recirculation flow near the backward facing step and increased fuel-air mixing. It also requires an analysis of flame behavior related to reactant flow and flame stabilization in a micro-/meso-scale combustor with a backward facing step. Thus, it is necessary to investigate flame behavior in the form of flame mode and flame mode map on combustion stabilization in micro-/meso-scale combustors with constant reaction zones to understand the effects of utilizing backward facing step while the heat loss to heat generation ratio remains constant.

3. The aim and objectives of the study

This research aims to find out flame behavior inside a constant diameter cylindrical meso-scale combustor with a different backward facing step size.

To achieve this aim, the following objectives were set:

– to provide flame behavior in the flame modes that occurred due to the influence of the backward facing step size on the cylindrical meso-scale combustor at various equivalence ratios and flow velocity of reactant;

– to provide the flame mode maps, which is the distribution of flame mode on the graph of reactant velocity to equivalence ratio, as a result of variation of backward facing step size on the cylindrical meso-scale combustor.

4. Materials and methods of the research

The schematic of the test equipment in this study is presented in Fig. 1. Butane (C_4H_{10}) and air were applied as fuel and oxidizer in this study. Butane was provided from a pressurized fuel tank, and its flow rate was measured with a flow meter for butane (Kofloc, RK 1250, the flow rate of 2–20 mL/min). Air was supplied from an air compressor tank, and the air flow rate was measured by a flow meter for air (Kofloc, RK 1250, the flow rate of 50–500 mL/min).

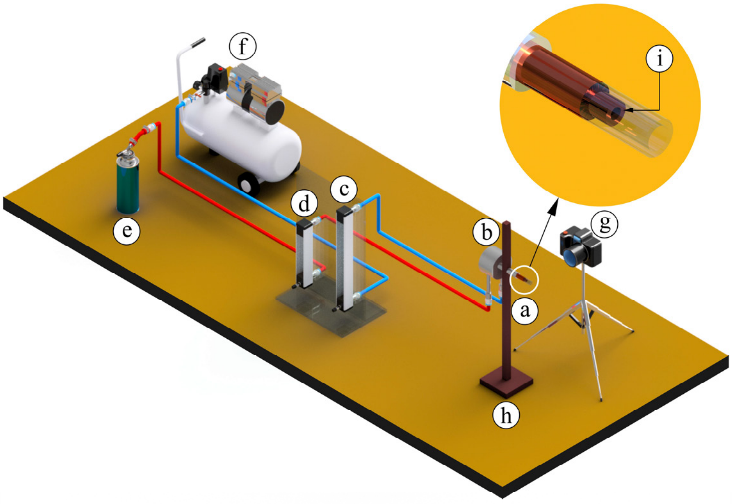


Fig. 1. The schematic of the test equipment: a — Cylindrical meso-scale combustor; b — Mixer; c — Air flow meter; d — C_4H_{10} flow meter; e — C_4H_{10} tank; f — Air compressor; g — Camera; h — Combustor holder; i — Backward facing step

The geometry of the cylindrical meso-scale combustor with the backward facing step is presented in Fig. 2. The combustor was made from copper for the inlet side and quartz glass pipe for the outlet side. The diameter of the outlet side (*D*2) was kept constant at 4.7 mm, while the inlet diameter (*D*1) was varied, as presented in Table 1. These variations were intended to find out the flame behavior and flame stability in meso-combustor with backward facing step without any effect of enlargement on the combustion reaction area, which only focused on the existence of a backward facing step with various backward facing step size (*D*1/*D*2 ratio).

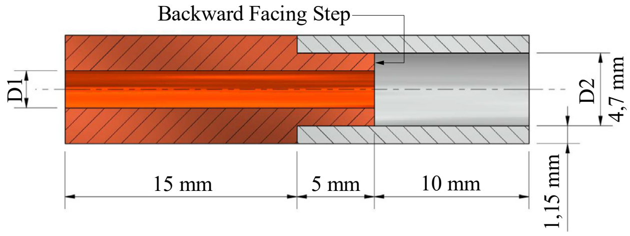


Fig. 2. The schematic of the cylindrical meso-scale combustor with the backward facing step

The butane and air are supplied from the pressurized fuel tank and air compressor tank, respectively, as explained in the previous section. Fuel and airflow rates were varied from minimum to maximum, where stable or unstable combustion occurred inside or at the rim of the combustor. Before entering the combustion chamber, air and fuel are mixed in the mixing chamber to produce a premixed mixture. The flame was ignited by a torch which is located at the combustor rim. The premixed mixture of fuel and air mixture was ignited at the combustor exit and propagates inside the combustor, then reaches stable/unstable condition depending on the velocity and equivalence ratio of reactant. Otherwise, the flame was extinguished, flashback, or blow-off. Digital camera (Canon EOS 60D) was utilized to capture the flame visualizations from the side direction. The side view images provided the axial position of the flame in the combustor. The flame behavior was mapped as a flame mode map in the graph of reactant velocity (*v*) to equivalence ratio (ϕ).

Table 1

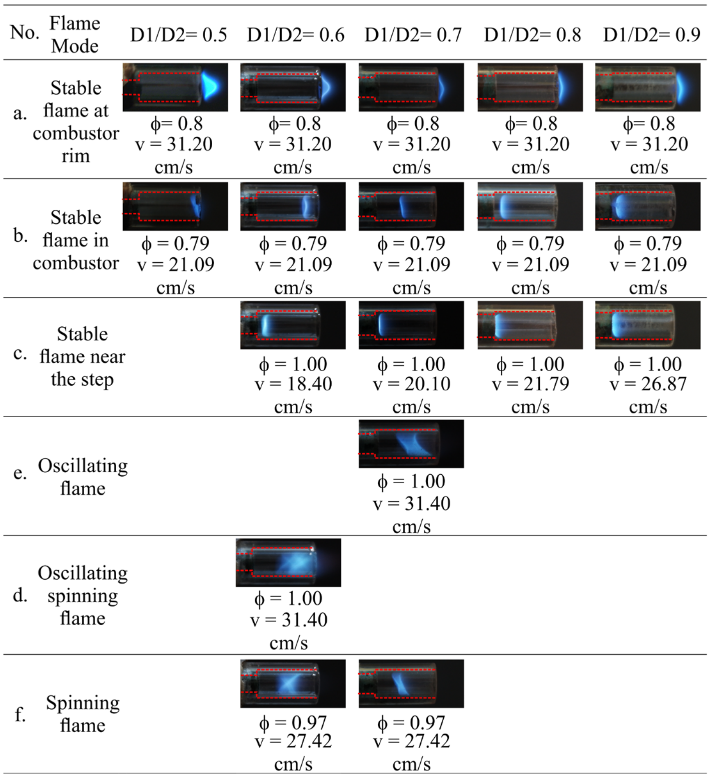
Variations of combustor diameters

Inlet Diameter, *D*1 (mm)	Outlet Diameter, *D*2 (mm)	*D*1/*D*2 Ratio
2.4	4.7	0.5
2.8	4.7	0.6
3.3	4.7	0.7
3.8	4.7	0.8
4.2	4.7	0.9

5. Results of the flame behavior inside constant diameter cylindrical meso-scale combustor with different backward facing step size

This research was conducted by observing flame behavior in the premixed combustion of the butane-air mixture in cylindrical meso-scale combustors with the backward facing step for various *D*1/*D*2 ratios (different backward facing step size). Cylindrical meso-scale combustor with different *D*1/*D*2 ratios was made by varying the inlet diameter of the combustor (*D*1) while the outlet diameter of the combustor (*D*2) was kept constant, so the combustor had a constant reaction zone of combustion. This method was conducted to understand the effect of backward facing step size on the flame stability, without influenced by diameter enlargement on the combustion reaction zone. As clearly understood in the previous research that flame stability significantly increases with the increase of combustor diameter [4, 6, 15, 17].

Fig. 3 shows the flame visualization in the cylindrical meso-scale combustor with various backward facing step sizes (different *D*1/*D*2 ratio). The figures indicate the existence of some flame modes in this experiment, i. e., stable flame at combustor rim, stable flame in combustor, stable flame near the step, oscillating flame, spinning flame, and oscillating spinning flame. Stable flame at combustor rim and stable flame in combustor mode were established on all combustors with different *D*1/*D*2 ratio.



No.	Flame Mode	D1/D2= 0.5	D1/D2= 0.6	D1/D2= 0.7	D1/D2= 0.8	D1/D2= 0.9
a.	Stable flame at combustor rim	ϕ= 0.8 v = 31.20 cm/s	ϕ= 0.8 v = 31.20 cm/s	ϕ= 0.8 v = 31.20 cm/s	ϕ= 0.8 v = 31.20 cm/s	ϕ= 0.8 v = 31.20 cm/s
b.	Stable flame in combustor	ϕ = 0.79 v = 21.09 cm/s	ϕ = 0.79 v = 21.09 cm/s	ϕ = 0.79 v = 21.09 cm/s	ϕ = 0.79 v = 21.09 cm/s	ϕ = 0.79 v = 21.09 cm/s
c.	Stable flame near the step		ϕ = 1.00 v = 18.40 cm/s	ϕ = 1.00 v = 20.10 cm/s	ϕ = 1.00 v = 21.79 cm/s	ϕ = 1.00 v = 26.87 cm/s
e.	Oscillating flame			ϕ = 1.00 v = 31.40 cm/s		
d.	Oscillating spinning flame		ϕ = 1.00 v = 31.40 cm/s			
f.	Spinning flame		ϕ = 0.97 v = 27.42 cm/s	ϕ = 0.97 v = 27.42 cm/s		

Fig. 3. Flame mode

As seen in Fig. 3, stable flame at combustor rim occurs when a flame performs stably at the combustor rim in all D1/D2 ratios at lean mixture ϕ=0.8 at high reactant velocity, around 31 cm/s. The stable flame in the combustor is the flame performed stably in the position at a distance longer than 1 mm from the backward facing step. This flame type occurs at a lower reactant velocity, around 21 cm/s at a slightly leaner mixture ϕ=0.7. While the stable flame near the step is the flame formed stably at a distance ≤1 mm from the backward facing step. This flame exists at stoichiometry at a wide range reactant velocity from 18 cm/s to around 27 cm/s. The oscillating flame mode is the flame that moves forth and back, which occurs at stoichiometry only at $D1/D2$ ratio=0.7 at reactant velocity of 31.40 cm/s. While the oscillating spinning flame is the flame that spins while it is moving back and forth, which occurs at stoichiometry only at $D1/D2$ ratio=0.6 at reactant velocity of 31.40 cm/s. In the spinning flame mode, the flame only rotates in the combustor, which occurs at near stoichiometry at $D1/D2$ ratio=0.6 and 0.7 at reactant velocity of 27.42 cm/s. At $D1/D2$ ratio equals 0.5, there are three modes observed, namely stable flame at combustor rim mode, stable flame in combustor mode, as well as the no ignition condition. The $D1/D2$ ratio=0.6 produces stable flame at combustor rim, stable flame in combustor, stable flame near the step, oscillating spinning flame, and spinning flame mode. At the $D1/D2$ ratio=0.7, stable flame at combustor rim, stable flame in combustor, stable flame near the step, oscillating flame, and spinning flame mode are found. At the $D1/D2$ ratio=0.8 and 0.9, the flashback occurs beside the stable flame at combustor rim, stable flame in combustor, and stable flame near the step mode.

Fig. 4 shows the flame mode at the equivalence ratio (ϕ)=1 at various reactant velocities (v) for various $D1/D2$ ratios. With the arrangement as shown in Fig. 4, it can be seen that there are three types of reactant flow that control flame stability, i. e., jet flow, vortex, and average flow.

As seen in Fig. 4, at a small $D1/D2$ ratio, flame stability is controlled mainly by reactant jet flow. At medium $D1/D2$ ratio, vortex flow starts to predominate in controlling the flame stability. At large $D1/D2$ ratio, the jet flow and vortex flow diminish, and the average flow of reactant takes over the control on flame stability. As shown in Fig. 4, at a low $D1/D2$ ratio, the flame is almost extinct because shear stress destructs flame stability. At medium $D1/D2$ ratio, especially at low reactant velocity, the vortex tends to stabilize the flame near the step. However, as the reactant velocity increases, the vortex stretches the flame and makes it spinning and oscillating. At high $D1/D2$ ratio, especially at low reactant velocity, the flame is flashed back due to the flame speed is much higher than the reactant velocity. As the reactant velocity increases, the flame speed tends to be overridden by the reactant and move downward unstably to the combustor rim.

No.	v(at D2) (cm/s)	D1/D2 = 0.5	D1/D2 = 0.6	D1/D2 = 0.7	D1/D2 = 0.8	D1/D2 = 0.9
1.	18.40	No Ignition	Stable flame near the step	Stable flame near the step	Flashback	Flashback
2.	20.10	No Ignition	Spinning flame	Stable flame near the step	Flashback	Flashback
3.	21.79	No Ignition	Spinning flame	Stable flame near the step	Stable flame near the step	Flashback
4.	23.48	No Ignition	Oscillating spinning flame	Stable flame near the step	Stable flame near the step	Flashback
5.	31.40	No Ignition	Oscillating spinning flame	Oscillating flame	Stable flame in combustor	Stable flame near the step
6.	33.10	Stable flame at combustor rim	Oscillating spinning flame	Oscillating flame	Stable flame in combustor	Stable flame in combustor
7.	34.79	Stable flame at combustor rim	Spinning flame	Oscillating flame	Stable flame in combustor	Stable flame in combustor
8	36.48	No Ignition	Stable flame at combustor rim	Oscillating flame	Stable flame at combustor rim	Stable flame in combustor
9.	38.18	No Ignition	No Ignition	Oscillating flame	Stable flame at combustor rim	Stable flame in combustor
10.	39.87	No Ignition	No Ignition	Stable flame at combustor rim	Stable flame at combustor rim	Stable flame in combustor

Fig. 4. Flame mode at equivalence ratio (ϕ)=1 with the change in reactant velocity

Fig. 5–9 show detailed flame mode maps in the graph of reactant velocity (v) to equivalence ratio (ϕ) of various combustion flame modes for the five variations of the $D1/D2$ ratio. The flame mode area is plotted accordingly in Fig. 5–9, consisting of some flame modes such as the stable flame at combustor rim, stable flame in combustor, stable flame near the step, oscillating flame, oscillating spinning flame, spinning flame, flashback, and no ignition.

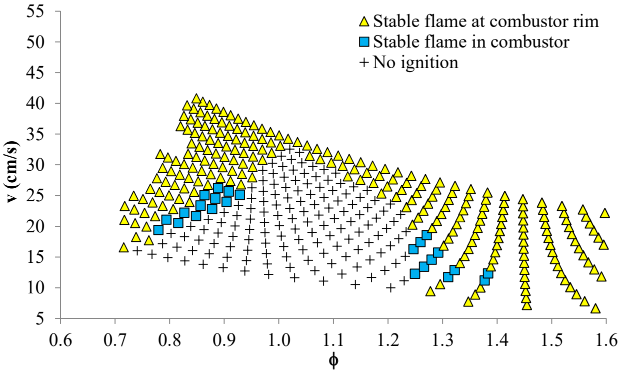


Fig. 5. Flame mode map at D1/D2 ratio=0.5

As shown in Fig. 5, at the $D1/D2$ ratio=0.5, the stability region of the stable flame in the combustor is very narrow at low reactant velocity. This shows that shear stress of the jet flow destructs flame stability to be extinct at higher reactant velocity.

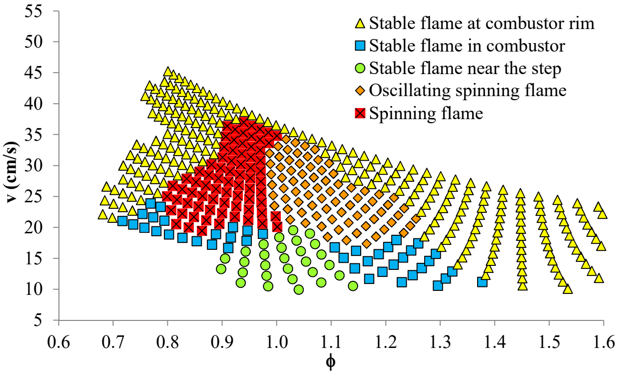


Fig. 6. Flame mode map at $D1/D2$ ratio=0.6

As the $D1/D2$ ratio is increased to 0.6, the flame stability region becomes wider, as shown in Fig. 6. The stable flame near the step exists at lower reactant velocity. With increasing reactant velocity, the flame spins and oscillates, formed the spinning flame and oscillating spinning flame modes. This shows that vortex flow strongly controls the flame stability.

As seen in Fig. 7, at the $D1/D2$ ratio=0.7, the stable flame near the step region becomes wider while the spinning flame region becomes narrower. Oscillating spinning flame mode disappears, replaced by the appearance of the oscillating flame. This shows that vortex flow domination on flame stability weakens. But its influence on the oscillation flame is still dominant.

With a further increase in the $D1/D2$ ratio to 0.8 (Fig. 8), the spinning and oscillating flames region disappears. However, the flashback conditions start to take place. This indicates that the average flow regime regulates the flame stability.

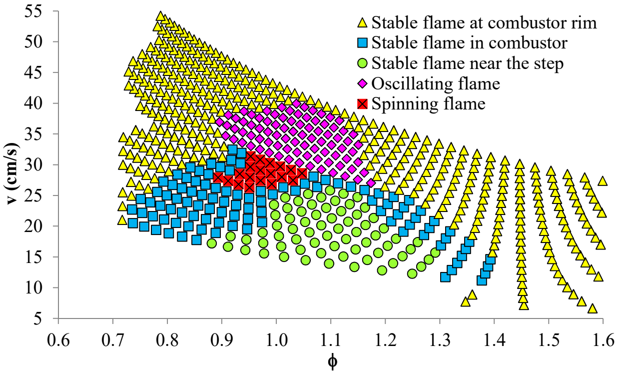


Fig. 7. Flame mode map at $D1/D2$ ratio=0.7

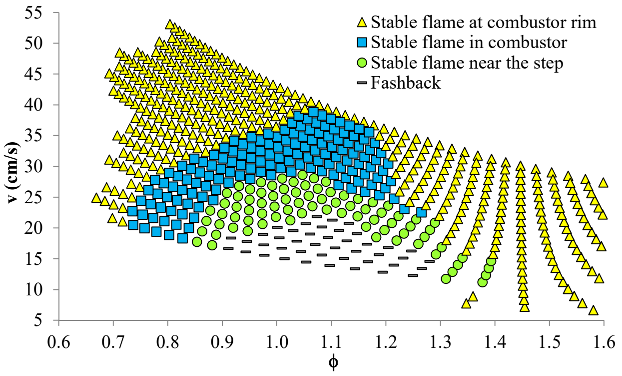


Fig. 8. Flame mode map at $D1/D2$ ratio=0.8

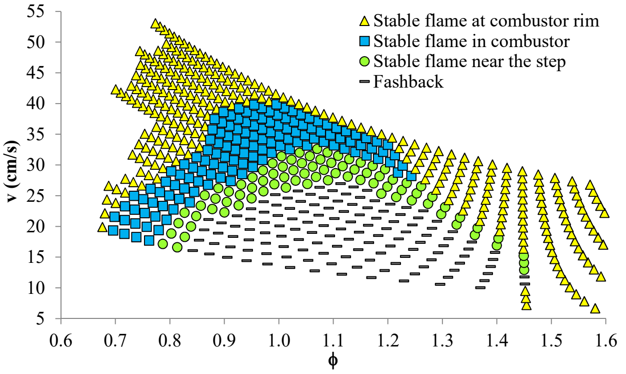


Fig. 9. Flame mode map at $D1/D2$ ratio=0.9

With a further increase in the $D1/D2$ ratio to 0.9, the backward facing step size is very small. The average flow regime becomes very dominant. The very weak jet flow due to the very small backward facing step size makes combustion speed overridden average velocity, and thereby flashback region becomes wider.

6. Discussion of the flame behavior inside constant diameter cylindrical meso-scale combustor with different backward facing step size

Fig. 3 shows that the difference in the $D1/D2$ ratio of the combustor results in different forms of flame with the same conditions of equivalence ratio (ϕ) and reactant velocity (v). The difference in the shape of the flame is caused by variations in the $D1/D2$ ratio of the combustor, which results in differences in reactant flow velocity behavior, namely jet flow, vortex flow, and average velocity. The jet flow was formed at the entrance of the combustion reaction zone, i. e., at the backward facing step of the combustor, when the entrance flow velocity was high enough. Since the reactant enters the combustion reaction zone, the flow develops throughout the combustor cross-section. Vortex flow is formed when the entrance velocity of the reactant is high, and the backward facing step size is large enough. The average velocity is the average velocity of reactant in the combustion reaction zone. In jet flow, shear stress is dominant, whereas, at vortex flow, recirculation and reattachment are overriding. While the backward facing step size is small enough, entrance flow velocity is almost the same as the average velocity, all phenomena related to the high velocity of entrance flow and vortex flow vanish [18].

The stable flame at combustor rim for the $D1/D2$ ratio=0.5 produces a flame shape that tends to be thicker and experiences stretching away from the combustor rim. This is because of the shear stress of reactant jet flow velocity produced in a narrow inlet passage at the backward facing step. The shear stress stretches the flame and to be driven out. In the larger $D1/D2$ ratio of 0.6 to 0.9, the shape of the flame tends to be smaller and thinner, with less stretch on the flame. The higher $D1/D2$ ratio causes the backward facing step size to be smaller with a wider inlet passage so that vortex flow and jet flow decrease, thereby shear stress is smaller. Therefore, the flame is more stable at the combustor rim.

The stable flame in combustor mode occurs when the flame is in the combustor reaction zone. The flame propagated into the combustor as the reactant velocity decreases and stops in position according to the characteristics of each combustor variation. In the combustor with the $D1/D2$ ratio of 0.5, the position of the flame is in the downstream of the combustor, as shown in Fig. 3. With the increasing of the $D1/D2$ ratio from 0.6 to 0.9, the flame positions become closer to the backward facing step area. It is in line with the decreasing of reactant velocity, jet flow, and vortex flow.

The flame is stable near the step at an equivalence ratio (ϕ) around 1. However, at the $D1/D2$ ratio=0.5, the flame is extinct at the backward facing step (Fig. 4). This is due to the fact that the strong shear stress from jet flow destructs the reaction zone, and unstable flame tends to be driven away from the backward facing step area to the more stable region. Increasing the $D1/D2$ ratio from 0.5 to 0.9, the flame becomes more stable and attached to the backward facing step. This is because of the shear stress from jet flow getting weaker, and vortex flow favors the combustion reaction.

As shown in Fig. 4 at the $D1/D2$ ratio=0.6 at stoichiometry, the flame is vibrating and spinning. This shows that the vortex flow starts to take over the control on flame stability while jet flow still takes part weakly. When flame propagates, upstream jet flow stretches the flame, then moves downstream. Then vortex flow strengthens the flame stability by recovering heat from the wall via spinning so that flame propagates upstream. The combined action of jet flow and vortex flow makes flame to oscillate and spin. As the $D1/D2$ ratio is increased to 0.7, the inlet passage is wider, and the jet flow becomes weaker so that the flame is only regulated by the vortex flow to be stable in spin mode due to the thermal wall interaction, which stretches the flame in the tangential and axial direction as stated in [8].

Flashback flames occur when the propagation speed of a flame in the combustor channel is higher than the reactant flow velocity [17]. In this study, flashback flame mode takes place in the combustor with the $D1/D2$ ratio of 0.8 and 0.9. In this case, jet flow and vortex flow disappear completely due to the large inlet passage and the very small backward facing step size. Thus, when combustion reaction is getting faster, then flame propagation speed overrules the average flow, thereby flashback takes place.

The stable flame case in the combustor duct consists of the stable flame in the combustor and stable flame near the step modes, as shown in Fig. 4. This situation is achieved under conditions when a flame enters the duct during ignition, propagates upstream very slowly, and is stable at specific locations in the channel. The location of the stable flame, in this case, is also substantially downstream from the recirculation zone flow through the backward facing step and in the backward facing step area. In a combustor with the $D1/D2$ ratio=0.5, the flame mode that occurs is only the flame at the combustor rim for various reactant velocities, while stable flame in the combustor establishes only at a few points as shown in Fig. 5. This is caused by the narrow inlet at this combustor, which generates a strong jet flow with strong shear stress. Consequently, flame stability is destroyed in the combustor.

Other flame modes that are formed outside the flame mode described earlier are the no ignition and flashback modes. The no ignition mode occurs when the premixed butane-air mixture cannot be ignited even after several attempts, or the flame immediately extinguished when releasing the ignition source (lighter). This situation occurs at low to high reactant velocity in the test range of the combustor with a D1/D2 ratio of 0.5. Flashback mode occurs in combustors with a $D1/D2$ ratio of 0.8 and 0.9 at low reactant velocity. Flashback mode occurs with a moment of ignition, and then the flame propagates upstream of the combustor and is extinguished. This is caused by the speed of flame propagation that is higher than the reactant flow velocity in the combustor duct.

Fig. 5–9 shows that the flame mode maps formed on the graph of reactant velocity (v) to equivalence ratio (ϕ) depend on the reactant flow velocity and the equivalence ratio in each of the D1/D2 ratio variations in the size of the backward facing step of the cylindrical meso-scale combustor. The area of the flame mode is the stable flame at combustor rim, stable flame in combustor, stable flame near the step, oscillating flame, spinning flame, oscillating spinning flame, flashback, and no ignition on the graph of reactant velocity (v) to equivalence ratio (ϕ). The occurrence of these eight characteristic phenomena of flame mode maps is influenced by the $D1/D2$ ratio. The variation of the $D1/D2$ ratio generates three distinct reactant flow behaviors, namely, jet flow at very small $D1/D2$ ratio, vortex flow at medium $D1/D2$ ratio, and average flow at large $D1/D2$ ratio. The strong shear stress in the jet flow destructs flame stability, and no ignition is obtained. At the transition from the jet flow to the vortex flow, the flame oscillates and spins. When the vortex flow is dominant, the spin flame mode exists. At the transition from vortex flow to average flow, the flame is very stable and very thin around the stoichiometry condition. At average flow, the flame is flashed back since wall thermal interaction due to vortex flow no longer regulates the flame. The no ignition and flashback mode conditions are undesirable in the heat generation process of the meso-combustor, so Fig. 5–9 is very useful to illustrate the processes that occur when the operating conditions are performed. Thus, the selection of the $D1/D2$ ratio can be obtained from these flame mode maps. The most exciting condition is the condition where the value of the $D1/D2$ ratio is 0.6 due to various flame behaviors. The choice of operating conditions in the $D1/D2$ ratio must be considered to obtain a stable flame condition to optimize the heat generation process of the meso-combustor.

In all of the $D1/D2$ ratios, as shown in Fig. 5–9 for conditions of high reactant velocities and in conditions of low and high equivalence ratios, the flame is formed stable on the combustor rim with the stable flame at combustor rim mode. For this flame mode, there will be a diffusion process from environmental air so that the actual equivalence ratio will be affected by environmental air conditions becoming poorer than the calculated equivalence ratio. For all variations of the $D1/D2$ ratio for high reactant velocity, the flame will be driven away in the combustor rim. The large inlet reactant velocity causes the reattachment length and shear stress flow so that the flame formed will be in the combustor rim. The smaller $D1/D2$ ratio gives a more elongated shape of the flame mode. The smaller $D1/D2$ ratio will form a vortex flow with larger recirculation area, which will make the flame driven towards the combustor rim. In the low and high equivalence ratio areas for various reactant velocities, the stable flame at the combustor rim mode is formed. A flame with all equivalence ratios can ignite stably at high reactant velocity and will continue to burn in the combustor rim. This flame can be stable because of the effects of environmental air diffusion.

The stable flame in combustor mode is formed with a stable flame in the combustor duct. Fig. 5–9 shows that the combustor with a higher $D1/D2$ ratio gives a wider area of the stable flame in combustor mode. This shows that the weaker vortex flow with the smaller recirculation region makes the flame able to hold stable in the combustor duct. Enlarging the $D1/D2$ ratio from 0.5 to 0.9 decreases backward facing step size, and therefore the shear stress due to jet flow and recirculation due to vortex flow are weakened so that the flame can be stable inside the combustor. The stable flame in combustor mode occurs at the lean and rich equivalence ratio areas, and the low to medium reactant velocity for the combustor with the $D1/D2$ ratio of 0.5, 0.6 and 0.7. At the $D1/D2$ ratio of 0.8 and 0.9, the stable flame in combustor mode established in a wider area for low to high reactant velocity. This suggests that the stability of the flame in the stable flame in combustor mode can be achieved with the increasing $D1/D2$ ratio related to the weak shear stress due to jet flow and weak recirculation due to vortex flow. The higher $D1/D2$ ratio makes the stable flame in combustor mode more stable.

Furthermore, with changes in reactant flow velocity and equivalence ratio, the flame will shift to the stable flame near the step mode, and the flame attaches to the backward facing step area. At the $D1/D2$ ratio=0.5, the stable flame near the step mode area cannot be realized. This is caused by the fact that shear stress is very strong due to strong jet flow generated in the very narrow inlet at a small $D1/D2$ ratio. At the $D1/D2$ ratio=0.6 to 0.9, the flame can be established stably near the step. The stable flame near the step mode exists at the equivalence ratio around unity with low to moderate reactant velocity for the combustor with the $D1/D2$ ratio of 0.6 and 0.7. This was caused by the role of vortex flow to regulate the wall-thermal interaction to favor the combustion reaction. At the $D1/D2$ ratio of 0.8 and 0.9, the flame near the step mode area is more stable at an equivalence ratio around 1 and a higher reactant velocity. However, the flashback occurs at a low reactant velocity and equivalence ratio near 1, due to higher flame propagation speed larger than reactant velocity. The flame performed for a moment, then propagated upstream and extinguished. At high $D1/D2$ ratio and low reactant velocity, the vortex flow is very weak or disappears. This indicates that vortex flow plays an important role in regulating wall-thermal interaction to stabilize the flame.

The oscillating flame mode is only formed at the $D1/D2$ ratio=0.6 and 0.7. The oscillating flame mode exists in the area with an equivalence ratio around 1 and extends to the larger equivalence ratio for medium to high reactant flow velocity, as shown in Fig. 6, 7. The flame formed oscillates from downstream to upstream and vice versa inside the combustor and continuously oscillates without extinguished. The spinning flame mode occurs at equivalence ratios <1 to equivalence ratio=1 with medium to high reactant velocity for the combustor with $D1/D2$ ratio of 0.6, and around the equivalence ratio=1 with medium reactant velocity for the combustor with $D1/D2$ ratio of 0.7. This suggests that the appropriate setting of the shear stress-equivalence ratio determines the existence of an oscillating flame.

In summary, the shortcomings of the research are: the backward facing step as a flame holder plays a very important role in flame stability. Too small or without backward facing step, the flame is flashed back, whereas too large backward facing step the flame is destroyed by the vortex. In between, vortex due to the backward facing step oscillates the flame. The restrictions that can be imposed on the use of the results is that special attention must be paid to the complexity between heat loss and fluid dynamics.

To make the results applicable in Micro Power Generator (MPG), the research should be developed to the catalytic combustion in the micro-/meso-scale combustor. The backward facing step or flame holder should be coated by catalytic materials to boost the combustion reaction so that the vortex generated by the backward facing step cannot destruct the flame stability. However, the catalyst material and coating technology are difficulties that must be solved.

7. Conclusions

1. Variation of backward facing step size ($D1/D2$ ratio) in cylindrical meso-scale combustor with backward facing step gives different flame behavior, which in general forms flame modes: stable flame at combustor rim, stable flame in combustor, stable flame near the step, oscillating flame, oscillating spinning flame, and spinning flame, and the condition of the flame extinguished namely flashback and no ignition. This is caused by the couple between reactant flow behavior at various backward facing step sizes ($D1/D2$ ratio), jet flow, vortex flow, and average flow with equivalence ratio variations in the possible test range.

2. Different backward facing step sizes ($D1/D2$ ratio) of the cylindrical meso-scale combustor with backward facing step result in different flame mode maps due to

different reactant flow velocity behavior, jet flow generating shear stress, vortex flow controlling wall-thermal interaction, and average flow. At a high equivalence ratio, the flame tends to be unstable. A steady flame tends to be performed around the stoichiometry and lean mixture. At high reactant flow velocities, the flames that are formed tend to be unstable. However, at low to medium reactant flow velocity, the flame that is formed tends to be stable in the combustor.

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References

1. Xu, B., Ju, Y. (2007). Experimental study of spinning combustion in a mesoscale divergent channel. Proceedings of the Combustion Institute, 31 (2), 3285–3292. doi: https://doi.org/10.1016/j.proci.2006.07.241
2. Ju, Y., Maruta, K. (2011). Microscale combustion: Technology development and fundamental research. Progress in Energy and Combustion Science, 37 (6), 669–715. doi: https://doi.org/10.1016/j.pecs.2011.03.001
3. Chou, S. K., Yang, W. M., Chua, K. J., Li, J., Zhang, K. L. (2011). Development of micro power generators – A review. Applied Energy, 88 (1), 1–16. doi: https://doi.org/10.1016/j.apenergy.2010.07.010
4. Mikami, M., Maeda, Y., Matsui, K., Seo, T., Yuliati, L. (2013). Combustion of gaseous and liquid fuels in meso-scale tubes with wire mesh. Proceedings of the Combustion Institute, 34 (2), 3387–3394. doi: https://doi.org/10.1016/j.proci.2012.05.064
5. Wan, J., Shang, C., Zhao, H. (2018). Anchoring mechanisms of methane/air premixed flame in a mesoscale diverging combustor with cylindrical flame holder. Fuel, 232, 591–599. doi: https://doi.org/10.1016/j.fuel.2018.06.027
6. Yang, W. M., Chou, S. K., Shu, C., Li, Z. W., Xue, H. (2002). Combustion in micro-cylindrical combustors with and without a backward facing step. Applied Thermal Engineering, 22 (16), 1777–1787. doi: https://doi.org/10.1016/s1359-4311(02)00113-8
7. Maruta, K., Kataoka, T., Kim, N. I., Minaev, S., Fursenko, R. (2005). Characteristics of combustion in a narrow channel with a temperature gradient. Proceedings of the Combustion Institute, 30 (2), 2429–2436. doi: https://doi.org/10.1016/j.proci.2004.08.245
8. Akram, M., Kumar, S. (2011). Experimental studies on dynamics of methane–air premixed flame in meso-scale diverging channels. Combustion and Flame, 158 (5), 915–924. doi: https://doi.org/10.1016/j.combustflame.2011.02.011
9. Deshpande, A. A., Kumar, S. (2013). On the formation of spinning flames and combustion completeness for premixed fuel–air mixtures in stepped tube microcombustors. Applied Thermal Engineering, 51 (1-2), 91–101. doi: https://doi.org/10.1016/j.applthermaleng.2012.09.013
10. Di Stazio, A., Chauveau, C., Dayma, G., Dagaut, P. (2016). Combustion in micro-channels with a controlled temperature gradient. Experimental Thermal and Fluid Science, 73, 79–86. doi: https://doi.org/10.1016/j.expthermflusci.2015.09.020
11. Alipoor, A., Mazaheri, K. (2016). Combustion characteristics and flame bifurcation in repetitive extinction-ignition dynamics for premixed hydrogen-air combustion in a heated micro channel. Energy, 109, 650–663. doi: https://doi.org/10.1016/j.energy.2016.05.042
12. Taywade, U. W., Deshpande, A. A., Kumar, S. (2013). Thermal performance of a micro combustor with heat recirculation. Fuel Processing Technology, 109, 179–188. doi: https://doi.org/10.1016/j.fuproc.2012.11.002
13. Pan, J. F., Wu, D., Liu, Y. X., Zhang, H. F., Tang, A. K., Xue, H. (2015). Hydrogen/oxygen premixed combustion characteristics in micro porous media combustor. Applied Energy, 160, 802–807. doi: https://doi.org/10.1016/j.apenergy.2014.12.049
14. Pan, J., Zhang, R., Lu, Q., Zha, Z., Bani, S. (2017). Experimental study on premixed methane-air catalytic combustion in rectangular micro channel. Applied Thermal Engineering, 117, 1–7. doi: https://doi.org/10.1016/j.applthermaleng.2017.02.008
15. Li, Z. W., Chou, S. K., Shu, C., Xue, H., Yang, W. M. (2005). Characteristics of premixed flame in microcombustors with different diameters. Applied Thermal Engineering, 25 (2-3), 271–281. doi: https://doi.org/10.1016/j.applthermaleng.2004.06.007
16. Xue, H., Yang, W., Chou, S. K., Shu, C., Li, Z. (2005). Microthermophotovoltaics power system for portable mems devices. Microscale Thermophysical Engineering, 9 (1), 85–97. doi: https://doi.org/10.1080/10893950590913431
17. Baigmohammadi, M., Tabejamaat, S., Farsiani, Y. (2015). Experimental study of the effects of geometrical parameters, Reynolds number, and equivalence ratio on methane–oxygen premixed flame dynamics in non-adiabatic cylinderical meso-scale reactors with the backward facing step. Chemical Engineering Science, 132, 215–233. doi: https://doi.org/10.1016/j.ces.2015.04.008
18. Sanata, A., Wardana, I. N. G., Yuliati, L., Sasongko, M. N. (2019). Effect of backward facing step on combustion stability in a constant contact area cylindrical mesoscale combustor. Eastern-European Journal of Enterprise Technologies, 1 (8 (97)), 51–59. doi: https://doi.org/10.15587/1729-4061.2019.149217