

# EFFECT OF BACKWARD FACING STEP ON COMBUSTION STABILITY IN A CONSTANT CONTACT AREA CYLINDRICAL MESO-SCALE COMBUSTOR

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*В даному експерименті досліджується вплив зміни розміру зворотного уступу на стійкість горіння в циліндричній мезомасштабній камері згорання з постійною площею контакту. Зворотний уступ варіювався шляхом зміни вхідного діаметра камери згорання, в той час як діаметр камери згорання в зоні горіння залишався постійним, тобто мав постійну площу контакту. Газ бутан ( $C_4H_{10}$ ) використовувався в якості палива, а повітря – як окислювач. Результат показує, що зворотний уступ відіграє важливу роль в механізмі стабілізації горіння. Стабільне полум'я можна стабілізувати в мезомасштабній камері згорання зі зворотним уступом. Без зворотного уступу полум'я гасне, потім стабілізується на ободі камери згорання. Рециркулюючий потік виникає в області за зворотним уступом. Збільшення розміру зворотного уступу призводить до збільшення швидкості подачі реагенту, рециркулюючого потоку і напруги зсуву поблизу зворотного уступу. При великому розмірі зворотного уступу, висока швидкість подачі реагенту разом з великим напруженням зсуву гасить полум'я, в той час як тепла, утилізованого рециркулюючим потоком, недостатньо для стабілізації полум'я і полум'я переміщується нижче по потоку. Отже, більший розмір зворотного уступу призводить до більш вузької області межі стійкості полум'я. Чим менше розмір зворотного уступу, тим ширше межа стійкості полум'я, яка більше зміщується до областей нижчого коефіцієнта надлишку палива і високої швидкості подачі реагенту. Зменшення розміру зворотного уступу знижує швидкість подачі реагенту в зону реакції горіння, а також зменшує рециркулюючий потік і напругу зсуву, нівелюючи ефект гасіння. Менший рециркулюючий потік сприяє стабілізатору полум'я в підвищенні стійкості полум'я в мезомасштабній камері згорання. Отже, невеликий розмір зворотного уступу грає дуже важливу роль в утилізації теплової енергії, стабілізуючи полум'я в мезомасштабній камері згорання*

*Ключові слова: зворотний уступ, циліндрична мезомасштабна камера згорання, постійна площа контакту, стабілізатор полум'я, межа стійкості полум'я*

## 1. Introduction

In the last two decades, miniaturization of power generator based on the combustion in micro- and meso-scale has been investigated extensively [1]. This is motivated by the high energy density of micro-power generators, which is higher than the energy density of lithium-ion batteries used today [2–7]. Micro-power generator consists of two main parts, which are micro- or meso-scale combustor and thermal to electric energy conversion module [4]. The chemical energy of the fuel is converted to heat energy in a micro- or meso-scale combustor. Furthermore, heat is converted into electrical energy. One way to convert heat energy into electrical energy is by using Thermophotovoltaic (TPV) technology. Thermophotovoltaic requires a high and uniform combustor wall temperature to get a high-efficiency micro-power generator. Stable combustion at a high fuel flow

rate and high efficiency of thermal to electric energy conversion are required to obtain high energy density micro-power generator.

## 2. Literature review and problem statement

It is well understood that it is troublesome to stabilize stable combustion inside the micro- or meso-scale combustor, especially at a high fuel flow rate. This is caused by inadequate reaction time due to short fuel residence time, high heat loss to heat generation ratio related to high surface to volume ratio as well as the presence of thermal quenching near the combustor wall [1]. Especially micro- or meso-scale combustors with liquid fuel require more attention related to fuel vaporization and fuel-air mixing before the combustion process [8]. Decreasing of combustor diameter results in

an increase of the surface to volume ratio, hence intensifies the heat loss to heat generation ratio and reduces flame stability inside the combustor [1, 5, 9]. Many research has been conducted to improve the stability of combustion in micro- or meso-scale combustors [6], such as using catalytic combustion [10], application of porous media combustion for micro thermophotovoltaic system [11], combustion of hydrogen-oxygen mixture using microporous media [12], external heating [13], and heat recirculation in the combustor [14]. Stable combustion also could be established inside the meso-scale combustor using inserted wire mesh which has two functions as a flame holder and increases heat recirculation from the flame to burn reactant [1].

Some researchers investigated the role of backward facing step on the combustion stability in the micro-combustor. The use of the backward facing step in the micro-combustor could improve the stability of combustion at higher reactant velocities with larger equivalence ratio ranges [2]. This is due to the improvement of reactant mixing with the formation of recirculation flow around the backward facing step and increasing the residence time of reactants inside the combustor, promoting complete and stable combustion. Micro-combustor with backward facing step was used as a component of the micro thermophotovoltaics power system successfully [3]. Flame-vortex interaction inside the combustor with a backward facing step has been investigated. The results indicated that the interaction of the flame and vortex has a significant role in the flame dynamics in the combustor with the backward facing step. The stability of the flame could be achieved with the smaller vortex size on a combustor of gas turbines. On the contrary, as the size of vortex grew larger, the stability of the flame diminished [15]. The other research showed that the increase of the step height (increasing of the inner diameter of the reactor) could increase flame stability, flame front becomes less sensitive to imposed perturbations [16].

However, in the previous researches at the micro-scale combustor, backward facing step was made by increasing the diameter of the combustion reaction zone, while the inlet diameter was kept constant, such as combustors with an inlet diameter of 2.15 mm and outlet diameter of 2.76 and 2.96 mm respectively [2]. The same size combustors were used to build a micro power system using thermophotovoltaic [3]. Flame dynamics inside combustors with an inlet diameter of 2.2 mm and different outlet diameters of 3 and 5 mm were investigated using methane fuel and oxygen as an oxidizer [16]. The diameter of the combustion reaction zone has a great influence on the flame stability within the micro- or meso-scale combustor as shown by [9] and [1]. [9] showed that the increase in combustor diameter generated the higher average flame temperatures and more uniform temperature distribution area at the center combustor was wider, while the combustor with smaller diameter had parabolic temperature distribution. The volumetric heat loss is larger in the combustor with a smaller diameter, promoting unstable combustion. In [1] showed that changing the combustor diameter from 2.5 mm to 5.4 mm increases the maximum velocity in which stable combustion occurred inside the combustor near flame holder, the maximum reactant velocity increased from 24.8 cm/sec to 34.5 cm/sec. Furthermore, combustion may occur in a stable condition at poorer or richer mixture, or in the wider equivalence ratio interval. Hence, the increasing of flame stability in the combustor with the backward facing step in the previous researches is

actually affected by two parameters, the first is the existence of backward facing step, the second is increasing of combustor diameter. Based on these results, it can be concluded that the better combustion stability in the previous researches is caused by two factors, namely backward facing step [2] and the presence of diameter enlargement at the reaction zone. These facts were observed in the straight micro combustor with wire mesh and different diameters [1], inside combustors with backward facing step with various outlet diameters at a constant inlet diameter [2], as well as in a numerical simulation of combustion inside micro combustors with different diameters [9]. It can be concluded that the combustor diameter at the reaction zone is a very sensitive factor in combustion stability inside the micro-/meso-scale combustor. Therefore, it is not clear whether the stability of the combustion is supported by the backward facing step or reduction of heat loss due to the enlargement of the combustor diameter. To understand exactly the effect of backward facing step on the flame stability in the meso-scale combustor, in this research the changing of heat loss effect is eliminated by keeping the diameter of the combustion reaction zone at a constant value. Variation of backward facing step size is done by changing the inlet diameter.

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### 3. The aim and objectives of the study

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The aim of this research is to find out the effect of backward facing step on combustion stability in a constant contact area cylindrical meso-scale combustor.

To achieve this aim, the following objectives were set:

- to provide reactant flow pattern simulation and the sketch of the flame position, the graph of the ratio of the inlet velocity to the reactants velocity in the reaction zone, and the graph of velocity gradient in the combustor versus combustor diameter at backward facing step position and flame position in a constant contact area cylindrical meso-scale combustor with various backward facing step size ratios;
- to analyze the flame visualization and the graph of the flame stability limits on a constant contact area cylindrical meso-scale combustor with various backward facing step size ratios.

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### 4. Materials and methods of research

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Fig. 1 shows the schematic of the test equipment in this study. Fuel and oxidizer in this study are butane ( $C_4H_{10}$ ) and air. Butane is supplied from a pressurized tube, in which the flow rate is measured using a flowmeter for Butane (Kofloc, RK 1250, the maximum flow rate of 20 ml/min), while air is supplied from an air compressor tank. The air flow rate is adjusted using an air flow meter (Kofloc, RK 1250, the maximum flow rate of 500 mL/min).

Detail geometry of the cylindrical meso-scale combustor with the backward facing step is shown in Fig. 2. The combustor was made of copper at the inlet side and quartz glass tube at the outlet side, with a constant outlet diameter of 4.7 mm ( $D_2$ ). To understand the flame stability in the cylindrical meso-scale combustor due to the existence of backward facing step without any effect of the outlet diameter (burning zone) enlargement, inlet diameter varied to obtain the  $D_1/D_2$  ratio variation. The values of  $D_1$ ,  $D_2$ , and  $D_1/D_2$  ratios can be seen in Table 1.

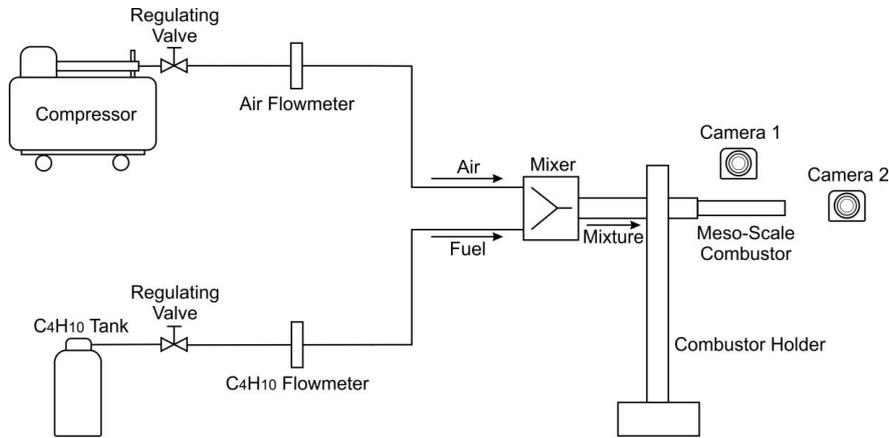


Fig. 1. Schematic of test equipment

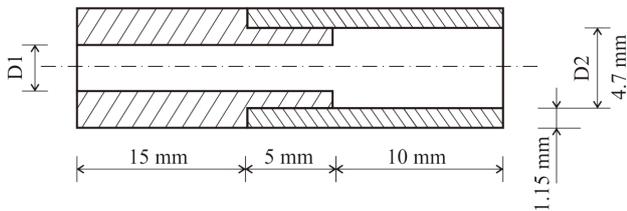


Fig. 2. Schematic of the cylindrical meso-scale combustor with backward facing step

was simulated in the reaction zone using Ansys Fluent 15.0 software, which is based on the finite volume method. In this numerical simulation process, the fluid flow modelling was made in steady state two-dimensional flow field with constant flow rate.

The combustor used has a varying inlet diameter and constant outlet diameter as shown in Table 1. In Fig. 3, the domain of the numerical scheme of a half-part cylindrical meso scale combustor is shown with a total length of 30 mm, where the combustor is divided into two parts that are the 20 mm inlet section with a variation of inlet diameter and the outlet section is 10 mm long with a constant outlet diameter of 4.7 mm (radius=2.35 mm). Between these two parts, there is a limit of enlargement of the combustor diameter as a backward facing step that functions as a flame holder. The first numerical procedure performed was combustor geometry modelling, which was then followed by the process of meshing the Ansys Fluent 15.0 software. The results of the meshing process are shown in Table 2 and Fig. 4.

Table 1

Variations of combustor geometry dimensions

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

The butane and air gases are supplied respectively from fuel and air compressor tank, and their flow rate is controlled through butane and air flowmeters (Kofloc, RK 1250) with measurement range at 2–20 mL/min and 50–500 mL/min respectively. Fuel and air flow rates were varied from the minimum to maximum value in which stable flame could be established inside the meso-scale combustor. Before entering the combustor, air and fuel were mixed in the mixing chamber to produce a premixed mixture. The mixture was ignited using a torch at the combustor rim, then flame propagates and stable inside the combustor at the suitable air and fuel flow rate. Otherwise, the flame was extinguished, flashback or blow-off. This data was used to build a flame stability area in the total velocity-equivalence ratio plane.

Flame visualizations are obtained using the digital camera (Canon EOS 60D). Two cameras provided visualization of the flame from the front and side view. The latest flame visualization allows us to know the axial position of the flame in the cylindrical meso-scale combustor. The factor affecting flame stability namely the reactant flow pattern

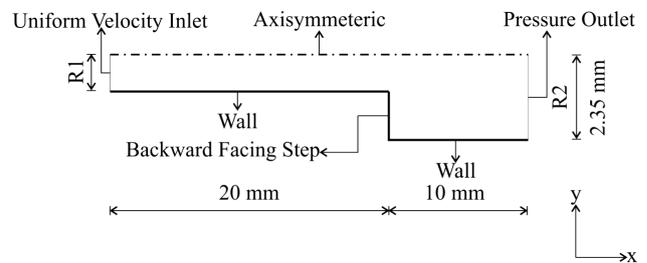


Fig. 3. The domain of the numerical scheme

Table 2

The results of the meshing process

Inlet Diameter, $D_1$ (mm)	Outlet Diameter, $D_2$ (mm)	Elements Unit
2.4	4.7	18989
2.8	4.7	20588
3.3	4.7	22584
3.8	4.7	24583
4.2	4.7	26180

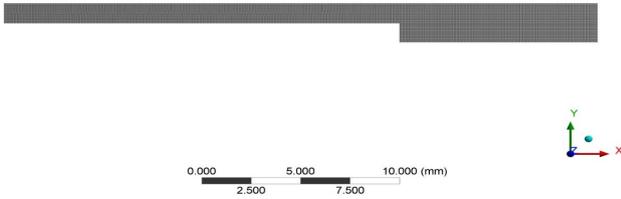


Fig. 4. Meshing (example of meshing at  $D_1=2.4$  mm and  $D_2=4.7$  mm)

Governing equations used in this numerical simulation are:

– the continuity equation:

$$\frac{\partial}{\partial x}(\rho v_x) + \frac{\partial}{\partial y}(\rho v_y) = 0; \tag{1}$$

– the momentum equation:

– X axis direction

$$-\left[ \frac{\partial(\rho v_x v_x)}{\partial x} + \frac{\partial(\rho v_x v_y)}{\partial y} \right] - \frac{\partial \rho}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial x} = 0; \tag{2}$$

– Y axis direction

$$-\left[ \frac{\partial(\rho v_y v_x)}{\partial x} + \frac{\partial(\rho v_y v_y)}{\partial y} \right] - \frac{\partial \rho}{\partial y} + \frac{\partial \tau_{yx}}{\partial x} + \frac{\partial \tau_{yy}}{\partial x} = 0. \tag{3}$$

The next stage is the setting of boundary conditions where the arrangement was done by varying the  $D_1/D_2$  ratio until the iteration reaches convergence. The following stage was the solving process and the last was the result plotting stage. Table 3 describes the summary of the model setup. Zero heat flux (insulation) was inputted to the boundary conditions around the combustor wall. At the outlet boundary conditions, the pressure was conditioned to be fixed. The flow in the inlet boundary condition was set to be turbulent flow with a speed of 15 cm/s.

Table 3

Summary of the model setup

Parameters	Model setup
Solver	Pressure-based, steady state and axisymmetric
Press.-velocity coupling	SIMPLE
Spatial discretization	First-order upwind scheme
Turbulence model	$k$ -epsilon ( $k-\epsilon$ ) standard
Convergence criteria	$1 \times 10^{-3}$ for continuity and velocity

### 5. Results of the effect of backward facing step on combustion stability in a constant contact area cylindrical meso-scale combustor

In this research to keep the constant combustor contact surface area, i. e., constant heat loss, the backward facing step was varied by changing the combustor inlet diameter ( $D_1$ ) keeping constant the combustor diameter at the reaction zone ( $D_2$ ). In this case, the flow through the combustor generates a recirculation flow region in the downstream of the backward facing step due to flow separation and reat-

tachment. Larger backward facing step will result in larger recirculation flow region size [17]. The scale of the recirculation flow region is proportional to the backward facing step size as shown by the simulation result in Fig. 5. Fig. 5 shows the flow pattern of the reactant and the recirculation flow region that occurs due to the variation of the size of the backward facing step. It is also shown that with the large recirculation flow region, the position of the flame will move further away from the backward facing step (ratio  $D_1/D_2$  0.5, 0.6 and 0.7). In the small recirculation flow region due to the small backward facing step size, the flame position will be attached to the backward facing step for the  $D_1/D_2$  ratio of 0.8 and 0.9.

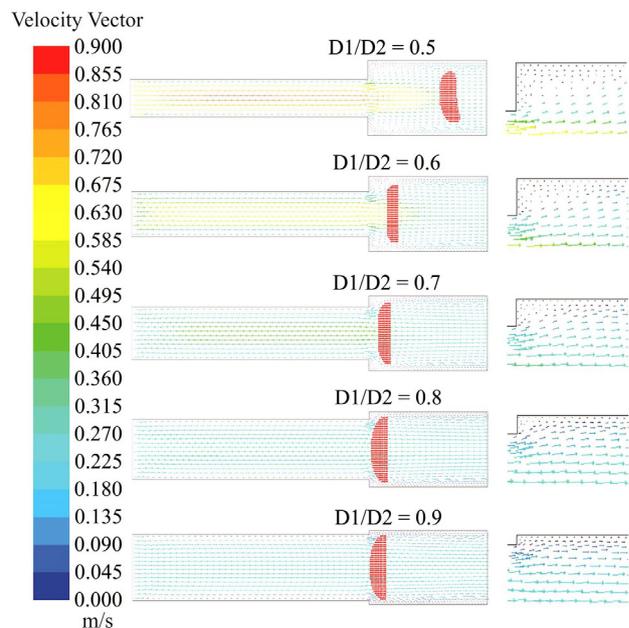


Fig. 5. Reactant flow pattern simulation and flame position (red color) sketch on the cylindrical meso-scale combustor with backward facing step

As shown in Fig. 6, the inlet flow velocity to reactant velocity at a reaction zone ratio ( $v_{in}/v$ ), estimated from Fig. 5, increases drastically with increasing backward step size (or lowering  $D_1/D_2$ ). The backward facing step size variation will result in the speed of reactants entering the inlet region varied for  $D_1/D_2$  variation ratio and resulting in reactant velocity entering the reaction zone increases with the smaller ratio (the larger backward facing step). The increase of reactant velocity as a function of magnification of the backward facing step size can be seen in Fig. 6 which is a comparison between inlet velocity to velocity in the reaction zone ( $v_{in}/v$ ) at various  $D_1/D_2$  ratios. The velocity at the reaction zone ( $v$ ) is the average axial velocity that is calculated based on the reactant volume flow rate and cross section area in the reaction zone.

Increase in  $v_{in}/v$  with increasing step size or decreasing  $D_1/D_2$  (Fig. 6) increases the transversal velocity gradient ( $du/dy$ ) at backward facing step as shown in Fig. 7, a. The  $du/dy$  represents shear stress. It is seen in Fig. 7, a that at large shear stress in the core velocity region, the flow region with low shear stress gets narrower. In this condition, the flame is very unstable so that it drifts far to the downstream as shown in Fig. 5 for  $D_1/D_2=0.5$ .

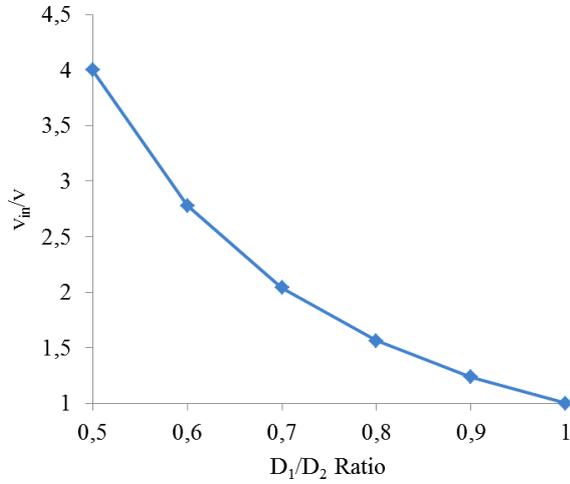


Fig. 6. Inlet velocity to reactant velocity at the reaction zone ( $v_{in}/v$ ) ratio at various  $D_1/D_2$  ratios

step position (in the direction of the x-axis) for each variation of the  $D_1/D_2$  ratio is shown in Table 4.

Table 4  
The distance of the flame position from the backward facing step position

$D_1/D_2$ Ratio	Distance, $x$ (mm)
0.5	6.3
0.6	1.7
0.7	1
0.8	0.3
0.9	0.1

The result of several factors analysis is also proved by giving the combustion stability through flame visualization

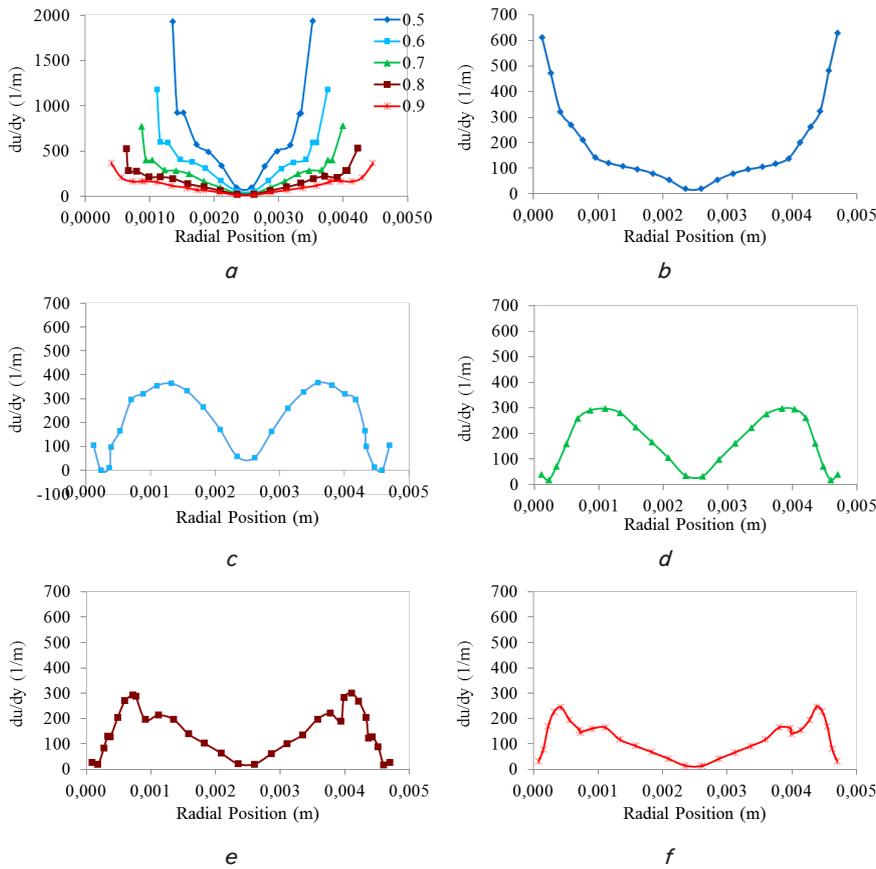


Fig. 7. Velocity gradient in the combustor versus radial position: *a* – at  $x=0$  mm (backward facing step position); *b* – at  $x=6.3$  mm (flame position for  $D_1/D_2$  of 0.5); *c* – At  $x=1.7$  mm (flame position for  $D_1/D_2$  of 0.6); *d* – At  $x=1$  mm (flame position for  $D_1/D_2$  of 0.7); *e* – At  $x=0.3$  mm (flame position for  $D_1/D_2$  of 0.8); *f* – At  $x=0.1$  mm (flame position for  $D_1/D_2$  of 0.9)

(Fig. 8) and combustion stability map in the form of the flame stability limit graph (Fig. 9) below. Fig. 8 shows the visualization of flame in the cylindrical mesoscale combustor with  $D_1/D_2$  ratio variation at 1.4 equivalence ratio with reactant velocity of 15 cm/s. Flame visualization is done from the combustor side and front view. Side view flame visualization allows seeing backward facing step size effect on the flame shape and position in the axial direction. Based on Fig. 8, the flame position is getting farther away from backward facing step along with reduced  $D_1/D_2$  ratio (increasing backward facing step size). In the  $D_1/D_2$  ratio 0.5, 0.6, and 0.7, the flame position is located far from the backward facing step. But for the  $D_1/D_2$  ratio of 0.8 and 0.9, the flame position is attached to the backward facing step.

Fig. 9 presents a flame stability limit in the cylindrical meso-scale combustor with various  $D_1/D_2$  ratios at 1.4 equivalence ratio and reactant velocity of 15 cm/s. The reactant velocity is calculated based on the combustor diameter at the reaction zone ( $D_2$ ). The increasing  $D_1/D_2$  ratio from 0.5, 0.6, 0.7, 0.8 to 0.9 makes the backward facing step inside the combustor getting smaller. The results show that the larger the backward facing step size, the narrower the flame stability limit area and flame can only be stable at low reactant velocity. The flame stability limit is very narrow at very large step size ( $D_1/D_2=0.5$ ).

As shown in Fig. 7, *b*, to *f*, the  $du/dy$  at the flame position is relatively small. Except in Fig. 7, *b*,  $du/dy$  in the flame position tends to decrease toward the wall from the maximum value which indicates the recirculation flow region as described by the velocity vector in Fig. 5. In Fig. 7, *b*, the flame position is at the downstream of the recirculation. This is due to the very high reactant inlet velocity at  $D_1/D_2=0.5$  (Fig. 6). The distance of the flame position from the backward facing

Overall, the flame stability area in fuel-rich conditions ( $\phi>1$ ) area. The backward facing step size variation will cause a shift in the flame stability limit area. Wider shifts lead toward lower equivalence ratios and smaller shifts toward a high equivalence ratio. Fig. 9 also shows a phenomenon that the shift of flame stability limit area based on reactant velocity direction increases along with decreasing size of the backward facing step.

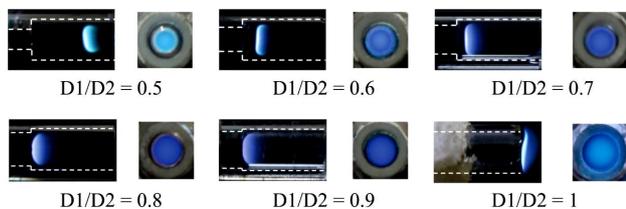


Fig. 8. Visualization of flame in the cylindrical meso-scale combustor at various backward facing step  $D_1/D_2$  ratios

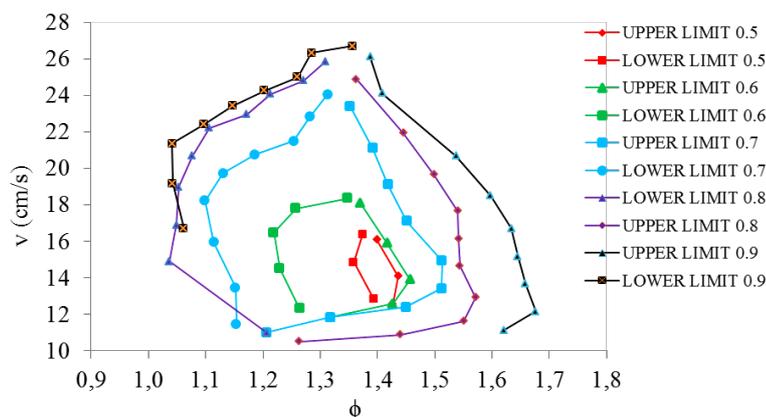


Fig. 9. Flame stability limit on the cylindrical meso-scale combustor with backward facing step

### 6. Discussion of the effect of backward facing step on combustion stability in a constant contact area cylindrical meso-scale combustor

The recirculation flow caused by backward facing step has a role to return heat loss and unburned reactant to the reaction zone that stabilizes the flame. But too large recirculation at a bigger backward facing step ( $D_1/D_2$  ratio=0.5) tends to bring more mass into the reaction zone which disrupts the flame stability. This cause the flime to stretch and the balance between heat and mass in the reaction zone cannot be achieved. Consequently, the flame drifts downstream (Fig. 5). The smaller the recirculation the more sufficient heat recovered. Consequently, the flame stability is better fixed on the step at  $D_1/D_2=0.9$ . However, without a backward facing step ( $D_1/D_2$  ratio=1) the flame blows out of the combustion chamber. In this case, the combustion process is not able to occur inside the combustor, which causes the flime to be washed away (blow off from the combustor). This suggests that very small recirculation flow is very important as a flame holder that recovers the heat loss.

High inlet velocity to reactant velocity at a reaction zone ratio ( $v_{in}/v$ ) is another factor that disturbs the flame stability at large recirculation flow. From Fig. 6 it is shown that as the smaller inlet diameter (smaller  $D_1/D_2$  ratio) the reactant velocity entering the reaction zone becomes larger. Increasing the velocity of this reactant inlet leads to a significant decrease in combustion stability inside the combustor with higher backward facing step size. Stability of combustion will be achieved if the velocity of reactant and combustion velocity is balanced. In a combustor with backward facing step there will be a flow separation due to sudden channel enlargement, then the flow will return to fill the channel after a certain distance that is called reattachment length. The  $D_1/D_2$  ratio greatly influences the reattachment length

and the reattachment point position, where the smaller the  $D_1/D_2$  ratio leads to smaller inlet diameter, larger cross-section changes, and larger inlet velocity, resulting in greater reattachment length and reattachment point position far from the backward facing step [15]. Once the reactant flow reaches the reattachment point increase in reactant velocity will be equal to the speed increase as shown in Fig. 6 earlier according to the variation of the ratio of  $D_1/D_2$  respectively. In the reattachment length area, the reactant has a higher velocity so that the fire becomes unstable and blow-off occurred because the reactant velocity is greater than the flame propagation speed.

The shortcomings and restrictions of this research were reactant velocity before entrance to the reaction zone was distinct depend on the  $D_1/D_2$  ratio. We could not use the results to understand the role of backward facing step on the flame stability for the same reactant inlet velocity as well as the constant diameter of the reaction zone.

In this research, the larger the backward facing step size, the higher the velocity gradient and shear stress also, as shown in Fig. 7. The increase of the velocity gradient and shear stress is caused by a reactant velocity increase entering the reaction zone. The flame stability will be achieved if shear stress is not significant because of less heat transfer. In this case, shear stress has deformation properties (distortion) to the flame and tends to damage the flame. Shear stress plays a role in increasing heat transfer from the reaction zone to the combustor wall due to transport momentum. If shear stress is significant it will cause the heat wasted out of the reaction zone to increase and cause unbalanced mass and heat conditions for combustion that tend to cause the stretching flame. If the flame is stretching, then the amount of unburned mass will increase and heat loss for the reaction occurred. This will cause a difficult burning so the flame will be extinguished and unable to sustain the reaction. Significant shear stress will cause the stability of combustion decrease due to more heat transfer that occurs. This suggests that the flame stability is determined by the reactant inlet velocity, shear stress, and recirculation which respectively tends to blow the flame out, to transport the thermal energy from the flame toward the wall that quenches the flame, and to recover the heat energy toward the flame.

The proposed feature is the role of backward facing step in increasing flame stability by varying inlet diameter keeping the diameter of the combustor reaction zone to be constant. This method removes the effect of increasing of the combustion reaction zone as well as the heat loss ratio which was included in the previous research. The results show that backward facing step is very important to stabilize the flame inside the combustor, however smaller size is better. In this study, the size of the backward facing step is varied with a constant diameter of the combustion reaction zone. The results showed that stable combustion occurs in small backward facing step size. The flame fulfilled the combustor cross section so that higher wall temperatures are expected to be produced. This combustor is the main part of a micro power generator that will produce more electrical energy than other combustors. In the previous study, the larger backward facing step resulted in stable combustion, but low wall temperatures. Even though what is needed for micro power generators is stable combustion with uniform and

high wall temperatures. So the method used in this study is more profitable, namely by varying the size of the backward facing step while maintaining a constant reaction zone.

Fig. 8 shows the flame position, geometry, and color at various  $D_1/D_2$ . As shown in Fig. 8, at  $D_1/D_2=0.5$  the flame position is at two combustor diameters downstream from the step. This is due to the fact that too high reactant inlet velocity (Fig. 6) together with very large recirculation that brings large reactant mass to the flame destabilize the flame so that the flame drifts to the downstream of the recirculation region (Fig. 5, 7). This indicates that the flame position is played by the reactant inlet velocity and the recirculation flow. In the combustor with the  $D_1/D_2$  ratio of 0.5, 0.6, and 0.7 the reactant inlet velocity and the recirculation flow tends to be larger than the  $D_1/D_2$  ratio of 0.8 and 0.9. As discussed earlier, the larger recirculation flow ( $D_1/D_2$  ratio of 0.5, 0.6, and 0.7) tends to carry more mass than heat. The flame is unable to approach the backward facing step due to the increased mass concentration around the backward facing step as larger recirculation flow. The stability of the combustion will be disrupted if the reactant velocity and the recirculation flow in the reaction zone are too high. The flame geometry indicates that without heat recovery by the recirculation the flame is quenched at a region near the wall by the heat loss due to shear stress. As the step size decreases with increasing  $D_1/D_2$  ratio the flame shifts upstream closer to the step. This is the consequence of the decrease in reactant inlet velocity and the shear stress as presented in Fig. 6, 7. Therefore, the smaller recirculation flow starts to play the role to recover heat energy that stabilizes the flame.

The heat transfer from the reaction zone to the combustor wall reduces the heat for the reaction so that the flame will withstand the shear stress towards lower mass conditions (away from the backward facing step). The greater shear stress results in an increase in distortion properties. The flame cannot survive the large shear stress. The flame will find the place where the shear stress is low so that the distortion is relatively small. In the  $D_1/D_2$  ratio of 0.8 and 0.9 fire is stable in the backward facing step because in both combustors the resulting shear stress is low so that the distortion effect against heat is low. In addition to the  $D_1/D_2$  ratios of 0.8 and 0.9, the small recirculation flow is formed and tends to carry more heat than the mass. This is also accompanied by small shear stress value due to the small velocity gradient. The recirculation flow presence will add more heat to the reaction zone and reduce heat transfer from the reaction zone to the combustor wall because of less shear stress. That phenomenon describes recirculation flowability to act as a flame holder because the flame is able to survive in the backward facing step area.

The color of the flame confirms the role of reactant speed, shear stress that loses the heat energy to the wall, and recirculation which recovers the heat energy. At large step ( $D_1/D_2=0.5$ ) the flame front color is bright and tends to green on the product side indicating that the combustion is rich at the high inlet reactant velocity. Since the flame position is downstream of the recirculation (Fig. 5) so the heat loss due to shear stress is larger than the heat supplied to the flame by recirculation. This matches the color of the flame which indicates that the Lewis number is less than unity, i. e., reactant mass flux to the reaction zone is larger than the heat flux to the flame. As  $D_1/D_2$  increases or step size decreases the flame color tends to become blue indicating that the flame becomes nearly stoichiometry with Lewis number around

unity. This confirms the role of the decrease of reactant flow rate, heat loss due to shear stress, and the increase of heat recovery due to recirculation. At a zero step size ( $D_1/D_2=1$ ), however, the flame cannot be stabilized inside the combustor but it is blown out to the combustor rim. This suggests that the smallest step size plays a very important role as a flame holder that stabilizes the flame toward stoichiometry.

This study investigated the effect of the backward facing step inside the meso-scale combustor at the same combustion reaction zone diameter, compared to the previous study which has larger combustion reaction zone diameter while the step size was increased. The diameter of combustion reaction influences significantly the heat loss from the combustor, and then improves flame stability. Therefore, this study is important to investigate the role of backward facing step on the flame stability by removing the effect of combustion reaction zone diameter and heat loss ratio from the combustor. Both of combustor diameter and heat loss from the combustor are a very important factor to establish the stable flame in micro-/meso-scale combustions. The result of this study shows the opposite tendency compared to the previous research. The smaller size of the step in the combustor develops more stable combustion.

In this study, the results were the superiority of this study, namely that backward facing step has a better role as a flame holder on a smaller backward facing step size. While the combustor without backward facing step will cause the flame to blow off on the combustor rim. In previous studies [1–3, 9, 15, 16], it was generally stated that flame stability was influenced by the presence of backward facing step effects which increased mixing of reactants, residence time and combustion stability, and the effect of enlarging diameters that decreased heat loss so that the flame stability increases, and it is not clear whether the stability of the flame is caused by the presence of a backward facing step effect or because of the enlargement of the diameter. In this study specifically, it was found that the step backward facing effect (without enlarging the reaction zone diameter/constant diameter of the combustor reaction zone) could increase the flame stability.

Some of the factors that have been shown previously greatly affect the level of combustion stability, where the stability of combustion will be disrupted if the inlet reactant velocity into the reaction zone is too high causing the shear stress to increase thereby increasing the heat transfer from the reaction zone to the combustor wall and recirculation is too large causing the fire to stretch due to the increase in mass coming into the reaction zone. This indicates that the quenching effect due to high reactant inlet velocity and large shear stress is very dominant compared to the heat supplied by recirculation to the flame. As the step size getting smaller the flammability limit becomes wider (Fig. 9). The stability limit tends to become wider to the lean mixture and to the high reactant velocity at the smaller step size. This is due to the fact that at the smaller step the shear stress is smaller so that the heat loss reduces while heat recovered by the recirculation getting larger. The slightly larger heat recovered more readily for burning of the leaner mixture than the richer one. At the smallest step, however, the stability limit tends to become wider to the rich mixture. In this case, the shear stress and reactant inlet velocity become less dominant and the small recirculation starts to play the dominant role in pumping thermal energy to the flame that stabilizes the flame more at the richer mixture. The slightly wider flame

stability limit to the lean mixture region might be due to the inhibition effect of nitrogen molecule. Nevertheless, it could be concluded that the smaller the step size the more stable the flame and becomes very stable at very small step size. However, without backward facing step, the flame is blown out. This suggests that the smallest step plays a very important role in recovering heat energy as a flame holder in the cylindrical meso-scale combustor.

Fig. 9 shows that flame stability points in fuel-rich conditions ( $\phi > 1$ ) area and a narrowing flame stability limit area occur due to the backward facing step effect that forms a recirculation flow. In this case, the recirculation flow has a high intensity to the diffusion process (both mass and thermal diffusion), so a large amount of energy is used for the decomposition than combustion reaction process. If the reactant mixture is in poor condition then there will be more air than fuel hence causing more energy absorption for air decomposition than fuel decomposition process. Oxygen contained air decomposition requires the higher temperature than the fuel decomposition process, so in excessive air conditions (poor mixture) more energy will be absorbed for decomposition process than for reaction. This will result in flame quenching due to low unburned energy. When in the rich condition, the percentage of fuel is much more than the air. The energy absorption for oxygen contained air decomposition process becomes lesser than in the poor conditions, so the energy needed for combustion reaction will be fulfilled. This causes the flame stability limit graph to narrow and its stability points in fuel-rich mix conditions.

The backward facing step size variation will cause a shift in the flame stability limit area, as shown in Fig. 9. Wider shifts lead to lower equivalence ratios and smaller shifts toward a high equivalence ratio. This relates to the energy absorption and mass intensity contained in each mixture. At a lower equivalence ratio, the mass intensity will be lower than the high equivalence ratio. This causes the energy absorption for the decomposition process at a lower equivalence ratio less than the high equivalence ratio. The combustion reaction process will be easier to occur at a lower equivalence ratio so that the shift of the flame stability limit area tends to be wider in the direction of the lower equivalence ratio area. Conversely, the mass intensity at a higher equivalence ratio is greater so that the energy absorption for the decomposition process will increase. The combustion reaction process will be more difficult to achieve at a high equivalence ratio and the shift of the flame stability limit area to the higher equivalence ratio tends to be smaller. Fig. 9 also shows a phenomenon that the displacement of the flame stability limit region based on the direction of the reactant velocity increases with the decrease in the size of the backward facing step. This corresponds to the reaction rate at which flame stability can occur when the velocity of the reactant and the reaction rate reach equality. As noted above, the decrease in the size of the backward facing step results in a decrease in the size of the recirculation flow in the backward facing step area. This is related to the intensity of the mass and the intensity of the heat caused by the recirculation flow. In large vortices, the mass intensity will increase and tend to absorb a lot of energy for the decomposition process rather than the reaction process. As a result, the reaction process becomes more depressed which causes the reaction speed to decrease. In contrast to the small backward fac-

ing step, the resulting recirculation flow is also small and tends to carry less heat and masses. Energy absorption for decomposition is lesser than in large recirculation flow conditions, so the reaction process will be easier hence increasing the reaction rate.

Beside effect of the recirculation flow, the shift of flame stability limit graph region is also affected by shear stress on each combustor. A small shear stress is obtained along with decreasing backward facing step size. As discussed earlier, large shear stress tends to throw more heat from the reaction zone to the combustor wall. This resulted in the insufficient heat for the reaction process and causes the reaction rate to be slower or even turned off. In contrast to small shear stress, the heat transferred from the reaction zone to the combustor wall is not significant. The combustion reaction process can be achieved and the reaction rate increases. If connected between recirculation flow and shear stress an equality will be obtained where a low shear stress value occurs along with a small recirculation flow. Small recirculation flow tends to carry heat but lesser mass. The heat energy in the reaction zone will be increased but heat loss effect is insignificant due to low shear stress. In this condition, the combustion velocity increases and causes combustion to take place at higher reactant velocity.

The development of this research is a straight cylindrical meso scale combustor model with concentric ring insertion. This model aims to generate effects similar to the backward facing step model. This effect can be generated in the reactant inlet velocity and combustor reaction zone diameter which are kept constant as in the backward facing step model. This effect is precisely carried out in the development of the next backward facing step model because it is expected to produce the same effect as a backward facing step model. The threat of developing this research area is difficult to maintain the stability of combustion on a small scale due to a large amount of heat loss in the combustor.

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## 7. Conclusions

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1. Increasing backward facing step size leads to an increase in recirculation flow size, reactant inlet velocity, velocity gradient, and shear stress, which have an important effect on the flame stability. The big size of reactant inlet velocity, shear stress, and recirculation flow tends to blow the flame out, induce the heat transfer from the flame toward the combustor wall that quenches the flame. Flame stabilization mechanism through flow recirculation was diminished by high reactant inlet velocity and shear stress effect.

2. The flame was stabilized near the backward facing step at the small backward facing step size. The flame color tends to become dark blue indicating that the combustion process takes place at the nearly stoichiometry condition. At the larger backward facing step size, the flame position is getting farther away from backward facing step due to higher reactant inlet velocity and larger recirculation flow size, as shown by the numerical results of reactant flow pattern. Without the backward facing step, flame only could be stabilized at the combustor outlet. Flame stability limit area decreases with the increasing of backward facing step size, and flame can be stabilized only at low reactant velocity. As the backward facing step size getting smaller,

the flame stability limit becomes wider. This area expands toward lower and higher equivalence ratios. More shifting occurs toward the lower equivalence ratio. The small backward facing step plays a very important role to stabilize the flame by heat recovering and flow recirculation mechanism which acts as a flame holder in the cylindrical meso-scale combustor.

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