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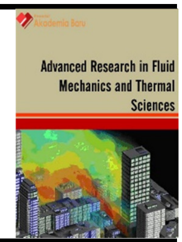

Study on The Effect of Bluff Body with Slit in the Micro-Channel Combustor

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W. M. A. W. Shuib [1], Azam Che Idris[1], Mohd Rashdan Saad[1], Mohd Faizal Hasan[2], Mohd Rosdzimin Abdul Rahman[1,*]

[1] Department of Mechanical Engineering, Faculty of Engineering Universiti Pertahanan Nasional Malaysia, Kem Sg Besi, 57000 Kuala Lumpur, Malaysia
[2] Automotive Development Centre, Institute for Vehicle System and Engineering, Faculty of Mechanical Engineering Universiti Teknologi Malaysia, 81310 Skudai Johor, Malaysia

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ABSTRACT

Effect of the bluff body with slit in the micro-channel combustor has been numerically studied. Two-dimensional computational domain with the height and length of the channel is H = 1 mm and L = 16 mm were used. The height of the bluff body is 0.5 mm and located at 2 mm from the inlet. The slit gap percentage utilized in this study is 0% to 70%. Percentage of the slit size is a ratio between slit gap height and the bluff body height. The one-step reaction mechanism of CH_4/air mixture is used. Results of the numerical work shows that the combustion characteristic is significantly influenced by the slit gap percentage. The highest emitter efficiency is for the case of 5% slit. Moreover, increase in slit percentage to 10%, the flame zone is moving downstream. Later, as the slit percentage increase to 30%, the flame zone moves towards the upstream. This observation is suggested due to the secondary vortex exist behind the bluff body as slit gap increases and pull the flame to the upstream. This study is helpful to improve the understanding on the micro-channel combustion with slit bluff body.

1. Introduction

Progression of miniaturized products such as micro unmanned aerial vehicles, micro-robots, and tiny scale electronics devices are becoming important nowadays. In spite of the configuration diversity, these micro systems required a power pack that can supply energy in a long period and have higher power to weight ratio. Therefore, researchers utilize liquid hydrocarbon fuel that has high-specific energy in micro scale combustor to generate power and lighten loads. The dimension of the micro combustor may vary from certain micrometers. Due to reduction of size, the system efficiency becomes relatively poor as a result of less stable flame and tends to blow off due to loss of heat from the combustion process to the combustor boundary.

[*] *Corresponding author.*
E-mail address: rosdzimin@gmail.com (Mohd Rosdzimin Abdul Rahman)

Studied on micro combustor geometry configuration and size have been made by several researchers. Epstein and Senturia [1] developed a micro heat engine, while Mehra *et al.,* [2], Hua *et al.,* [3] and Chan *et al.,* [4] study on micro-gas turbine. Moreover Yang *et al.,* [5-6] carried a study on micro-thermo photovoltaic (TPV) system. Combustion at a small scales in a micro combustor is hard to sustain due to the increased of wall radical capture and dissipation of heat due to the huge surface area-to-volume ratio [7,8]. Lots of studies on micro combustion stability have been reported [9-16]. For instance, Pan *et al.,* [9] and Bhupendra *et al.,* [10] conducted a study on the micro-cylindrical combustors with a different backward facing step and founds that the rearward step enhances the flame stability inside the micro-combustor. Moreover, Li *et al.,* [11] study on the effects of the flow velocity and combustor diameter and observed that the flame temperature increases as increase in combustor diameter, but inversely proportional to flow velocity. Li *et al.,* [11] also found that a 2D planar channel micro combustor gives a higher flame temperature compared to a cylindrical tube micro combustor at an equal hydrodynamic diameter. Later, Jun *et al.,* [12] revealed that a cylindrical micro combustors experience higher heat loss because a small combustor give higher surface to volume ratio. Wan *et al.,* [13] using a cavity to improve the flame stability in a planar micro combustor and found that the length depth ratio of the cavity and the channel gap distance affect the flame blow-off limit [14]. Furthermore, Yang *et al.,* [15] conduct study on a double-cavity micro combustor and observed that the radiation energy and radiation efficiency of the double-cavity is higher than that of the single-cavity combustor.

In spite of the several methods mentioned previously to stabilize the combustion inside the micro combustor, a bluff body technique is another method to stabilize and enhance the combustion efficiency. Some research work have shown that the inserted the bluff body inside the micro combustor can stabilize the combustion [16] and extended the combustion blow-off limit [17] - [20]. Aiwu *et al.,* [18] observed that the dimension of the bluff body affected the blow-off limit was indicates by the blockage ratio. Aiwu *et al.,* [19] found that the triangular bluff body has a smaller blow-off limit in comparison to semicircular bluff body. It is because of the stronger flame stretching was occurred in the semicircular bluff body case. Ghobad *et al.,* [20] investigated different shapes of bluff body which are circle, ellipse, diamond semicircular, half ellipse, triangle, crescent, arrowhead and wall-blade at three different velocities and found that the wall-blade bluff body produces most stable combustion. Zhang *et al.,* [21] using a hollow hemispherical bluff body and found that the hollow hemispherical bluff body gives 2.5 times higher blow-off limit than that without a bluff body. Recently, a study on the effects of trapezoidal bluff bodies CH_4/air mixture in a micro combustor was done by Juntian *et al.,* [22] and found that the blockage ratio of 0.4 is an optimum value with a flow velocity of 2 m/s.

Although the optimum choice of trapezoidal bluff body have been noted, the impacts of trapezoidal bluff body with a slit gap in the middle of the bluff body have not been studied. The utilization bluff body with slit gap is to increase the efficiency of the combustor. Thus the objective of this research is to study the combustion characteristics of CH_4/air in a 2D micro channel with bluff body having varied slit size.

2. Numerical Setup

A computational domain and the boundary conditions of the system are shown in Figure 1. The height and length of the channel is H = 1 mm and L = 16 mm respectively. The bluff body height is H_{bluff} = 0.5 mm height and located at x = 2 mm from the inlet. Slit gap percentages of 0% to 70% have been selected in this study. Percentage of the slit gap is defined by the ratio between height of slit, H_{slit} and height of the bluff body, H_{bluff}.

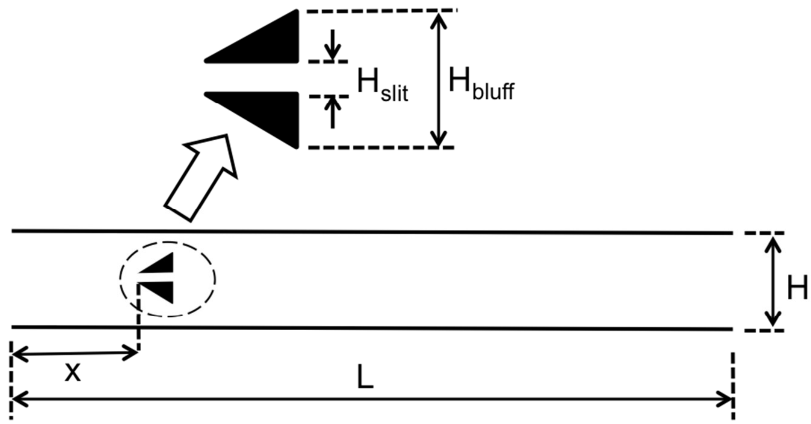

Fig. 1. Micro-combustor with slit gap of bluff body

The analysis was performed in a two dimensional configuration. CH_4/air mixture is issued from inlet at temperature 300 K. The selection of the CH4/air is because of the simple reaction mechanism compare to propane. Moreover, the CH_4/air is easy to stored compare to hydrogen. Outlet of the combustor is assumed to be a fully developed flow. In the present study, air is assumed to be a mixture of O_2 and N_2 with 21 mol% and 79 mol% respectively. One-step reaction mechanism of CH4/air was used in this study. The Arrhenius type of reaction mechanism is given as.

$$r_{CH4} = 1.3 \times 10^8 exp(-2.027 \times 10^8/RT) \times [CH_4]^{0.2}[O_2]^{1.3} \quad (1)$$

The governing equations of the mass, species, momentum and energy are given as follows.

$$\frac{\partial\,(\rho u_j)}{\partial\,(x_j)} = 0 \quad (2)$$

where ρ is the density of mixed gas, u_j is the radial velocity.

$$\rho u_j \frac{\partial Y_i}{\partial x_j} = \frac{\partial}{\partial x_j}\left[D_i \rho \frac{\partial Y_i}{\partial x_j}\right] + R_i \quad (3)$$

where Y_i is the mass fraction of species i, D_i is the diffusion coefficient of species i, and R_i is the generation or consumption rate of species i.

$$\frac{\partial}{\partial x_j}(\rho u_j u_i) = -\frac{\partial p}{\partial x_j} + \frac{\partial}{\partial x_j}[\mu(\rho u_j u_i)] \quad (4)$$

where u_i is an axial velocity, p is a pressure, and μ is a dynamic viscosity.

$$\frac{\partial(\rho u_j h)}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\lambda \frac{\partial T}{\partial x_j}\right) + \frac{\partial}{\partial x_j}\left(\sum_i^\infty D_i \rho \frac{\partial Y_i}{\partial x_j} h_i\right) \quad (5)$$

where h is a enthalpy of fuel, λ is a thermal conductivity of mixed gas, and T is the temperature.
The ideal gas state equation.

$$P = \rho RT \Sigma \frac{Y_i}{M_i} \quad (6)$$

Ansys Fluent 14.5 was applied to solve a set of the conservation equations using a segregated solver with an under relaxation method. A uniform size of grid with a size of 1×10^{-5} m × 1×10^{-5} m was used. Laminar model was used following the suggestion from Kuo and Ronney [23] since the Reynolds number, *Re* < 500. Quartz was used as a material for both the bluff body and channel. The discrete ordinates (DO) radiation model was used to for the surface-to-surface radiation between the inner surfaces of the micro channel.

A non-slip and impermeable wall surfaces boundary condition are applied at the combustor walls. Both natural convection and thermal radiation heat transfer have been assigned at the outer surface of the combustor walls. The solid surface emissivity and heat transfer coefficient of 0.65 and 17 W/(m^2·K) were used respectively [15]. Initially an isothermal flow was solved. Artificial ignition was setting by the higher temperature zone at 2500 K. After the reaction was started and the flame exists, the artificial ignition temperature was off. The convergence criterion was set for energy residual less than 10^{-6}. One important characteristics of the micro combustor is emitter efficiency. The emitter efficiency is a ratio between the total radiation of the combustor wall to the total energy input [20].

$$\eta = \frac{(d+2t)\varepsilon\sigma\sum_{i=1}^{N} T_{w_0}^4 X_i}{\dot{m}_{H_2} H_c} \tag{7}$$

where H_c is a heating value of CH_4, $\dot{m}_{CH4}$ is a mass flow rate of CH_4 (kg/s), the Stefan-Boltzmann constant is σ = 5.67 x 10^{-8} W/m^2 K^4 and T_{w_0} is a temperature of the micro-combustor walls.

Moreover, the total heat loss in micro-combustor is important in determining the stability of the combustion. Higher heat loss will destabilize the combustion. In this study, the heat losses consists of the heat loss by the convection Q_N and the radiation Q_R given by

$$Q_{loss} = \frac{Q_N + Q_R}{Q} \tag{8}$$

$$Q_N = h_{out}(T_{w.o} - T_\infty) \tag{9}$$

$$Q_R = \alpha\sigma(T_{w.o}^4 - T_\infty^4) \tag{10}$$

Where h_{out} = 17 W/($m^2.K$) is a heat transfer coefficient of the natural convection, the ambient temperature is $T_\infty = 300K$ and the emissivity of the solid surface is taken as α=0.65.

3. Results and Discussion

Figure 2 shows temperature contours in a micro channel with vary the slit percentage. It is seen for the 0% and 5% slit percentage a temperature contour is wavy. Beyond the 5% slit, the temperature zone is stable. At 5% slit gap a wavy temperature become severe compared to 0% slit gap. Moreover, increase in slit gap to 10% flame zone move towards downstream and the temperature contour is more stable. Interestingly, at a slit gap percentage of 15% the flame moves upstream in comparison to 10% case. At 30% slit the flame attached to the bluff body but the flame zone is separated into two. This separation is occurring due to incoming fresh mixture of CH_4/air flows through the slit and cut the flame zone into two. Separation of the flame zone is obvious as increase in the slit percentage.

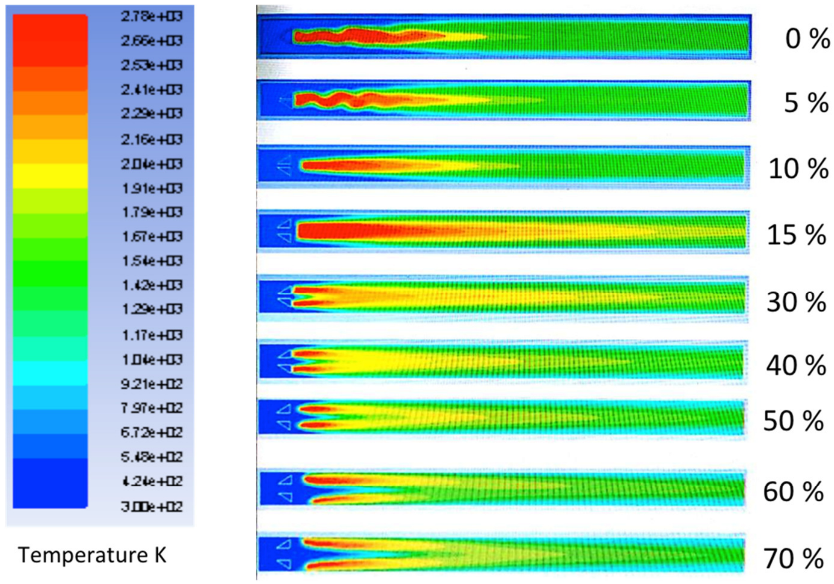

Fig. 2. Temperature contour in channel with trapezoidal bluff body with different slit gap percentage at inlet velocity 0.8 m/s and equivalence ratio 0.9

Furthermore, flame moves upstream at 30% slit after moving downstream at 10% slit is interesting. This observation is supposed due to secondary vortexes that exist as increase in slit percentage that pull the flame to the upstream. Figure 3 shows a graph of outer wall temperature along the combustor length.

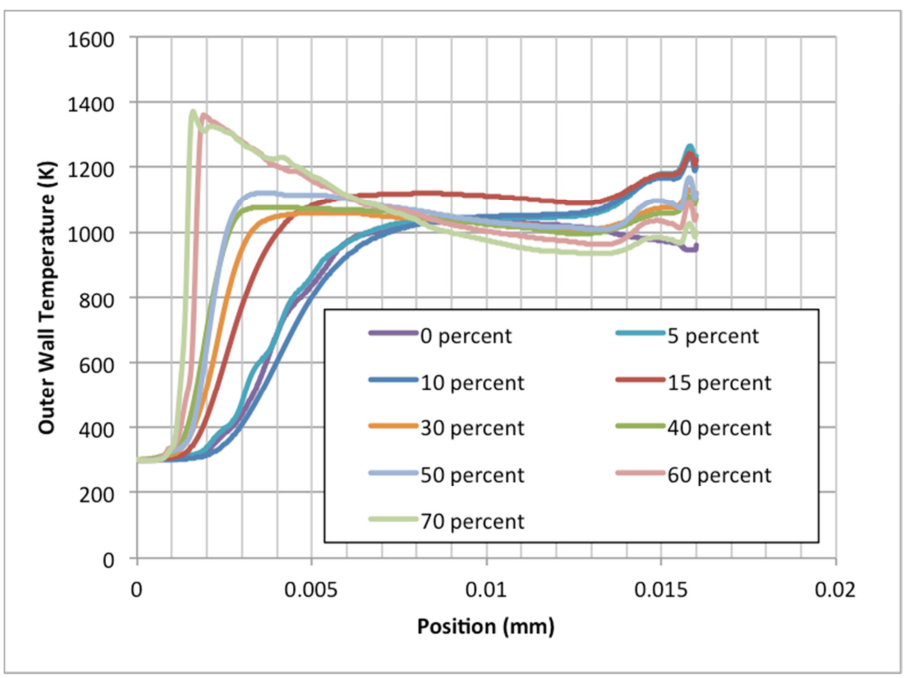

Fig. 3. Outer wall temperature versus combustor length

Micro-channel with slit gap percentage of 60% and 70% show that the highest temperature at the combustor inlet and gradually decreases toward the outlet. This observation is due to expansion of the flame zone that separated into two zones as seen in Figure 2. This separation extended the flame zone and nearly hit the inner wall of combustors, thus it transferred more heat to the wall. At 0%, 5% and 10% slit cases, the outer wall temperature relatively low due to smaller flame zone thus slit gap is not significantly affected the flame shape. Moreover, at 15% until 50% the outer wall flame temperature is constant from inlet towards the outlet. Figure 4 shows an emitter efficiency of the micro combustor.

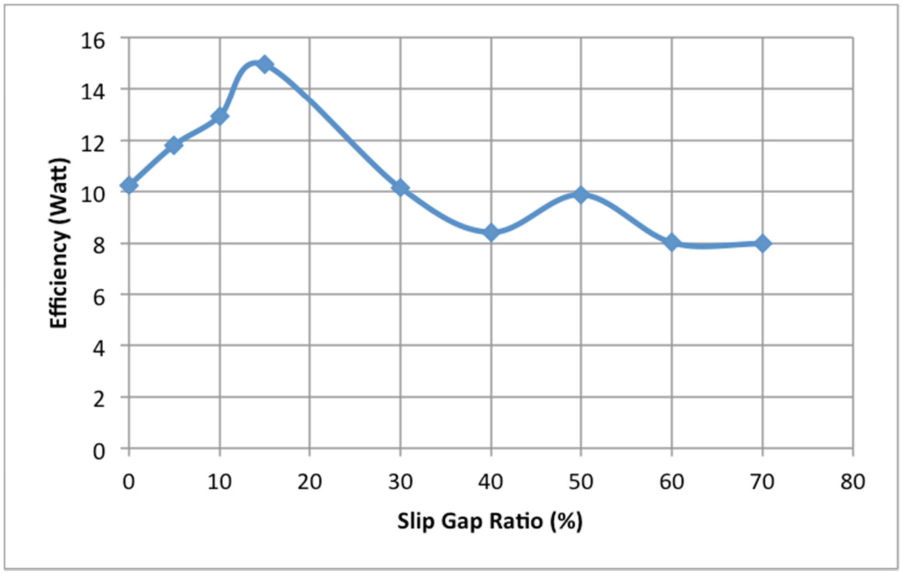

Fig. 4. Combustion efficiency versus slit gap percentage

It can be seen that an emitter efficiency is a very high in a micro-combustor with slit gap percentage of 5% and it is because of the constant heat flux as seen in Figure 3. The lowest emitter efficiency is for the case of 70% slit gap percentage. As previously seen in Figure 3, the temperature distribution for 70% slit gap is not uniform thus it contribute to lower emitter efficiency. Variation of heat loss with increase in slit gap percentage in micro channel shown in Figure 5.

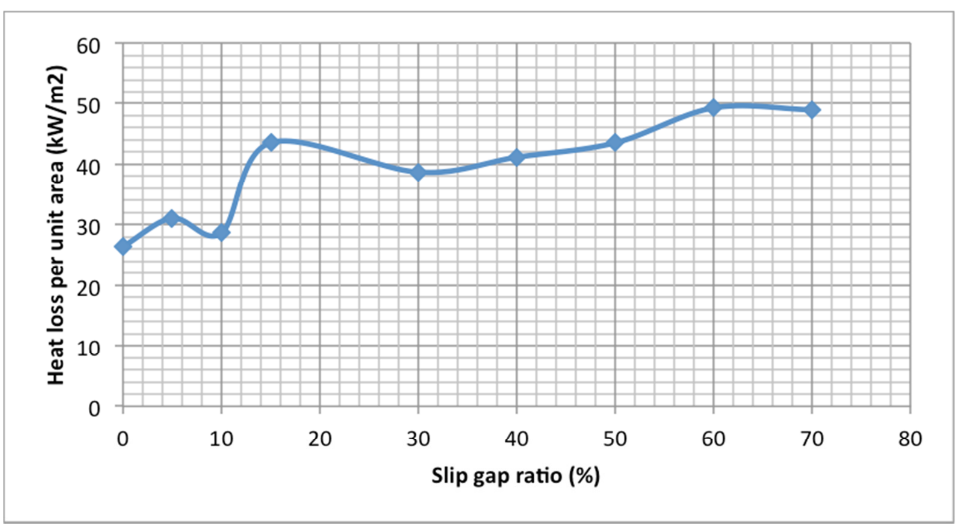

Fig. 5. Heat loss versus slit gap percentage

In Figure 5, the 0% slit gap indicates lowest heat loss 26.41 kW/m^2 and the highest heat loss is 49.28 kW/m^2 at 60% slit gap. Phenomenon of the heat loss trend can be explained by referring to Figure 2, as the flame zone far from combustor wall the lower heat loss is seen (0% – 10% slit gap) meanwhile as the flame zone getting close to inner wall of combustor the higher heat loss will be produced (15% – 70% slit gap).

4. Conclusion

Numerical study on the effects of bluff body with slit in the micro-channel combustor has been done. It can be seen that the slit gap percentage is significantly influence the combustion characteristics. Increases the slip gap percentage brings the flame zone to the downstream. It can be explained because of the incoming unburned mixture flow through the slit gap push the flame zone. Interestingly, as the slit gap keep increased, the flame zone moves to the upstream and attach to the bluff body edge. This observation is suggested due to the secondary vortex exist behind the bluff body as slit gap increases and pull the flame to the upstream.

References

[1] A. H. Epstein, S. D. Senturia. "Macro power from micro machinery." *Science* 26, 1997.
[2] A. Mehra, A. A Ayon, L. A Waitz, M. A Schmidt. "Microfabrication of high-temperature silicon devices using wafer bonding and deep reactive ion etching." *Journal of Microelectromechanical Systems* 8 (1999): 152-160.
[3] J. S Hua, M. Wu, K. Kumar. "Numerical simulation of the combustion of hydrogen-air mixture in micro-scaled chambers, Part II, CFD Analysis for a micro-combustor." *Chemical Engineering Science* 60 (2005): 3507-3515.
[4] X. C. Shan. Z. F Wang, Y. F Fm, M. Wu, J. Hua, C.K Wang, R. Maeda. "Studies on a micro combustor for gas turbine engines." *Journal of Micromechanics and Microengineering* 15 (2005): 215-221.
[5] W. M. Yang, S. K. Chou, C. Shu, Z. W. Li, H. Xue. "Development of microthermophotovoltaic system." *Applied Physics Letter* 81 (2002): 5255-5257.
[6] W. M. Yang, S. K. Chou, C. Shu, Xue, Z. W Li. "Development of a prototype micro-thermophotovoltaic power generator." *Journal Physics D: Applied Physic* 37 (2004):1017-1020.
[7] J. W. Li, B. J. Zhong. "Experimental investigation on heat loss and combustion in methane/oxygen micro-tube combustor." *Applied Thermal Engineering* 28 (2008): 707-716.
[8] H. L. Yang, Y. X. Feng, X. H. Wang, L. Q. Jiang, D. Q. Zhao, N. Hayashi, H. Yamashita. "OH-PLIF investigation of wall effects on the flame quenching in a slit burner." *Proceeding of the Combustion Institute* 34 (2013): 3379-3386.
[9] Pan J. F., Huang J., Li D. T., Yang WM, Tang W. X., Xue H. "Effects of major parameters on micro-combustion for thermophotovoltaic energy conversion." *Applied Thermal Engineering* 27 (2007): 1089-1095.
[10] Bhupendra Khandelwal, Anil A. Deshpande, Sudarshan Kumar. "Experimental studies on flame stabilization in a three step rearward facing configuration based micro channel combustor." *Applied Thermal Engineering* 58 (2013): 363-368.
[11] J. Li, S. K. Chou, W. M. Yang, Z. W. Li. "A numerical study on premixed micro-combustion of CH4–air mixture: Effects of combustor size, geometry and boundary conditions on flame temperature." *Chemical Engineering Journal* 150 (2009): 213–222.
[12] Jun Li, Siaw Kiang Chou, Zhiwang Li, Wenming Yang. "Development of 1D model for the analysis of heat transport in cylindrical micro combustors." *Applied Thermal Engineering* 29 (2009): 1854–1863.
[13] Jianlong Wan, Aiwu Fan, Yi Liu, Hong Yao, Wei Liu, Xiaolong Gou, Daiqing Zhao. "Experimental investigation and numerical analysis on flame stabilization of CH4/air mixture in a mesoscale channel with wall cavities." *Combustion and Flame* 162 (2015): 1035–1045.
[14] Jianlong Wan, Aiwu Fann. "Effect of channel gap distance on the flame blow-off limit in mesoscale channels with cavities for premixed CH4/air flames." *Chemical Engineering Science* 132 (2015): 99–107.
[15] Yang Su, Jinlin Song, Jiale Chai, Qiang Cheng, Zixue Luo, Chun Lou, Peifang Fu. "Numerical investigation of a novel micro combustor with double-cavity for micro-thermophotovoltaic system." *Energy Conversion and Management* 106 (2015): 173–180.
[16] Santosh J. Shanbhogue, Sajjad Husain, Tim Lieuwen. "Lean blowoff of bluff body stabilized flames: Scaling and dynamic." *Progress in Energy and Combustion Science* 35 (2009): 98–120.

[17] Jianlong Wan, Aiwu Fana, Kaoru Maruta, Hong Yao, Wei Liu. "Experimental and numerical investigation on combustion characteristics of premixed hydrogen/air flame in a micro-combustor with a bluff body." *International Journal of Hydrogen Energy* 37 (2012): 19190-19197.

[18] Aiwu Fana, Jianlong Wan, Yi Liu, Boming Pi, Hong Yao, Kaoru Maruta, Wei Liu. "The effect of the blockage ratio on the blow-off limit of a hydrogen/air flame in a planar microcombustor with a bluff body." *International Journal of Hydrogen Energy* 38 (2013): 11438-11445.

[19] Aiwu Fan, Jianlong Wan, Yi Liu, Boming Pi, Hong Yao, Wei Liu. "Effect of bluff body shape on the blow-off limit of hydrogen/air flame in a planar micro-combustor." *Applied Thermal Engineering* 62 (2014): 13-19.

[20] Ghobad Bagheri, Seyed Ehsan Hosseini, Mazlan Abdul Wahid. "Effects of bluff body shape on the flame stability in premixed micro-combustion of hydrogen air mixture." *Applied Thermal Engineering* 67 (2014): 266-272.

[21] Li Zhang, Junchen Zhu, Yunfei Yan, Hongliang Guo, Zhongqing Yang. "Numerical investigation on the combustion characteristics of methane/ air in a micro-combustor with a hollow hemispherical bluff body." *Energy Conversion and Management* 94 (2015) 293–299

[22] Juntian Niu, Jingyu Ran, Liya Li, Xuesen Du, Ruirui Wang, Mingchu Ran. "Effects of trapezoidal bluff bodies on blow out limit of methane/air combustion in a micro-channel." *Applied Thermal Engineering* 95 (2016): 454–461.

[23] C. H. Kuo, P. D. Ronney. "Numerical modeling of non-adiabatic heat-recirculating combustors." *Proceeding of the Combustion Institute* 31 (2007): 3277–3284.