Jurnal Teknologi

Full Paper

INFLUENCE OF MODIFIED AIR ON COMBUSTION CHARACTERISTICS IN MESO-SCALE VORTEX COMBUSTOR

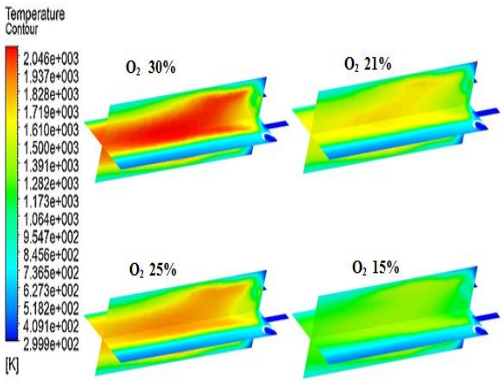
Mostafa Khaleghi, Mazlan A. Wahid*, A. Saat, M. Y. M. Fairus, M. M. Sies, N. Kamaruzaman, Md. Mizanur Rahman, M. Mohammad Amri, H. A. Mohammed

High-Speed Reacting Flow Laboratory (HiREF), Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia

Article history
Received
27 April 2016
Received in revised form
10 May 2016
Accepted
20 May 2016

*Corresponding author
mazlan@fkm.utm.my

Graphical abstract



Abstract

The need to supply power for miniaturized mechanical devices opens exciting new opportunities for combustion, especially in the field of micro-power generation. Because of the need for power supply devices with high-specific energy (small-size, low weight, long duration) and power. Meso/micro scale combustion has been considered as a potential solution for many small-volumes and energy demanding systems, such as power supplies for portable device. In this study the structure of turbulent diffusion flames in a meso scale combustor with different oxygen concentration has been investigated using a new design of vortex combustor. Methane gas was used as a fuel. Numerical investigations have been performed on the temperature distribution, swirl number, heat loss, and emitter efficiency in vortex combustion. The results have been obtained for various O_2 concentrations in the air as oxidizer. The results shows that thermal flame behaves depend strongly on the oxygen content in the oxidizer. When the oxygen concentration increases from 15% to 30%, the flame temperature of the meso-combustion rises in all cases. Emitter efficiency is very high in the meso-combustor with high O_2 concentration in oxidizer.

Keywords: Meso-scale combustion, Vortex flame, Heat loss, Oxygen concentration

1.0 INTRODUCTION

In the past decade there have been numerous interests with in the research community to advance the field of combustion and power generation at small scale. The interest in producing miniaturized mechanical devices opens exciting new opportunities for combustion, especially in the field of micro-power generation, because of the need for power supply devices with high-specific energy (small-size, low weight, long duration) and power. If the chemical energy can be extracted from the hydrocarbons and converted into power, then it can be used in miniature device, and also replace existing batteries. Meso/micro scale combustion has been considered as a potential solution for many small-volumes and energy demanding systems, such as power supplies for portable devices[1-4]. It is well known that the stored energy density of hydrocarbon fuels may be as large as two orders of magnitude more than that provided by current battery technologies. Numerous micro-combustion power generation techniques have been proposed with several studies already demonstrating feasibility of the concept. For example, Waitz *et al*. reported a micro-gas turbine engine that successful could produce 10-50 W of power in a volume less than 1 cm^3 [5]. A comprehensive review on micro power generation using combustion is given in Ref. [6]. Moreover, heat loss from the combustor walls is higher in micro-scale combustors because the ratio of surface area to the volume of micro-combustor increases and thus thecombustion efficiency decreases by micro-combustor size reduction [7-8]. Limited flow residence time is also another issue to be taken into consideration regarding the flame stability. In several gas phase combustion studies, flame behavior at small scales has been investigated [9-11]. Wu *et al*. [1] could deploy swirl to stabilize flames in meso-scale combustion systems for micro-thruster applications. The author [12] discussed about the mechanism of flame stability and chamber design yielding forced vortex field which is also the adopted design of the current study yet in a difference scale. Many different types of systems have been proposed, but only a limited number have been investigated at the meso and micro scale [13-15]. In the present paper, results are presented on the development of meso-scale vortex combustor. In particular, the influence of oxygen concentration percent in oxidizer under constant flow rate of fuel and oxidizer on the flame distribution, wall temperature and emitter efficiency are discussed.

2.0 NUMERICAL METHODOLOGY

A three dimensional, finite volume solver has been used to discretize the 3D flow domain through a second-order upwind scheme. Several triangular grids have been generated for the purpose of ensuring that the solution is grid-independent. The SIMPLE algorithm has been used to achieve the mass conservation between the pressure and velocity terms in the discretized momentum equation. Chemical reaction has considered volumetric and Eddy-Dissipation algorithm has chosen for turbulence-chemistry interactions. The Eddy-Dissipation reaction model ignores chemical kinetics (i.e., the Arrhenius rate) and uses only the parameters in reaction flow[16]. The operating pressure and temperature were set to 1.01 bars and 300 K, respectively. In the numerical effort, the solution was obtained by considering convergence when the residuals of each governing equation at consecutive iterations became less than 1×10^{-4} except energy equation and chemical reactions equation (1×10^{-6}). The equivalence ratio, air mass flow rate and fuel mass flow rate in all cases are constant and equal to $\varphi=1$, 2.15×10^{-5} kg/s, 1.25×10^{-6} kg/s, respectively. The design of meso-scale chamber is same as [9] with new dimensions of meso-scale vortex combustor, as: a=2 mm, b=1 mm, d=10mm and L=30 mm. The fuel and air inlet nozzles are circular in cross section with a diameter of 1mm and 1.5 mm, respectively. The equivalence ratio is stoichiometric for all cases but oxygen concentration of oxidizer change from 15%, 21%, 25% to 30%.

3.0 RESULTS AND DISCUSSION

3.1 Flame Structure

The effect of oxygen concentration as oxidizer on the performance of vortex combustion flame is analyzed while the mass flow of fuel and air are kept constant. Therefore, the equivalence ratio was constant in this investigation equaling to unit. Figure 1 demonstrates the temperature contours in two various surfaces. There are obvious differences in these contours. From this figure, it can be interpreted that decreasing of oxygen concentration in inlet oxidizer with constant mass flow rate leads to decreases temperature flame.

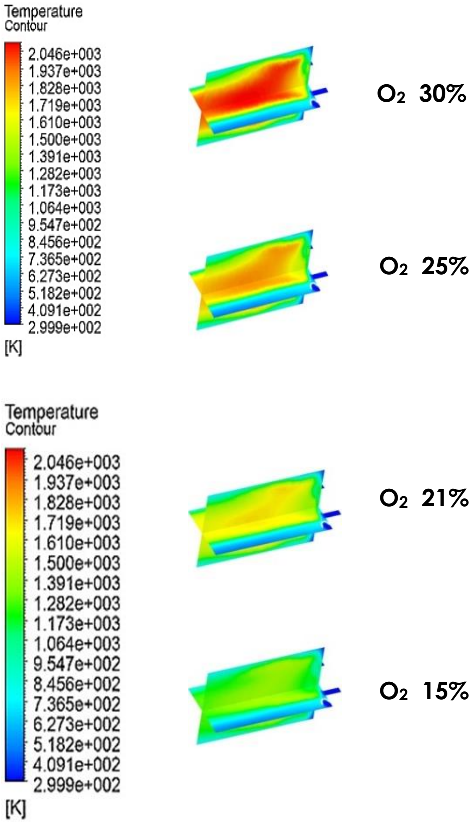


Figure 1 Flame pattern along the vortex combustor with different O_2 concentration

3.2 Swirl Number

The central recirculation zone is strongly dependent on the swirl number, which is a non-dimensional number (Eq. 1) representing the axial flux of swirl momentum divided by the axial flux of the axial momentum, times the equivalent nozzle radius.

$$S = \frac{\int(\rho u_x u_\theta)rdA}{\int \rho u_x^2 dA \times D/2} \qquad (1)$$

High swirl favors the generation of a central recirculation zone. Figure 2 presents the axial evolution of the swirl number in the chamber with different oxygen concentration in air at P = 1atm. It is found that an increase in oxygen concentration of air cannot effect on swirl number along the central axis of meso-combustor.

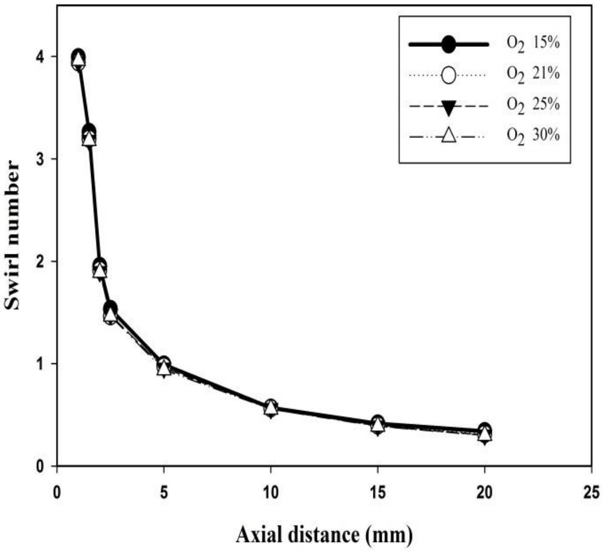


Figure 2 Axial evolution of swirl numbers in the chamber

3.3 Effects of Oxygen Concentration on the Heat Loss

The combustion heat release rate is dependent on the concentration of components of oxidizer, which is a crucial factor affecting the stability of flame. Therefore, combustion tests with oxygen concentration of 15%, 21%, 25% and 30% in the meso-scale vortex combustor are performed, and the effect of the oxygen concentration in oxidizer on heat loss is studied. Figure 3 shows comparisons of external heat loss of the meso-scale vortex combustion at four oxygen concentration. It is seen that with the increase of the oxygen concentration, the combustion heat power rises linearly. When the oxygen concentration equals 0.15, the heat power is low and the wall temperature is not high. Consequently, the heat loss power is small.

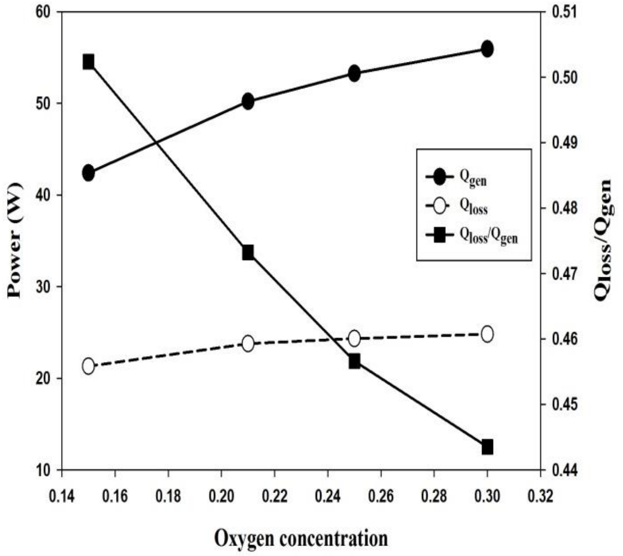


Figure 3 Heat loss of meso-combustor at different oxygen concentration

3.4 Emitter Efficiency

Thermal radiation from the micro/meso combustor wall is applied for power generation in some cases (such as micro-TPV generator), thus the meso combustor is considered as an emitter and the radiation heat loss from the combustor wall plays an important role [17]. The ratio of the total radiation through the combustor wall to the total energy input is defined as emitter efficiency given by Eq. (2) [18].

$$\eta = \frac{\pi(d+2t)\varepsilon\sigma\sum_{i=1}^{N} T_{w0}^{4} L_i}{\dot{m}_f H_c} \qquad (2)$$

η is emitter efficiency, H_c is higher heating value of fuel, $\dot{m}_f$ is fuel mass flow rate (kg/s), σ is Stefan-Boltzmann constant (= 5.67× 10^{-8} W/m^2k^4), T_{w_o} is meso- combustor wall temperature and L_i is the length wall in which temperature is uniform. It is obvious from Figure 4 that concentration of oxygen in oxidizer has not significant effect on wall temperature, thus for all these cases the emitter efficiency is close to approximately 14% according to Eq. (2).

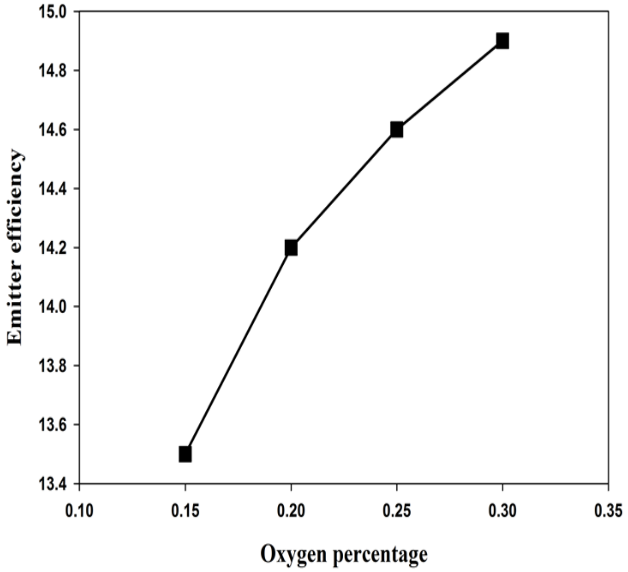


Figure 4 Emitter efficiency of meso-scale vortex combustor

3.5 Vortex Flame Structure

Figure 5 displays the stoichiometric vortex flame digital photos of in daylight settings. Two stoichiometric fuel jets have been shown without the vortex flow field. The flame shape and color of the two jets are similar to the typical non-premixed free jet flames. On the other hand, the abbreviated flame length of the vortex flame is quite clear in Figure 5 (b). In comparison with the total length of the meso-combustor, the vortex flame has a short length. The color of vortex flame is blue as depicted in Figure 5 (b) which is a main characteristic of premixed flames.

(a) (b)

Figure 5 Digital photos with daylight settings of (a) side view of stoichiometric fuel jets without the air vortex and (b) top view of stoichiometric vortex flame

4.0 CONCLUSION

Due to the very small size of meso-combustors, residence time reduces dramatically and flame stability encounters a few problems in these devices. Thus, flame stability should be ensured in micro-combustors by taking some appropriate strategies. In this paper, the combustion characteristics of a meso-combustor with vortex combustion under various oxygen concentrations have been investigated numerically to obtain the desirable conditions. Flame temperature raised by increasing the oxygen concentration in oxidizer. It is seen that with the increase of the oxygen concentration, the combustion heat power rises linearly. When the oxygen concentration equals 0.15, the heat power is low and the wall temperature is not high. Consequently, the heat loss power is small. The maximum swirl number in the chamber with different oxygen concentration of air at P = 1atm is about four and it happens in a region near to inlet air and inlet fuel. It is found that an increase in oxygen concentration of air cannot effect on swirl number along the central axis of meso-combustor.Emitter efficiency as well as wall temperature was increased by increasing of oxygen concentration in oxidizer.

For various oxygen concentration in oxidizer (15%, 20%, 25% and 30%), the emitter efficiency is close to approximately 14%. Despite the fact that the current study of meso-scale combustor deals with the non-premixed vortex flames, the features of premixed flames such as color and temperature were observed.

Acknowledgement

The authors would like to thank Ministry of Higher Education (MOHE) and Universiti Teknologi Malaysia (UTM) for supporting this research activity under Fundamental Research Grant Scheme under a Grant Research No R.J130000.7824.4F777.

References

[1] M. Wu, Y. Wang, V. Yang, and R. A. Yetter. 2007. Combustion In Meso-Scale Vortex Chambers. *Proceedings of the Combustion Institute*. 31(2): 3235-3242.

[2] W. M. Yang, S. K. Chou, C. Shu, Z. W. Li, and H. Xue. 2002. Development Of Microthermophotovoltaic System. *Applied Physics Letters*. 81(27): 5255.

[3] G. Bagheri, E. Hamidi, M. A. Wahid, A. Saat, and M. M. Sies. 2013. Effects of CO_2 Dilution on the Premixed Combustion of CH_4 in Microcombustor. *Applied Mechanics and Materials*. 388: 251-256.

[4] S. E. Hosseini and M. A. Wahid. 2014. Investigation Of Bluff-Body Micro-Flameless Combustion. *Energy Conversion and Management*. 88: 120-128.

[5] I. A. Waitz, G. Gauba, and Y.-S. Tzeng. 1998. Combustors for Micro-Gas Turbine Engines. *Journal of Fluids Engineering*. 120(1): 109.

[6] S. K. Chou, W. M. Yang, K. J. Chua, J. Li, and K. L. Zhang. 2011. Development Of Micro Power Generators – A Review. *Applied Energy*. 88(1): 1-16.

[7] J. Li and B. Zhong. 2008. Experimental Investigation On Heat Loss And Combustion In Methane/Oxygen Micro-Tube Combustor. *Applied Thermal Engineering*. 28(7): 707-716.

[8] G. Bagheri, S. E. Hosseini, and M. A. Wahid. 2014. Effects Of Bluff Body Shape On The Flame Stability In Premixed Micro-

Combustion Of Hydrogen–Air Mixture. *Applied Thermal Engineering*. 67(1-2): 266-272.

[9] M. Khaleghi, M. A. Wahid, M. M. Seis, and A. Saat. 2013. Investigation of Vortex Reacting Flows in Asymmetric Meso Scale Combustor. *Applied Mechanics and Materials*. 388: 246-250.

[10] S. Karagiannidis, J. Mantzaras, G. Jackson, and K. Boulouchos. 2007. Hetero-/homogeneous Combustion And Stability Maps In Methane-Fueled Catalytic Microreactors. *Proceedings of the Combustion Institute*. 31(2): 3309-3317. Jan.

[11] G. a. Boyarko, C.-J. Sung, and S. J. Schneider. 2005. Catalyzed Combustion Of Hydrogen–Oxygen In Platinum Tubes For Micro-Propulsion Applications. *Proceedings of the Combustion Institute*. 30(2): 2481-2488.

[12] M. Khaleghi, S. Ehsan Hosseini, and M. Abdul Wahid. 2014. Emission and Combustion Characteristics of Hydrogen in Vortex Flame. *Jurnal Teknologi*. 66(2).

[13] Mostafa Khaleghi, S. E. Hosseini, and M. Wahid. 2015. Experimental And Numerical Investigations Of Biogas Vortex Combustion. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*. 1-15.

[14] M. Khaleghi, S. E. Hosseini, and M. A. Wahid. 2015. Vortex Combustion And Heat Transfer In Meso-Scale With Thermal Recuperation. *International Communications in Heat and Mass Transfer*. 66: 250-258.

[15] M. Khaleghi, S. E. Hosseini, and M. Abdul Wahid. 2015. Investigations of Asymmetric Non-premixed Meso-scale Vortex Combustion. *Applied Thermal Engineering*.

[16] S. E. Hosseini, G. Bagheri, and M. A. Wahid. 2014. Numerical Investigation Of Biogas Flameless Combustion. *Energy Conversion and Management*. 81: 41-50.

[17] W. M. Yang, S. K. Chou, K. J. Chua, J. Li, and X. Zhao. 2011. Research On Modular Micro Combustor-Radiator With And Without Porous Media. *Chemical Engineering Journal*. 168(2): 799-802.

[18] G. Bagheri and S. E. Hosseini. 2015. Impacts Of Inner/Outer Reactor Heat Recirculation On The Characteristic Of Micro-Scale Combustion System. *Energy Conversion and Management*. 105: 45-53.