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Research paper

Investigations of asymmetric non-premixed meso-scale vortex combustion

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HIGHLIGHTS

- In this paper non-premixed meso-scale asymmetric vortex combustion is investigated.
- The ratio of heat loss to heat generation is maximum, in the air mass flow rate 40 mg/s.
- For all air mass flow rates, blow-off occurs when the equivalent ratio is less than 0.2.
- The lean side of the vortex flame is more stable.

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ABSTRACT

A new design of asymmetric non-premixed meso-scale vortex combustor is introduced in this paper. The flame stability, heat loss from the combustor wall as well as thermal efficiency and pollutant formation are compared in various circumstances such as air/fuel inlet velocity and equivalence ratios. Furthermore, direct photography method is used to capture visible flame structures at a wide range of equivalence ratios in order to emphasize the exceptional stability of such flames. An essential model for the stability of non-premixed flames in meso-scale combustion spaces is provided in this research. The temperature of the combustor wall is one of the most important factors that influence the temperature of the reactants (preheating phenomena) by heat conduction through the body. The results show that in the stoichiometric circumstance, when air mass flow rate is at the lowest rate (40 mg/s), the ratio of heat loss to heat generation reaches the largest value (around 55%). The average temperature of the combustor wall increases with the flow velocity for the stable flame mode and remains mostly uniform and well distributed for the vortex flame in toroidal shape. At a constant airflow rates, the exhaust temperature increases monotonously with the decrease in equivalence ratio until the flame blows off. This implies that the maximum thermal efficiency of a meso-scale combustor occurs in its lean conditions.

1. Introduction

Recently, combustion phenomena in meso-scale combustion space have attracted attentions and its importance has been reported in numerous review papers [1–5]. Meso-scale combustion is defined with respect to the relative dimensions of the combustion system to the representative quenching distance and flame length. The dimensions of the combustor in meso-scale combustion (which exceeds 1 mm) affect the flame thickness and effective thermal diffusivity, which are the features of laminar flame. Therefore, the concept of combustion phenomena in meso-scale chambers should necessarily be taken into consideration for developing laminar flame theories in small-scale combustors. Flame quenching and flame stabilization are the two main barriers of small-scale combustors' development [6]. Premixed flames are usually used to prevent flame quenching when the combustor's size decreases, and likewise diffusion flames (Non-premixed flames) are employed to increase the flame stability. Due to the large surface-to-volume ratio in meso-scale combustors, some new configurations should be proposed.

As the micro-electronic mechanical systems (MEMS) developed, the importance of small energy carriers has been highlighted. Chia

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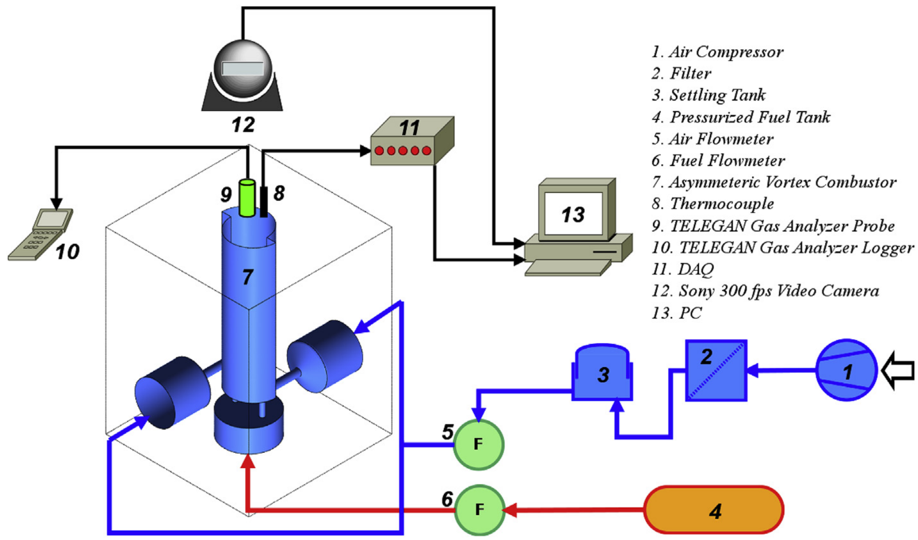

Fig. 1. Experimental setup.

et al. [7] and Chou et al. [8] suggested the application of fossil fuels due to their great energy density. As a practical method of using fossil fuel, various types of small-scale combustors have been proposed. The suggested small-scale combustors have been employed as thrusting devices, heat sources, fuel reformers, or photovoltaic sources [9–12]. The most important barrier to develop small-scale combustors is the quenching limits. Many experimental and numerical investigations have been carried out to improve quenching limits and protect flame against flash-back so that the safety of small-scale combustors can be ensured [13,14]. The proportional relation of quenching distance and flame thickness as well as the converse proportional relation of the flame thickness and the burning velocity are known [15]. Therefore, in the first step, flame thickness should decrease so that scale of the combustor reduces. In order to fulfill these objectives, several techniques such as enhancement of the pressure for reducing the molecular distance, application of special types of fuel or oxidants for intensifying burning velocity, and the application of catalytic reactions for preventing termination of the chemical chain reaction have been employed [16,17]. Nevertheless, these techniques are not directly concerned with the combustor configuration. They can be used for most combustors after determination of the best design of these combustors. Hence, the aim of the present study is to investigate vortex configuration of meso-scale combustor by employing heat recirculation technique to overcome the ordinary quenching limits.

Table 1
The details of boundary condition.

Viscos model	K-epsilon (Eq. (2)) RNG, with swirl dominated flow option	
Radiation model	Discrete ordinate (DO)	
Reaction model	Volumetric species transport reaction with Eddy dissipation of turbulence chemistry model	
Boundary condition	Air inlet	Velocity: various Temperature: 300 K Concentration: $O_2 = 23\%$, $N_2 = 77\%$
	Fuel inlet	Velocity: various Temperature: 300 K Concentration: $CH_4 = 97\%$
	Wall	Material: steel Thermal: mixed heat transfer, $h = 20\ w/m^2\ K$ Ambient temperature: 300 K

When the combustor size reduces, the surface-to-volume ratio rises and the combustion phenomena depends conspicuously on the combustor configuration. Thus, an investigation about the influences of practical design parameters on the performance of small-scale combustion is essential for further development miniaturized power generator.

The concept of vortex flames in meso-scale combustor was developed by Wu et al. [18] and Wang [19] in 2007 and 2006, respectively. The reaction phenomena as well as flow dynamics on such scales are fundamentally different from the macro-scale whirl combustion reported by Gabler et al. [20] and the vortex flame reported by Saqr et al. [21] and Khaleghi et al. [22].

In this paper, vortex flows as a means to stabilize non-premixed gaseous flames in meso-scale combustor are investigated. A miniaturized combustor with chamber radius as small as 5 mm were fabricated in high speed flow rate laboratory (HiREF) in Universiti Teknologi Malaysia (UTM) and were characterized with hydrocarbon fuel (methane). The system is based on the concept of asymmetric whirl combustion [23], which has illustrated unusual stability characteristics for macro-scale combustors at very lean conditions. Detailed computational study of the three-dimensional (3D) flow fields as well as experimental analysis was performed to investigate the combustion characteristics in the meso-scale circumstance. Results further verify the favorable temperature distribution and flow pattern of the asymmetric whirl combustion concept at meso-scales.

2. Experimental setup

The experimental stage was settled to allow direct photography from one plane and intrusive access of gas analyzer for emission and temperature measurements. A schematic of the experimental platform is shown in Fig. 1. Air is delivered at 2 bars from a gush tank connected to a single stage reciprocating compressor, equipped with a pressure gauge and regulator. Fuel (Natural-gas) is supplied at 1 bar from a pressurized cylinder. Two digital precision flow meters with flow-regulating screw from Cole-Palmer are used to measure the flow rate of fuel and air. Stretchy plastic plumbing is employed to connect the combustor chamber to the fuel-air supply system. A Sony 300 FPS digital camera is installed perpendicular to the outlet plane of the combustor to execute direct photographs for