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Entropy generation analysis of H_2/air premixed flame Ćin micro-combustors with heat recuperation

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HIGHLIGHTS

- The thermodynamic irreversibility in micro-combustion is analyzed.
- The effects of flow velocity and H_2/air equivalence ratio are investigated.
- The effect of heat recuperation on entropy generation is studied.
- 1.6% of the total exergy loss can be saved by using the heat recuperation.

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ABSTRACT

A theoretical analysis on entropy generation in H_2/air premixed flame is presented. The entropy transport equation is employed to evaluate the entropy generation rate caused by various irreversible processes such as chemical reaction, conduction, mass diffusion and viscous dissipation. The model is applied for premixed flames in a confined geometry under different inlet flow velocity levels and H_2/air equivalence ratios. Comparisons between the combustors with and without heat recuperation are done in terms of specific and total rate of entropy generation. It is found that a higher flow velocity and higher H_2/air equivalence ratio will increase the rate of entropy generation. The usage of heat recuperator decreases the rate of entropy generation which results in lower exergy loss.

1. Introduction

The rapid development of micro-electromechanical systems (MEMS) and miniaturized various daily usage devices have resulted in the demand for portable power sources with higher energy density (Hua et al., 2005; Li et al., 2004, 2009a; Park et al., 2012; Yang et al., 2009). Diverse concepts for micro-power generation are being developed such as micro-gas turbine engine (Waitz et al., 1998), micro-Wankel engine (Lee, 2004), micro-piezoelectric devices (Lu et al., 2004) and micro-thermophotovoltaic systems (Yang et al., 2002). Different from other micro-power generation engines, micro-thermophotovolatic system has the advantage of higher surface to volume ratio which indicates higher power density (Yang et al., 2003).

Entropy generation is a measure in evaluating the second-law irreversibility in energy conversion processes (Nishida et al., 2002). The energy conversion in H_2/air premixed flame involves both physical and chemical processes (Briones et al., 2009). Many of the processes are irreversible due to the existence of viscous dissipation, heat conduction, mass diffusion, chemical reaction and other effects. In order to improve the second-law performance of micro-combustion process, it is essential to evaluate the entropy generation and exergy loss caused by the effects mentioned above.

The studies on entropy generation have been conducted by many investigators. Entropy generation minimization (EGM) method was proposed in 1996 by Bejan (1996); the efficiency formulas for maximum power output were derived by EGM method in various systems such as storage systems, power plants systems and refrigeration plants systems. Alipanah et al. (2010) investigated the entropy generation for compressible natural convection in a square cavity. It was found that the entropy generation increased with increasing Rayleigh number and also increased with increasing dimensionless temperature difference. Zhao and Liu (2010) analyzed the entropy generation in electro-osmotic flow. They observed that the maximum volumetric entropy generation rates due to heat conduction and viscous dissipation existed near the wall, and the maximum volumetric

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entropy generation value due to Joule heating appeared at the center of the micro-channel.

Compared to the studies on heat and mass transfer problems, relatively less work focused on the entropy generation in combustion processes, especially in micro-combustor. Li et al. (2005) formulated the entropy generation equation in flame zone of a micro-cylindrical combustor based on the entropy balance. Their results showed that the combustion at or near the stoichiometric fuel–air ratios is the least efficient for the combustion process. The analysis further showed the range of useful gain through preheating. Bidi et al. (2010) investigated the entropy generation in porous media by entropy generation minimization method and found the optimum flame location in a porous burner. Nishida et al. (2002) analyzed the entropy generation and exergy loss during combustion in the gas turbine systems based on the theory of thermodynamics of irreversible processes (Hirschfelder et al., 1954). They evaluated the sources of large exergy loss during the combustion processes both in premixed flame and diffusion flame. They observed that the major process for the entropy generation and exergy loss in premixed flames was chemical reaction. Briones et al. (2009) investigated entropy generation in hydrogen-enriched methane–air propagating triple flames and found that there was no exergy loss when blending methane with hydrogen. Chen et al. (2010) studied the entropy generation in counter-flow combustion. They observed that the entropy generation due to chemical reaction was predominant as Reynolds number was smaller than 60 while the largest share of entropy generation came from fluid friction when Reynolds number was larger than 100. Datta (2005) investigated the effects of gravity on structure and entropy generation of laminar diffusion flames. They found that gravity had no influence on the entropy generation due to chemical reaction while the entropy generation due to conduction was greatly influenced by gravity. Chen et al. (2012) presented the effects of inlet air temperature on entropy generation. Their results showed that the entropy generation may increase as the dilution becomes more intense at certain oxidizer temperature. Yapıcı et al. (2005) calculated the entropy generation in a methane–air burner and found that swirling flow affected the temperature gradient and the entropy generation by thermal conduction. Pope et al. (2010) analyzed the entropy generation during transient methanol droplet combustion. Their results showed that the average entropy generation rate over the droplet lifetime was higher for the case that neglected surface tension effects. In the moving droplet case, entropy generation due to both heat and mass transfer decreased, and entropy generation due to chemical reaction increased, with the increase in initial Reynolds number. Jejurkar and Mishra (2011) investigated the effects of wall thermal conductivity on entropy generation and exergy loss in H_2/air premixed flame. They observed that the integrated entropy generation rates due to chemical reaction and conduction showed weak dependence on wall thermal conductivity and the availability loss increased with conductivity to a greater degree. Daw et al. (2006) presented the ways in minimizing the destruction of thermodynamic availability in hydrogen combustion. The irreversibility was reduced due to the elimination of a localized flame zone and associated high temperature gradients.

Heat recuperation is a technique which contributes to better energy efficiency by recovering heat from the exhaust gas. Yang et al. (2012) investigated the effects of heat recuperation in micro-modular combustors and observed that the total radiation energy and useful radiation energy can be increased by 44.4% and 83%. The results further showed that a more uniform temperature distribution can be observed with the effects of heat recuperation. The objective of this study is to investigate the effects of heat recuperation on entropy generation in micro-cylindrical combustors. This study is based on a complete analysis involving detailed simulations of H_2/air premixed flame. An experimental validation is performed to verify the numerical simulation results. The variables from simulation results are post-processed to formulate the entropy generation rate to evaluate the effects of flow velocity, fuel–air equivalence ratio and heat recuperation on micro-scale combustion.

2. Model formulation

2.1. Governing equation

In order to investigate the effect of heat recuperation on entropy generation, a micro-cylindrical combustor with a heat recuperator is designed. As shown in Fig. 1, the mixture of hydrogen and air enters the inlet tube which has the diameter of 2 mm. A backward facing step with a length of 2 mm is designed to stabilize the flame (Li et al., 2009b). Combustion will take place in the chamber with a diameter of 3 mm and a length of 18 mm. The distance between the outer wall of the combustor and the inner wall of the recuperator is 1 mm. Quartz glass is employed as the material of the recuperator since it is highly transparent. Based on the physical model, a 2-D axial symmetric computational domain is established.

Once the flame is stabilized in the micro-combustor, an energy balance will be achieved between the combustor and the environment. As a result, a steady-state model is employed. The body force and heat transport caused by concentration gradients can be neglected due to their small magnitude. Based on these, the following assumptions are made: (1) steady-state combustion; (2) no Dufour effects (Williams., 1985); (3) no work done by pressure and viscous forces; (4) insert wall with no surface reactions; (5) no gas radiation (Norton

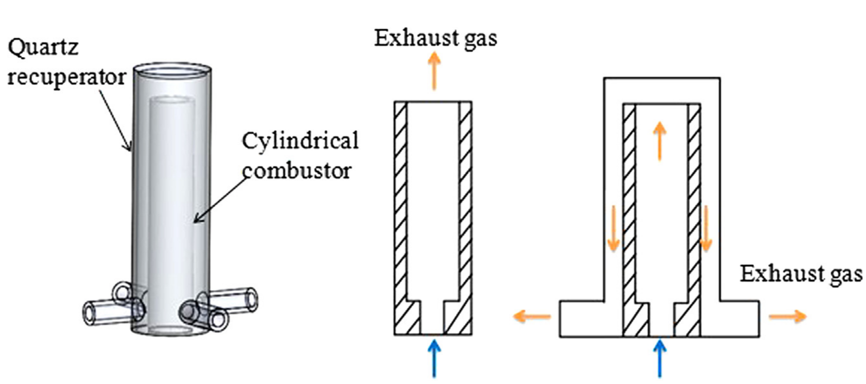

Fig. 1. Schematic diagram of micro-cylindrical combustor with recuperation.