

Development of a Catalytic Hydrogen Micro-propulsion System

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Introduction

Micro, even pico, satellites are getting popular and becoming desirable for both developed and developing countries. Minimizing the size and weight of the satellite and its accessories have recently attracted intensive attention and interest in the aerospace community. Micro-propulsion systems of various types are proposed to provide thrust for attitude control and orbit transfer. Micro-combustion may be applied to achieve these purposes and to generate power for small satellites or portable devices. Reducing the size of combustor would increase the surface-to-volume ratio, that enhances heat loss and radical depletion on the wall. These unfavorable factors make traditional combustion difficult to sustain in small-scale combustors. The residence time and the diffusion time are significantly decreased as the size is reduced. Furthermore, the chemical reaction time is increased owing to the radical depletion. Thus, the reaction inside a micro combustor may be suppressed or even incomplete.

Insulation and heat recirculation concepts were utilized and integrated in the micro-combustor design, for example, multiple quartz tubes [1] and the “Swiss roll” [2]. Recently, catalyst was also used to reduce the activation energy barrier and enhance reaction [3-5] and has been proven to sustain intensive reaction even in a size less than the quench distance. In this study, a platinum catalytic tube of inner diameter 500 μ m and length 1 cm is used as the reactor and placed inside a quartz casing with a convergent nozzle made of quartz for ease of observation. The effects of fuel/air flow rate, equivalence ratio and nozzle contraction ratio on the thruster performance are investigated both experimentally and numerically.

Experimental setup

As show schematically in Figure 1, compressed air and hydrogen from the cylinders are filtered, metered and premixed in the pipeline. The well-mixed fuel and air then passes through the quartz tube of inside diameter 1000 μ m and it is fully developed before entering the platinum catalytic tube. The outlet diameters of the nozzle are 324, 255, and 215 μ m respectively. Resistance coils outside the quartz tube are used to heat the catalyst for startup. Noncatalytically-coated R-type thermocouples and the IR detector are applied to measure temperature at the exit and on the surface of platinum tube respectively. A CCD camera is used for qualitative observation of the reaction process. Video images are digitized via frame grabber and stored in personal computer for further analysis. The thrust is measured by an electrical force sensor.

Numerical method

In this work, an axisymmetric flow field is assumed in modeling the micro-tube and the diameter of the tube is 500 μm . The thickness of the platinum tube is 250 μm and of the quartz tube is 1000 μm . The computational domain contains the gas phase, the wall surface, tube wall, and the surrounding. The Navier-Stokes equations are used to describe the momentum, energy, and species conservation in the gas phase reaction. The heat transfer equations are solved simultaneously for the wall and surrounding regions. Chemical reaction mechanisms are used in the gas phase and on the surface. The gas phase reaction mechanism, which consists 9 species and 20 reaction steps, is adopted from the mechanism proposed by Miller and Bowman (1989) with modification for hydrogen. The surface reaction mechanism has been compiled primarily from that proposed by Deuschmann et al. (1996) and has been tuned for catalytic ignition of hydrogen.

Result and discussion

As shown in Fig. 2, the results of a typical test case of velocity 10m/s in a micro-tube of 500 μm without nozzle agree with the experimental data. Figure 3 shows the photographs of the reacting processes in experiment. When external energy is added to initiate the reaction (Fig. 3a), the reaction start up from the inlet of the catalytic tube due to the high diffusivity of hydrogen and fast reaction on the platinum surface (Fig. 3b). The bright and red region of the tube indicates the zone of intensive reaction and high heat release rate. Reaction zone extends downstream by the heat transfer and the mass flow (Figs. 3c-3e), and then the reaction can be sustained steadily by itself (Fig. 3f). The wall temperature becomes higher with increasing velocity due to increased fuel supply rate and enhanced heat convection (Fig. 4). However, the reaction will not be maintained when the velocity exceeds a critical value. Figure 5 shows the exit temperature under the cases of different fuel concentrations and velocities. Unexpectedly, the measured temperature at the exit reaches a maximum value when the equivalence ratio is less than unity instead of the stoichiometric condition. It shows that the reaction mechanism on the catalytic surface wall differ significantly from the gas phase.

Reducing the size of the nozzle will decrease the exit temperature (Figs. 5-7) induced by transforming thermal energy to kinetic energy by the nozzle. Furthermore, the surface reaction may be suppressed by increasing pressure since the maximum temperature for different velocity cases appear with higher equivalence ratio when the nozzle size is decreased. Figures 8-10 indicate the thrust provided by the micro-propulsion system in different cases. The maximum thrust measured is 6.8 mN and the I_{sp} is 70 s for the hydrogen/air cases and a much higher I_{sp} can be reached if oxygen is used instead of air. The output of the micro-propulsion system is amply to be used in attitude control for a nano-satellite or a micro-satellite.

Acknowledgements

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References

- [1] Cooley, B.A., Walther, D.C., and Fernandez-Pello, A.C. (1999) Exploring the Limits of Micro-scale Combustion. *Proceeding of Western States Section of the Combustion Institute*, 99F-018, Irvine, CA.

- [2] Maruta, K. and Takeda, K (2001) Catalytic Combustion in Micro-channel for MEMS Power Generation. *Proceedings the 3rd Asia-Pacific Conference on Combustion*, Seoul, 219-222
- [3] Vesper, G. (2001) Experimental and Theoretical Investigation of H₂ Oxidation in a High-temperature Catalytic Micro-reactor. *Chem. Eng. Sci.*, **56**, 1265-1273.
- [4] Vican, J., Gajdeczko, B.F., Dryer, F.L., Milius, D.L., and Aksay, I.A. (2002) Development of a Micro-reactor as a Thermal Source for MEMS Power Generation. *Proc. Combust. Instit.*, **29**, 909-916
- [5] Chao, Y.C., Chen, G.B., Hsu, C.J. Leu, T.S., Wu, C.Y., and Cheng, T.S.(2004) Operational Characteristics of Catalytic Combustion in a Platinum Microtube. *Combust. Sci. and Tech.*, **176**, 1755-1777
- [6] Miller, J. A. and Bowman, C. T. (1989) Mechanism and Modeling of Nitrogen Chemistry in Combustion *Prog. in Energy and Combustion Science*, **15**, 287-338
- [7] Deutschmann, O., Schmidt, R., Behrendt, F., and Warnatz, J. (1996) Numerical modeling of catalytic ignition. *Proc. Combust. Instit.*, **26**, 1747-1754

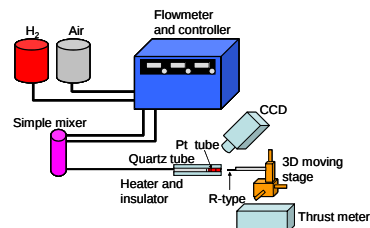


Fig. 1 The schematic experimental apparatus.

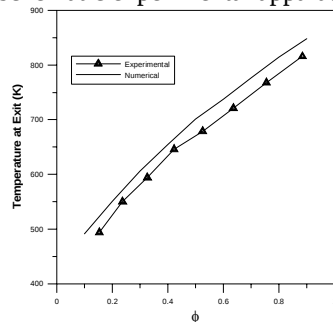


Fig. 2 Comparison of measured and numerical determined exit temperature for 500 μ m tube.

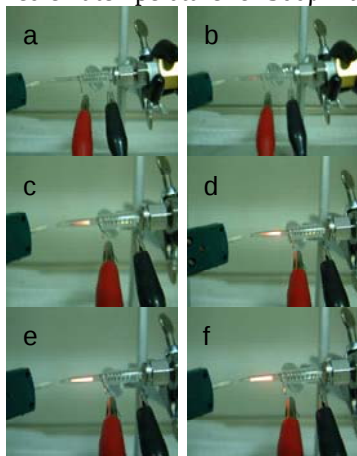


Fig. 3 The photographs of starting sequence: (a)

external heat was added, (b) reaction was ignited (c)-(e) reaction propagation, (f) steady operation of the device.

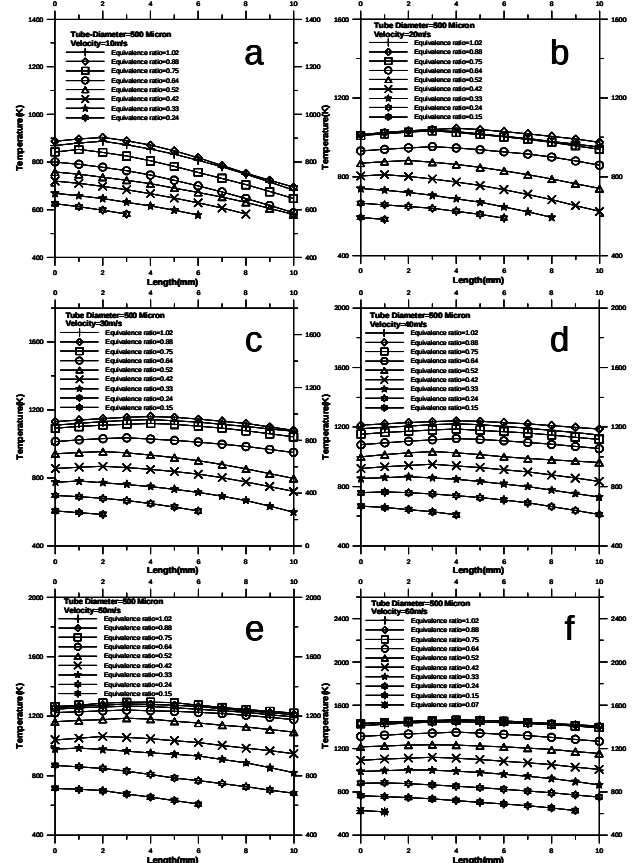


Fig. 4 Measured wall temperature of the PT tube with IR detector; the inlet velocity is (a)10m/s, (b) 20m/s, (c) 30m/s, (d) 40m/s, (e) 50m/s, (f) 60m/s.

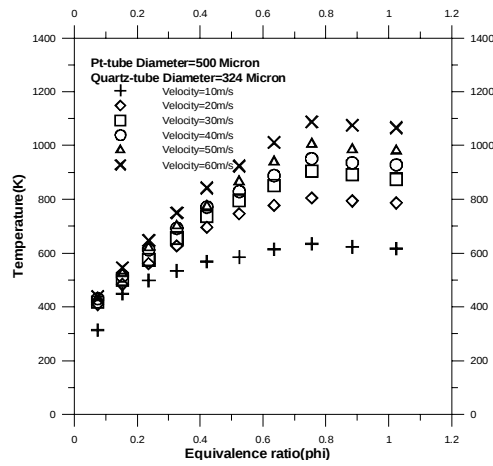


Fig. 5 Measured temperature at the 324 μm -diameter nozzle exit.

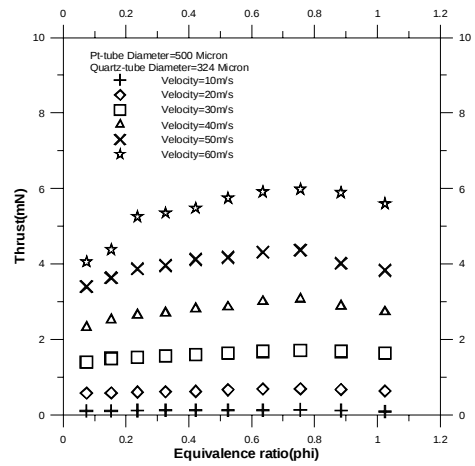


Fig. 8 Measured thrust for nozzle of diameter 324 μm .

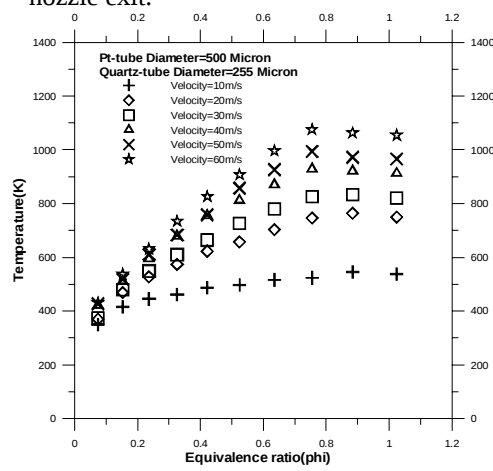


Fig. 6 Measured temperature at the 255 μm -diameter nozzle exit.

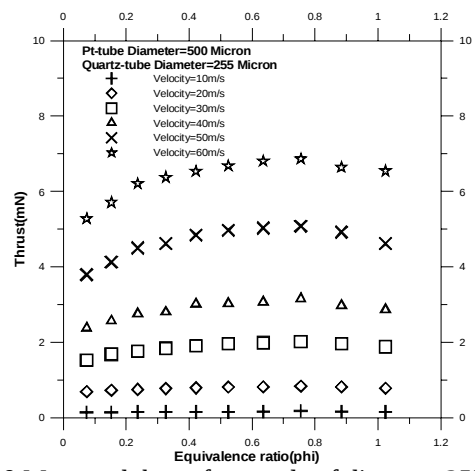


Fig. 9 Measured thrust for nozzle of diameter 255 μm .

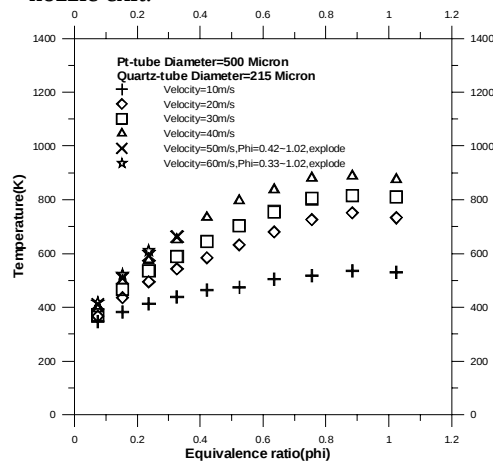


Fig. 7 Measured temperature at the 215 μm -diameter nozzle exit.

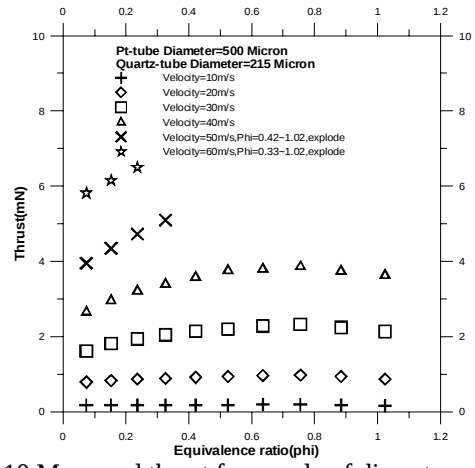


Fig. 10 Measured thrust for nozzle of diameter 215 μm .