Combustion Characteristics Analysis of Improved Combustor Structure of Micro Turbine Engine

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Abstract: In order to improve the performance of micro combustor, the 60 slots of the original combustor were modified into 120 slots for the MIT 6-wafer micro-combustor. The performance of the micro combustor with the improved and original design was compared through numerical simulation, and stable operating ranges was studied. It was found that the improved combustor can stabilize the flame under the condition of higher fuel/air mixture mass flow rate.

1 Introduction

With the development of micro devices such as microsensor, micro UAV and micro robots in recent years, micro combustion has received attention[1-2]. Compared with lithium batteries, the energy density of hydrogen fuel is higher (the energy density of hydrogen fuels is about 140kJ/g, and the lithium battery is about 1.2kJ/g). Therefore, the micro power system based on combustion has the great potential to replace the battery. Researchs on the micro energy system has been an important study subject now. [3-5]

Wang Zuo, et al. [6] modify the viscosity based on the effective mean molecular free path proposed by Dongari, numerical simulations are performed to analyse the micro scale Couette flow and periodic Poiseuille flow. It was demonstrated that the new LBM model of new effective viscosity improves the precision of the nonlinear phenomena of the LBM. Yan Han, et al.[7] investigated the flow characteristics of the gas in the microchannel under the coupling of velocity slip and random surface roughness through computational fluid dynamics. TANG Gang-zhi, et al.[8-9] found that the heat loss through wall has obvious influence on the combustion characteristics of the micro internal combustion engine. Jimsong Hua, et al.[10] analysed the combustion characteristics in a micro-combustor under various condition such as under various flow rate, heat loss conditions and fuel/air ratio. Zerrin Turkeli-Ramadan, et al. [11] performed numerical simulations to analyse the premixed laminar flow methane combustion in a two-dimensional micro-combustor with a diameter of 2mm. The flame has a laminar Bunsen type flame under adiabatic wall condition. Preheating the reactants can stabilize the flame at high inlet flow velocities.

The original MIT combustor will be blown out under conditions of higher mass flow. In order to stabilize the flame, a new structure for the micro gas engine is presented in this thesis. Figure 2 shows the new structure of the micro-combustor. The newly proposed combustor has 120 slots that staggered in different radial positions. A low velocity zone or recirculation zone is formed in improved combustor, so the improved design can extend the operational range of the inlet velocity.

In this paper, three-dimensional numerical simulations of hydrogen–air, premixed combustion are performed to analyse the flame behavior in the MIT micro-combustor and the improved combustor. The characteristics of the combustor is studied under different flow rate, fuel/air ratio.

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2. CFD model

2.1. Model geometry

The micro gas engine was manufactured by MEMS technology as shown in Figure 1. The combustion chamber is a cylindrical structure, Schematic geometry of combustor and its main dimensions has been represented in Fig.2. The volume of the combustion chamber is 190mm^3. The mixture passes through Compressor stator and enters the cooling jacket, then arrives at the slots of the chamber. The mixture is burned in the combustor and finally combustion products pass through stator blades of the turbine.

Figure 2 shows schematic geometry of MIT combustor. The inlet of the combustion chamber have 60 slots that each having a depth of 1 mm, length of 2.2 mm and the angle of 3.9° . Figure 3 shows schematic geometry of improved combustor. The inlet consists of 120 slots having a depth of 1 mm, length of 1.1 mm and the angle of 3° . The inner and external diameter of the inner slots is 6.9mm and 8.0mm respectively. The inner and external diameter of the external slots is 8.1 mm and 9.2mm. The slots are staggered in different radial positions. Because of the rotational periodic characteristic of the micro combustor, rotational periodic boundary condition is utilized to the radial cross section of the model.

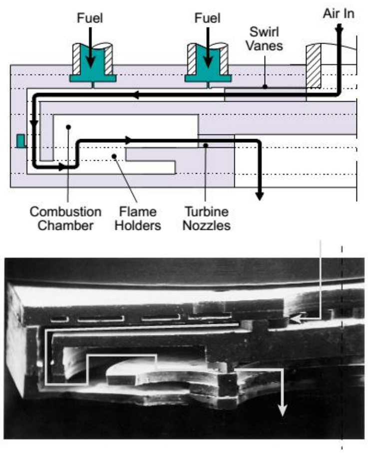

Fig.1 Schematic view of the MIT 6-wafer micro combustor [13]

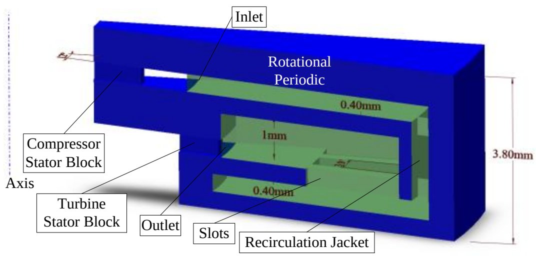

Figure.2 The model of the micro combustor with the original MIT structure

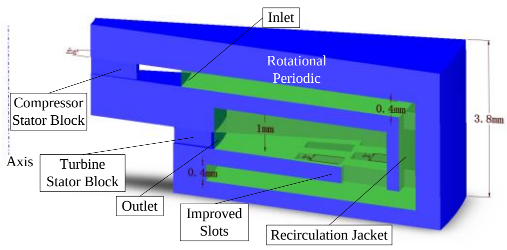

Figure.3 The model of the micro combustor with the improved MIT structure

2.2 Modeling equations

1). Continuity Equation:

$$\frac{\partial\rho}{\partial t}+\nabla\cdot(\rho\vec{v})=0 \quad (1)$$

2). Momentum Equation:

$$\frac{\partial}{\partial t}(\rho u_i)+\frac{\partial}{\partial x_j}(\rho u_j u_i)=-\frac{\partial p}{\partial x_i}+\frac{\partial \tau_{ij}}{\partial x_j} \quad (2)$$

Where the stress tensor τ_{ij} is given by

$$\tau_{ij}=\mu\left[\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)-\frac{2}{3}\frac{\partial u_i}{\partial x_j}\delta_{ij}\right] \quad (3)$$

Where μ is the molecular viscosity

3). Fluid energy conservation

$$\frac{\partial}{\partial t}(\rho E)+\frac{\partial}{\partial x_i}[u_i(\rho E+p)]=\frac{\partial}{\partial x_i}\left(k_{eff}\frac{\partial T}{\partial x_i}-\sum_j h_j J_j+u_j(\tau_{ij})_{eff}\right)+S_h \quad (4)$$

Where the E is given by

$$E=h-\frac{p}{\rho}+\frac{u_i^2}{2} \quad (5)$$

4). Species Conservation Equation:

$$\frac{\partial}{\partial t}(\rho Y_i)+\nabla\cdot(\rho\vec{v}Y_i)=-\nabla\cdot\vec{J}_i+R_i+S_i \quad (6)$$

2.3 Boundary conditions

Since the Reynolds number of the inlet is 240 as the mass flow is 0.2g/s, laminar viscous flow is considered. The chemical kinetic mechanism of hydrogen and oxygen consisting of 9 species and 19 reversible reactions, proposed by Tien et al. [12], was employed in this simulation.

The boundary conditions are defined for the mass flow rate-inlet, pressure outlet, the mass flow rate of inlet is 0.2 g/s. The inlet temperature is defined 300K in this paper. The equivalence ratio of the simulation case equals 0.5. No species flux normal to the wall surface and no-slip boundary condition are applied at the wall. The heat transfer coefficient at the outer wall is 200 $W/m^2/K$, the radiation emissivity is 0.85[10]. The wall heat conductivity equals 149W/(m·K), and the ambient temperature is 300K. The pressure of outlet is selected as 1.013×10^5Pa.

2.4 Meshing

A mesh sensitivity analysis was performed with two dimensional model of a prototype micro combustor under different grid spacing. The mass flow rate of flow is 0.2 g/s. the equivalence ratios are 0.5. The heat transfer coefficient at the outer wall is 200 $W/(m^2\cdot K)$, the radiation emissivity is 0.85[10]. The results of the calculation are as follows:

Table 1 Calculation results of different grid spacing in two dimensional structure of micro combustor

grid spacing (m)	outer wall temperature	exit gas temperature	mass fraction of hydrogen at the outlet
4e-05	563K	1341K	0.0317%
5e-05	564K	1344K	0.0308%
5.5e-05	564K	1345K	0.0311%
6e-05	565K	1347K	0.0304%

It can be seen from Table 1 that the simulation cases predict the flame temperature rather well when grid spacing ranges from 4×10^5m to 6×10^5m. So grid spacing of three dimensional model defined as 5.5×10^5m. The CFD model of the original design is meshed using about 290393 hexahedral cells. That of the improved combustor is 287550 hexahedral cells.

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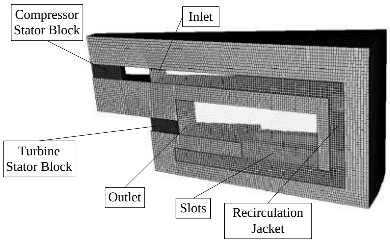

Figure.4 Original structure grid of micro combustor

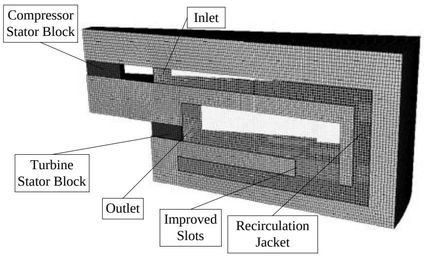

Figure.5 Improved structure grid for micro combustor

3 Discussion

3.1 Comparison of performance between the original and improved design

Fig.6 shows the temperature distribution on the section of the original and improved combustor when mass flow rate equals 0.4 g/s. The figure shows that the flame is going to blow out for the original design. Average temperature at the outlet is 483K, the wall temperature is only 421K. On the contrary, the flame can be stabilized in the improved combustor instead of blowing out under the same condition. Average exit temperature equals 1330K, the wall temperature is 612K. This simulation shows that the newly proposed design of the micro-combustor extends the operating range of inlet velocity.

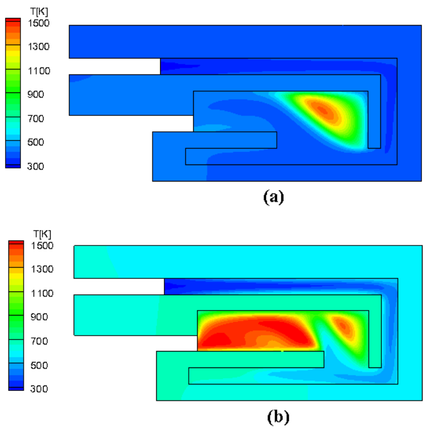

Figure.6 Temperature distribution on the cross section of the micro-combustor with the same mass flow rate of 0.4g/s: (a) original structure, (b) improved structure

Figure 7 presents the mass fraction distribution of species OH on the cross section of the engine with the original and improved design when mass flow rate equals 0.4 g/s. It shows that the high mass fraction zone of species OH is found only in one corner of the original combustor, the highest mass fraction distribution of species OH is about 0.352 percent. Most region of the combustor produced species of OH. The highest mass fraction distribution of species OH is about 0.544 percent which is higher than that of the original combustor. It shows that the improved design can stabilize the flame.

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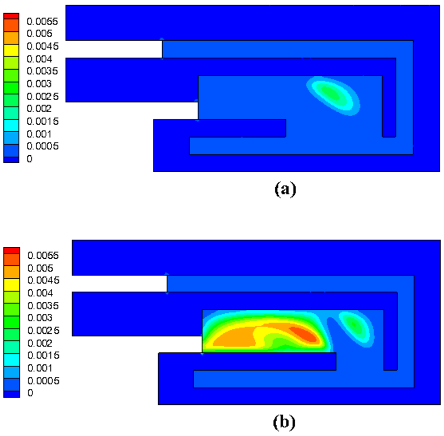

Figure.7 Mass fraction distribution of species OH on the cross section of the micro-combustor with the mass flow rate of 0.4g/s: (a) original structure, (b) improved structure

3.2 Effect of mass flow on the improved design

Fig.8 shows the alterations of the average mixture temperature at outlet area and the outer wall temperature as the mass flow changed. When mass flow rate is equivalent to 0.1 g/s, the average mixture temperature at outlet area and the outer wall temperature is 1143K and 586K respectively. The average mixture temperature at outlet area and the outer wall temperature is raised as the mass flow rate increased, the outlet temperature and the wall temperature rise to the highest, respectively 1347K and 618K when mass flow rate is 0.3 g/s. The temperature at outlet and outer wall temperature will go down slowly when the inlet flow rate range from 0.3g/s to 0.5g/s. The mixture temperature at outlet and outer wall temperature is decreased rapidly when inlet flow rate large than 0.5 g/s. Flame is going to blow out when inlet flow rate equals 0.7g/s. It can be concluded that the suitable flow rate range of the newly proposed combustor is 0.1–0.7 g/s

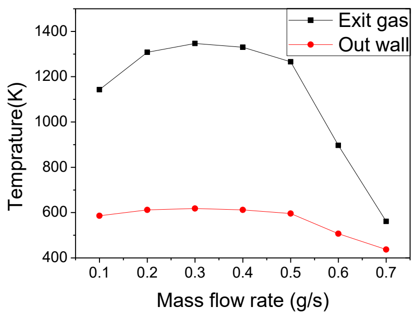

Figure.8 Effects of average mixture temperature at outlet area and the outer wall temperature for various mass flow rate

The combustion efficiency η can be defined by the hydrogen mass consume:

$$\eta = \frac{m_{H_2,in} - m_{H_2,out}}{m_{H_2,in}}$$

Where $m_{H_2,out}$ stands for the outlet flow rate of hydrogen; $m_{H_2,in}$ is the inlet flow rate of hydrogen.

Fig.9 reveals the effects of mass flow rate on combustion efficiency. The combustion efficiency decreases when the fuel/air mass flow is increased. The highest combustion efficiency is 0.996 when the inlet flow rate equal 0.1g/s. The combustion efficiency decreases slowly when the inlet flow rate range from 0.1g/s to 0.5g/s. Then the combustion efficiency decreases rapidly and the combustion efficiency is 0.215 as the inlet flow rate large than 0.5g/s.

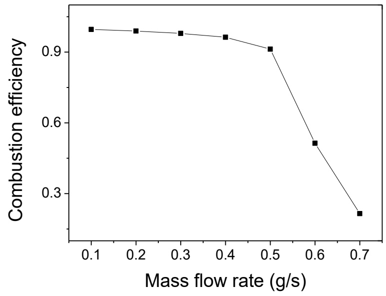

Figure.9 Effects of mass flow rate on combustion efficiency

4. Conclusions

In this paper, an newly proposed design of micrco-mbustor is presented. Three-dimensional CFD simulations of laminar, premixed, hydrogen–air flames at atmospheric pressure are utilized to analyse the combustion Characteristics in original and the improved combustor. The coupling of fluid dynamics, detailed chemical kinetics and heat transfer are performed in The CFD simulations.

Flame is going to blow out for the original design. On the contrary, the flame can be stabilized in the improved design under the same condition. The improved combustor extends the operating range of mass flow.

The numerical results under different mass flow rate show that the average temperature at outlet area and the outer wall temperature is increased when the mass flow is increased, then the outlet temperature and the wall temperature rise to the highest when mass flow rate is 0.3 g/s. Mixture temperature at outlet and outer wall temperature will go down slowly as inlet flow rate increased when the inlet flow rate range from 0.3g/s to 0.5g/s. The temperature at outlet and outer wall temperature is decreased rapidly when mass flow rate large than 0.5 g/s. the flame is going to be blow out when mass flow rate is 0.7g/s. so the suitable flow rate range of the newly proposed combustor is 0.1–0.7 g/s.

It can be concluded through CFD based combustion simulations that the combustion efficiency decreases when the mass flow increase. The combustion efficiency decreases slowly when the inlet flow rate less than 0.5g/s. Then the combustion efficiency decreases rapidly when the inlet flow rate large than 0.5g/s.

References

[1] Wan Jianlong，Liu Yi，Fan Aiwu, et al. Effect of channel gap on flame-splitting limit of a micro combustor with cavities[J]. *Journal of Huazhong University of Science and Technology*(Natural Science Edition), 2014 (8) :100-103

[2] CHEN Xin-jian，YAO Rong，LI Jun-wei, et al. Effects of Inlet Flow on Combustion Characteristics of n-Heptane in a Micro-Combustor[J]. *Journal of Propulsion Technology*, 2017，38(04):869-877.

[3] Mehra A, Zhang X, Ayon A A, et al. A Six-wafer Combustion System for a Silicon Micro Gas Turbine Engine[J]. *Journal of Microelectromechanical Systems*, 2001, 94(4):517-527.

[4] Mehra A, Ayon A A, Waitz I A, et al. Microfabrication of High-temperature Silicon Devices using Wafer bonding and Deep Reactive Ion Etching[J]. *Journal of Microelectromechanical Systems*, 1999, 8(2):152-160.

[5] CHEN Xiao-li，JIANG Xue-hui, HE Wu, et al. A Study on Key Technologies of Micro Combustor with a Slinger Injector[J]. *Journal of Propulsion Technology*, 2016，37(02):296-303.

[6] Wang Zuo，Liu Yan，Zhang Jia-Zhong. Simulation of micro flow in the transition regime using effective-viscosity-based multi-relaxation-time lattice Boltzmann model[J]. *Acta Physica Sinica*, 2016，65(1):299-308.

[7] Yan Han，Zhang Wen-Ming，Hu Kai-Ming, et al. Investigation on characteristics of flow in microchannels with random surface roughness[J]. *Acta Physica Sinica*, 2013， 62(17):298-303.
[8] TANG Gang-zhi, ZHANG LI, SHANG Hui-chao, et al. Mechanism Analysis of Thermodynamical Parameter Effect on Micro Scale IC Engine Combustion characteristics[J]. *Chinese Internal Combustion Engine Engineering*, 2015，36(2): 11-17.
[9] TANG Gang-zhi，ZHANGLi, DUBaocheng. influence numerical analysis of combustion chamber thermal boundary conditions on unsteady combustion characteristics in micro ICE[J]. *Journal of Chongqing University* (Natural Science Edition), 2014,(9):11-17.
[10] Jimsong Hua, Meng Wu, Kurichi Kumar. Numerical Simulation of the Combustion of Hydrogen–air Mixture in Micro-scaled Chambers Part II: CFD analysis for a micro-combustor[J]. *Chemical Engineering Science* 2005, 60: 3507-3515.
[11] Zerrin Turkeli-Ramadan, Rajnish N. Sharma, Robert R. Raine. Two-dimensional Simulation of Premixed Laminar Flame at Microscale[J]. *Chemical Engineering Science*, 2015. 138,414-431.
[12] Tien, J.H., Stalker, et al. Release of Chemical Energy by Combustion in A Supersonic Mixing Layer of Hydrogen and Air[J]. *Combustion and Flame*, 2002. 130, 329-348.
[13] Epstein, A.H., Jacobson, et al. L.G., 2000. Shirtbutton-sized Gas Turbines: the Engineering Challenges of Micro High Speed Rotating Machinery. In: 8th International Symposium on Transport Phenomena and Dynamics of Rotating Machinery (ISROMAC-8), Honolulu, March.