Applied Thermal Engineering 103 (2016) 874–882

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Thermal properties and energetic characteristics of a combustion system

X.Q. Fu, S.L. Song *, W.C. Zhong, D.P. Zeng, C.D. Gao

School of Power and Mechanical Engineering, Wuhan University, Wuhan 430072, China

HIGHLIGHTS

- The highest temperature appeared at the combustion chamber boundary.
- The thermal deformation of silicon was smaller than steel.
- The thermal stress was the main reason for the destruction of micro-thruster stability.

ARTICLE INFO

Article history:
Received 8 March 2016
Revised 12 April 2016
Accepted 21 April 2016
Available online 23 April 2016

Keywords:
Temperature distribution
Heat transfer
Model

ABSTRACT

In this paper, the thermal decomposition characteristics and the energy characteristics were studied to select a suitable propellant formulation. The temperature distribution of micro-thruster array was calculated to study the effect of heat loss on the combustion chamber shell. The monopropellant micro motor model was established, and the effect of heat loss on the micro-thruster performance was studied. Results indicated that 5:5 Lead Styphnate (LS)/Nitrocellulose (NC) was suitable as micro-motor formulation, and the highest temperature appeared at the boundary of the combustion chamber, where the thermal stress and deformation were the maximum. Furthermore, the thermal stress and deformation of silicon material was smaller than steel and the thermal stress was the main reason for the destruction of micro-thruster stability. In addition, the heat loss had great effects on micro-thruster performance: the thrust decreased by 21.7%, and the specific impulse also decreased by 11.8%.

1. Introduction

MEMS-based solid propellant micro-thruster has broad applications for small satellites operating at high attitude and orbit control technology because of its small size, high precision micro impulse and good integration [1,2]. The combustion in micro motors is very different from the main motor. For a micro motor, because the surface area/volume increases rapidly, rheological effects are obvious, and heat loss is large. As a result, the temperature of the internal flowing fluid more obvious increases, thereby affecting their flow and heat transfer.

In 2007, Louisos and Hitt [3] studied viscous flow and the heat transfer loss of 2D and 3D supersonic linear micro nozzle by the CFD software, it was found that there existed an intrinsic exchange between the viscous losses and losses which generated due to non-axial exports flow. In the three-dimensional simulation, because of the presence of longitudinal flat wall, the adhesive effect is more significant. Since the viscosity effect can be reduced due to the heat loss generated by flow and the corresponding reduction of subsonic boundary dimensions, the performance of the micro nozzle can be improved. In 2009, Louisos and Hitt [4] investigated the effects of heat loss on the micro-nozzle thrust. They found that the gas flow heat exchange reduced subsonic viscous layer area, the Rayleigh flow was accelerated, and the heat transfer of fluid to the substrate increased the gas density. In 2010, Moríñigo and Quesada [5] solved the NS equations by using second-order slip boundary model and gas–solid thermal coupling model to study the effects of the interaction between gas and wall on the micro nozzle performance. They revealed that solid wall had a huge impact on the flow of gas, and thus the performance of the micro nozzle. In 2011, in order to reduce the heat loss caused by subsonic boundary layer, the nozzles which expand half-angle were 15° and 30° was designed by numerical simulations by Cheah and Chin [6]. In 2013, the combustion simulations in a micro combustion chamber were carried by using the CFD software to analyze the various factors for the combustion performance [7]. Such simulations proposed an efficient methodology to reduce the heat loss and to improve the micro-combustor performance. Based on the previous work, recently Zhou and Zhang [8] simulated the gas flow process and heat loss of the two solid micro-thruster structures. He proposed a powerful method to improve the impulse performance of

---

* Corresponding author.
E-mail address: 80502083@qq.com (S.L. Song).

http://dx.doi.org/10.1016/j.applthermaleng.2016.04.113
1359-4311/

micro-thruster by using the glass or ceramic materials with good insulation properties. Furthermore, based on the practical working conditions of micro rocket motors Zhou et al. [9] established a heat transfer model for calculating the transient temperature field. The results showed that the copper shell can be kept at a relatively low temperature, and the temperature of the rear part of grain burning surface near the insulating layer could increase to a different level, which had an impact on the burning rate and can easily lead to the unstable combustion. Moreover, by the ANSYS calculations of the coupled transient thermal structure, Liu et al. [10] simulated the influences of unit number, gas temperature, reaction time and the array structure on the chamber thermal stress and thermal deformation of micro-thruster combustion. The results showed that the maximum thermal stress and thermal deformation of the hole was mainly concentrated in the combustion chamber boundary. Compared with a single unit, the equivalent thermal stress was large on the effect of the array, and the maximum deformation was smaller. The maximum equivalent thermal stress and maximum deformation increased with the increases of gas temperature, and the time and chamber diameter decreased with the increases of array element spacing. Li et al. [11] studied the influence of micro scale effects and flow loss on the thrust–time curve during the transient work process of thruster which combined dynamic mesh and fluid–solid coupled heat transfer model. The results showed that for the investigated micro-thruster, the micro scale had a significant effect on the flow field, but had little effect on the thrust. For the Corning Ceramic materials, the overall heat loss of micro-thruster was small and decreased with time, while it was large for Si material and increased with time.

Very recently, O'Neill et al. [12] investigated the heat and mass transfer behavior of a film evaporative MEMS tunable array thruster. Because of the small scale of this thruster, the powerful tools of mass transfer analysis such as Direct Simulation Monte Carlo methods have been employed. For example, the COMSOL Multiphysics was used to model the heat and mass transfer in the solid and liquid portions of the thruster, and the two methods were incorporated into a bisection solving scheme. The calculations showed that the performance of more than 20 micronewtons of thrust at approximately 65 s may be attainable, and the power can be regulated to provide a specific level or thrust or an impulse bit. Here it should be indicated that for the heat and mass transfer behavior, over the past decade various theoretical methodologies and models have been developed for different systems. For example, Sharafian and Bahrami [13] designed a heating and cooling system and investigated the thermal performance of the system. They further proposed the practical solutions such as the optimization of fin spacing and fin height, and enhancing thermal conductivity of adsorbent material in order to enhance heat and mass transfer rates. Aristov et al. [14] proposed a new methodology of studying the kinetics of heat transfer under operating conditions typically for isobaric stages. Hassan et al. [15] employed a realistic theoretical simulation model to deal with a tubular solar system. Furthermore, they [16] developed a dynamic model based on the D–A adsorption equilibrium equation and the energy and mass balances. Sun and Chakraborty [17] proposed a thermodynamic framework to describe the dynamic uptakes of water vapor on various sizes and layers of silica gels for adsorption cooling applications. Interestingly, they derived a thermodynamically consistent adsorption kinetics equation that can vary from the Henry's region to the saturated pressure, adsorption isotherm coefficient, and activation energy to overcome the limitations of the general LDF kinetics equation.

In this paper, a suitable propellant formulation was selected based on its energy characteristics and thermal decomposition characteristic. Thermal analysis calculation of the micro-thruster array was carried out, and temperature distribution, thermal stress and thermal deformation of the thruster array with the combustion chamber materials of silicon and steel was comparatively studied. A monopropellant engine physics and mathematics micro model was established, a three-dimensional numerical simulation was carried out, and finally the effects of heat loss on motor performance were studied.

2. Selection of propellant formulation for the micro motor

2.1. Energy characteristics of propellants

Due to the simple structure, less charge, and electric ignition of micro motor, it is impossible to use the traditional point pyrotechnic device. Therefore, the charge is required to be more sensitive to electro thermal, and to be easily ignited directly under electric conditions. However, solid propellants used for micro-thruster are quite different. It is necessary to seek a propellant with a high energy, high heat-sensitive characteristic, short ignition delay time, and excellent filling performance. In the present study, Ammonium Perchlorate (AP)/Nitrocellulose (NC), Lead Dinitramide (LD)/Nitrocellulose, Lead Styphnate (LS)/Nitrocellulose compositions were selected as propellants, and energetic and thermal characteristics of the different propellant formulations were investigated.

Thermodynamic calculations of the combustion chamber and nozzle were performed using the Minimum Gibbs free energy method to get some parameters that represent energy characteristics of the propellants. Thermodynamic calculation conditions as follows; initial temperature was set to room temperature at 300 K, the initial pressure of the combustion chamber was set to the atmospheric pressure 1 MP, the combustion chamber area and nozzle throat area $A_c/A_t = 1^2/0.246^2 = 16.52$, and nozzle expansion ratio $A_e/A_t = 0.6^2/0.246^2 = 5.95$. Table 1 given below gives the energy characteristic parameters of the four types of propellants in different proportion.

From Table 1, we can see that:

(1) A1, B1, and C1 contain the same number and variety of binder NC, the C^* (characteristic velocity) of C1 is 1246.3 m/s, which is 56.2 m/s higher than the value for A1 and 381.7 m/s higher than the value for B1. With the same binder and content, the AP propellant has higher energy. Fig. 1 shows the impulse changes of different formulation propellants. With the same binder conditions, the energy of the propellant with oxidizer AP is higher than that with oxidizers LS or LD, and the energy of the propellant with oxidizer LD is minimum.

Table 1
The energy characteristic parameters of propellants.

Propellant	Code	Ratio	Energy characteristics				
			T_f (K)	n_g (mol kg^{-1})	γ	I_{sp} (N s kg^{-1})	C^* (m s^{-1})
LS/NC	A1	8:2	2738.5	24.2	1.1	2087.2	1190.1
	A2	7:3	2715.7	26.1	1.1	2150.3	1226.3
	A3	6:4	2695.3	28.0	1.1	2211.7	1261.4
	A4	5:5	2676.8	29.9	1.1	2271.6	1295.4
LD/NC	B1	8:2	1529.7	22.0	1.1	1522.7	864.6
	B2	7:3	1603.5	24.7	1.1	1667.3	941.8
	B3	6:4	1849.9	27.3	1.1	1811.6	1016.8
	B4	5:5	2051.2	29.7	1.1	1954.2	1106.9
AP/NC	C1	8:2	2347.3	34.7	1.2	2150.9	1246.3
	C2	7:3	2594.0	34.2	1.2	2217.3	1316.3
	C3	6:4	2725.1	33.6	1.2	2310.2	1412.1
	C4	5:5	2815.7	33.0	1.2	2375.9	1488.9