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Optimal selection of appropriate fuels for a miniaturized motor and numerical simulations on its temperature distributions and thermal deformation

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ABSTRACT

In this work, the energy characteristics of different propellants were thermodynamically calculated using the Minimum Gibbs free energy method. Based on such calculations and the previous experimental results using the DSC investigations on the thermal decomposition behavior, an optimized propellant formulation was selected. The numerical simulations on the temperature distributions for a prepared miniaturized motor with this formulation were conducted, and the resultant thermal stress and deformation of the thruster array were investigated. In particular, a physical micro model was established, and the effects of combustion parameters on the thermal performance were studied. The results showed that the highest temperature occurred 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 maximum thermal deformation was small and had little effects on the thermal stability, whereas the thermal stress was the main reason for the poor thermal stability.

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 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 thruster. 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 with a half-angle from 15 ° to 30 ° was designed by Cheah and Chin [6]. In 2013, using the CFD software Li and Pan [7] conducted the simulations in a micro chamber to analyze the various factors for the combustion performance. Such simulations proposed an efficient methodology to reduce the heat loss and to improve the micro-combustor performance. Based on the previous work, for the first time H.Q. Zhou [8] simulated the gas flow process and heat loss of the two solid micro-thruster structure. He proposed a powerful method to

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improve the impulse performance of micro-thruster by using the glass or ceramic materials with good insulation properties. Furthermore, based on the practical working conditions of micro rocket motors, C. Zhou [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 small. The maximum equivalent thermal stress and maximum deformation was proportional to gas temperature, but the time and chamber diameter was inverse proportional to array element spacing. Li et al. [11] studied the influence of micro scale effects and flow loss on the thruster-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 thruster. 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, 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 thruster at approximately 65 s may be attainable, and the power can be regulated to provide a specific level or thruster or an impulse bit.

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 Baheami [13] designed a heating 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. 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. Here it should be pointed out that the above theoretical studies have achieved considerable success in the prediction of dynamic behavior of a heat transfer system. However, the proposed dynamic models involved in these studies were mainly based on the practically designed system where different working pairs and operating conditions were hardly considered due to the difficulties in both physics and mathematics. In particular, an employed operating thermodynamic cycle based on a basic one-bed system using the typical adsorbent-adsorbate pair for the heating purpose is over-simple even rough for practical applications. Obviously, the multi-bed schemes are enhancements on the basic one-bed system to increase the performance and to provide quasi-continuous operation, but very complex in some sense. In summary, to the best of our knowledge, up to now there are no such general and concise models that can handle the dynamic thermal-mechanical behavior for a miniaturized motor.

In this paper, an optimized propellant formulation was selected based on its energy characteristics and thermal decomposition characteristic. Thermal analysis calculations of the micro-thruster array was carried out. Then the temperature distribution, thermal stress and thermal deformation of the thruster array was comparatively studied based on a proposed micro model. In particular, a three-dimensional numerical simulation was carried out, and finally the effects of heat loss on motor performance were investigated.

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, thus the charge was required to be more sensitive to electro thermal, and to be easily ignited directly under electric conditions, solid propellant used for micro-thruster is quite different from common propellant, a high energy, high heat-sensitive characteristics, shorter ignition delay time, the excellent filling performance were required. Ammonium Perchlorate (AP)/Nitrocellulose (NC), Lead Dinitramide (LD)/Nitrocellulose, Lead Styphnate (LS)/Nitrocellulose compositions were selected as propellants. The above compositions were chemically pure and purchased from Sitan Chem. Co., Mianyang, China. Subsequently, the energy characteristics and thermal decomposition characteristics analysis of the different propellant formulations will be carried out to select the best formulation.

Thermodynamic calculations of the combustion chamber and nozzle were performed using the Minimum Gibbs free energy method to obtain the energy characteristics of the propellants. The equation of Gibbs free energy is expressed as:

$$f = \min G, G = \sum_{j=1}^{S} G_j^0 n_j + \sum_{j=S+1}^{C} \sum_{l-1}^{P} G_{jl} n_{jl} \tag{1}$$

where f is an objective function, G is Gibbs free energy, S is an independent phase, P is the number of phase, and C is the number of component. The confined conditions for Eq. (1) can be expresses as:

$$\sum_{i=1}^{C} n_i \Delta H^0_{f,feed,298} + \sum_{i=1}^{C} n_i H_i(T_{feed,i}) = \sum_{i=1}^{C} n_i \Delta H^0_{f,prod,298} + \sum_{i=1}^{C} n_i H_i(T_{prod,i}) + Q \tag{2}$$

where H_i is the normal enthalpy for component i, T is temperature, and Q is thermal loss. For the detailed mathematical analysis, one can refer to [18–20]. The followed thermodynamic calculation conditions were: initial temperature was set to room temperature at 300 K, initial pressure of the combustion chamber was set to the atmospheric pressure 1MP, combustion chamber area and nozzle throat area $A_c/A_t = 1^2/0.246^2 = 16.52$, and nozzle expansion ratio