Numerical Study of Catalyst Bed Performance of a Monopropellant Thruster Under Influence of Porosity Coefficient

MohammadReza Salimi[1], Hadiseh Karimaei[2*], Mostafa Gholampour Yazdi[3]

[1, 2 and 3] Aerospace research institute, Ministry of science research and technology

ABSTRACT

Hydrazine monopropellant thrusters are commonly used in the situation control and orbital transmission systems of satellites and space crafts. In these thrusters, hydrazine is decomposed into a hot gas product after passing through the catalyst bed during an exothermic reaction. The decomposition chamber of a monopropellant thruster is numerically modeled at pore scale. Then the effect of catalyst bed porosity coefficient, which is the most important parameter affecting the performance of the decomposition chamber, is investigated. Simulations were performed in two-dimensional axial symmetry as the steady flow in the gas phase. Catalyst granules with an average diameter of 1 mm with three porosity coefficients of 0.4, 0.55 and 0.65 has been considered and the inlet pressure of the decomposition chamber has been considered 15 bar. The results showed that the porosity coefficient has a very significant effect on the performance of the catalyst bed so that by decreasing this coefficient, the decomposition of hydrazine increases, the bed temperature and outer wall temperature increase and the mass flow rate decreases. Reducing the bed porosity coefficient from 0.65 to 0.4, causes about 40% drop in the bed pressure compared to the initial inlet pressure and also about 40% reduction in the mass flow rate through the bed. Therefore, the study of this parameter can greatly help the researchers in determining and optimizing the efficiency of decomposition chamber.

KEYWORDS

Hydrazine thruster, Catalyst bed, Decomposition chamber, Porosity coefficient, Pore scale.

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[*] Corresponding Author: Email: karimaei@ari.ac.ir

Introduction

In the monopropellant thrusters, the decomposition mechanism is used to release the chemical energy of the propellant. Zhang et al. [1] simulated the evaporation and decomposition of hydrazine using a mixed two-phase model considering mass transfer. Both homogeneous (gas phase) and heterogeneous (in the presence of catalyst) reactions are considered in their calculations and the steady-state temperature profile along the decomposition chamber was compared with the experimental data.

In the present paper, the decomposition chamber of a monopropellant hydrazine thruster is numerically modeled at pore scale. The effect of the catalyst bed porosity coefficient on the performance of the decomposition chamber, with an average granule diameter at a specified inlet pressure is investigated. Performance parameters of the decomposition chamber are such as mass flow rate, mass fraction of hydrazine, bed loading, bed temperature and outer bed wall temperature, axial velocity of bed flow, pressure changes and bed pressure drop. In many previous studies, the same method has been used as in the present study, i.e. to change the porosity coefficient of the bed, instead of changing the size of the granules, the distance between them has been changed. Zhou et al. [2] arranged the square particles in two dimensions and changed the distance between them to change the porosity coefficient. Zhu et al. [3] arranged the same spherical granules in three dimensions and, to change the porosity coefficient, changed their distance by changing their arrangement. At the pore scale simulation, no simplified model is included and therefore it has high accuracy.

Methodology

The present problem consists of two sections, the first is related to evaporation and gasification of propellant that occurs in the induction zone of the decomposition chamber. In this zone, the simplified energy equation is used according to the research of Shankar et al. [4]. In the second section, after determining the flow properties at the end of the induction zone, the analysis of hydrazine decomposition in the gas phase is performed on the catalyst bed.

Shankar et al. [4] extracted an energy equation for the induction zone and calculated the temperature along it. Note that the length of the induction zone is usually very short and can be ignored relative to the dimensions of the chamber. However, the temperature and mass fraction of the species at the end of this zone have a significant effect on the accuracy of the simulations. After calculating the temperature at the end of the induction zone, the mass fraction of chemical species is also calculated using the following equations [5]:

$$Y_g^{N2H4} = 0.87 - 0.0006T_{Ind} \tag{1}$$

$$Y_g^{NH3} = \left(\frac{M^{NH3}}{M^{N2H4}}\right)\left(1 - Y_g^{N2H4}\right) \tag{2}$$

$$Y_g^{N2} = \left(\frac{M^{N2}}{2M^{N2H4}}\right)\left(1 - Y_g^{N2H4}\right) \tag{3}$$

$$Y_g^{H2} = \left(\frac{M^{H2}}{2M^{N2H4}}\right)\left(1 - Y_g^{N2H4}\right) \tag{4}$$

After calculating the mass fraction of hydrazine, the mass fraction of other species has been calculated based on the stoichiometric coefficients of the decomposition equations of hydrazine and ammonia. The governing equations for the post-induction zone, along the decomposition chamber, for pressure, temperature, and pore density between catalyst granules can be obtained from the energy, momentum, and mass conservation equations for each species and the state equation for the mixture.

Figure 1 (a, b and c) shows the geometry of the studied catalyst bed in three porosity coefficients: 0.4, 0.55, 0.65 and with a granule diameter of 1 mm. The boundary conditions are selected at the inlet as pressure inlet and at the outlet of the nozzle as pressure outlet. In the granule wall, the reaction model has been activated in the software. Figure 1 (d) shows a view of the computational mesh created around the catalyst granule. Due to the fact that chemical reactions occur in the vicinity of the catalyst surface, high-density structured mesh is used.

Discussion and Results

Figure 2 shows a quantitative comparison of the mass fraction profiles of hydrazine along the bed. The results show a significant reduction in the mass fraction of hydrazine by reducing the porosity coefficient. It is noteworthy that the rate of hydrazine decomposition reaction in this study is limited to a very thin layer of the catalyst granule wall. Therefore, the rate of chemical reactions in this case is much higher than the rate of mass transfer from the fluid flow to the catalyst surface and from the catalyst surface into it. Thus, hydrazine is completely decomposed before penetrating into the catalyst granules.

It should be noted that by decreasing the porosity coefficient, due to the increase in the resistance of the porous medium, the permeability of the bed decreases, which in turn increases the pressure drop. Because catalyst bed granules do as obstacles.

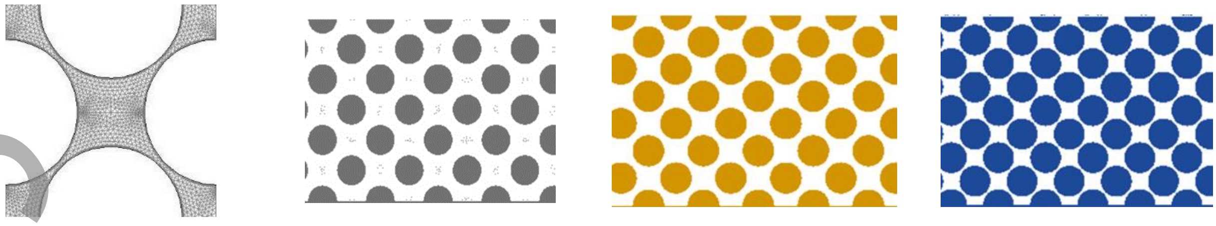
(d) (c) (b) (a)

Figure 1. The geometry of the bed with porosity coefficients of (a) 0.4, (b) 0.55, (c) 0.65 and a granule diameter of 1 mm and (d) a mesh view of the simulated model created around the catalyst granules

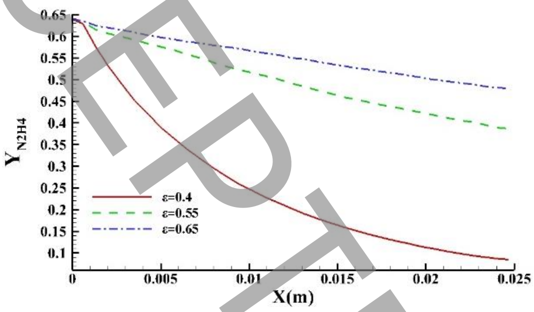

Figure 2. Mass fraction of hydrazine, with different porosity coefficients

Figure 3 compares the axial velocity profiles in the bed. Decomposition of hydrazine does not significantly increase the gas velocity in the catalyst bed. The reason for this is the presence of obstacles (granules) in the porous bed, which prevents a sharp increase in velocity. However, along the bed at a lower porosity coefficient, due to the greater pressure drop, the local velocity increases more. In addition, due to the complete decomposition of hydrazine along the bed and the resulting increase in temperature, the velocity at the end of the nozzle increases more. It is observed that with increasing the porosity coefficient, the velocity at the end of the catalyst bed as well as the end of the nozzle is reduced. Therefore, it is found that assuming the catalyst granule diameter and the inlet pressure are constant, increasing the porosity coefficient, due to the lower temperature of the decomposition chamber, will reduce the axial velocity.

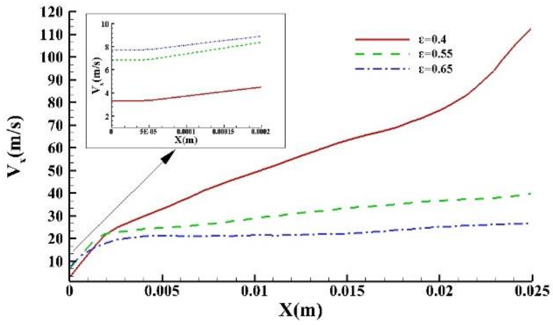

Figure 3. Axial velocity, with different porosity coefficients

Along the catalyst bed, the local velocity increased more by decreasing the porosity coefficient due to the greater pressure drop. However, the mass flow rate has increased less, which is normal, because when the pressure drop along the catalyst bed increases, consequently less flow will pass through. By increasing the porosity coefficient and thus decreasing the pressure drop, the mass flow has increased more. Therefore, by reducing the porosity coefficient, we can expect the thruster consumption to decrease.

Conclusions

By reducing the porosity coefficient, the effective contact surface for chemical reactions is increased, which leads to increased hydrazine decomposition, and improves the performance of the catalyst bed. Also, due to the higher temperature in the decomposition chamber, it leads to a further increase in flow velocity at the end of the catalyst bed. Due to greater pressure drop along the catalyst bed, it also reduces the mass flow.

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