Numerical Investigation of Effect of Combustor Length on Combustion Characteristics of Solid Fuel Ramjet

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Abstract. In this paper, the effect of solid fuel ramjet (SFRJ) combustor length on combustion characteristics with swirling turbulent reacting flow is investigated via numerical approach. An in-house code written in FORTRAN is employed to simulate the 2-dimensional turbulent reacting swirling flow in the combustor of SFRJ. The results indicate that increasing the combustor length will increase the temperature near the backward-facing step and the afterburning chamber and enhance the local heat flux at the reattachment point.

1. Introduction
Solid fuel ramjet draws attention throughout the world in recent years because of its characteristics of simple structure, low cost, and high mobility. However, the combustion characteristic of solid fuel ramjet is very hard to describe accurately. Moreover, the combustion efficiency and the working performance could be very sensitive to the flight condition, the geometry of the combustor and inlet conditions. Thus, many excellent efforts have been conducted to explore the combustion characteristic and the working performance of SFRJ.

According to the previous research, the main disadvantage of the SFRJ is the low fuel regression rate, usually less than one mm/s. It is widely known that increasing the residence time of the pyrolysis products and the mixing degree of the reactants could be a meaningful method to increase the regression rate of SFRJ. Therefore, swirling flows are employed to increase residence time and mixing degree of the reactants in the combustor of SFRJ owing to its larger tangential velocity and smaller axial velocity.

Liou et al. [1] performed an irreversible, one-step combustion model to describe the chemical reaction of the solid fuel ramjet. Lilley [2], [3] firstly proposed a numerical study of the flow features with and without chemical reaction in SFRJ with swirling flow. Omer Musa et al. [4], [5] experimentally and numerically investigated the combustion characteristics of swirl combustor of solid fuel ramjet. They found that the regression rate could be enhanced, the ignition time delay is decreased, and the combustion efficiency and stability could be improved. W. Li et al. [6] investigated the effect of geometry on the swirl combustor of SFRJ. The results indicated that the regression rate could be sensitive to the port-diameter and inlet diameters.
In this article, to investigate the combustion characteristics of SFRJ affect by different length of the combustor swirl incoming flow, we developed an in-house code which is written in FORTRAN to simulate the physical model of the SFRJ that fueled by High-Density Polyethylene (HDPE). The physical reasons for the effects of length of the combustion chamber on combustion characteristics were analyzed in detail.

2. Mathematical method

2.1. Governing equations of the fluid domain

The Reynolds-average Navier-Stokes equations is written in the following form [7]:

$$ \frac{\partial Q}{\partial t} + \frac{\partial E}{\partial x} + \frac{\partial F}{\partial y} = \frac{\partial E_u}{\partial x} + \frac{\partial F_v}{\partial y} + H + H_y + S $$  \hspace{1cm} (1)

Where the conservative vector \( Q \), convective flux vectors \( E, F \), viscous flux vectors \( E_i, F_i \), axisymmetric source terms of convective flux and viscous flux vectors \( H, H_y \), and source term produced by chemical reactions \( S \) could be expressed in the form below:

$$ Q = \begin{bmatrix} \rho \\ \rho u \\ \rho v \\ \rho w \\ \rho E \\ \rho_i \end{bmatrix}, E = \begin{bmatrix} \rho u \\ \rho u^2 + p \\ \rho u v \\ \rho w v \\ (\rho E + p)u \\ \rho_i u \end{bmatrix}, F = \begin{bmatrix} \rho v \\ \rho v^2 + p \\ \rho v w \\ \rho w v \\ (\rho E + p)v \\ \rho_i v \end{bmatrix}, \quad \begin{bmatrix} 0 \\ \tau_{xx} \\ \tau_{xy} \\ \tau_{wy} \\ \tau_{xv} + \nu \tau_{yv} + q_i \\ \rho D_i \partial \xi_i / \partial x \end{bmatrix}, \quad \begin{bmatrix} 0 \\ \tau_{xy} \\ \tau_{yx} \\ \tau_{yy} \\ \tau_{yv} + \nu \tau_{yv} + q_i \\ \rho D_i \partial \xi_i / \partial y \end{bmatrix} $$  \hspace{1cm} (2)

$$ H = -\frac{1}{y} \begin{bmatrix} \rho v \\ \rho w v \\ \rho(v^2 - w^2) \\ \rho (E + p)v \\ \rho_i v \end{bmatrix}, H_y = -\frac{1}{y} \begin{bmatrix} 0 \\ \tau_{vy} \\ \tau_{yy} - \tau_{wv} \\ \tau_{wy} + \nu \tau_{xy} + \nu \tau_{yw} + q_i \\ \rho D_i \partial \xi_i / \partial y \end{bmatrix}, S = \begin{bmatrix} S_p \\ S_{p\rho} \\ S_{pv} \\ S_{pw} \\ S_{pE} \\ w_i + S_{pE} \end{bmatrix} $$  \hspace{1cm} (3)

In Eq. (2) \( u, v, \omega, \rho, p \), and \( E \) are velocities in axial, radial and tangential directions, total density, pressure, and energy, respectively. In Eq. (2) and (3) \( \tau, \mu, \) and \( q_i \), \( q_j \) represent the shear stress, total viscosity, and heat fluxes, respectively. \( T \) and \( \lambda \) are temperature and thermal conductivity, respectively. The diffusion coefficient is represented by \( D_i \), the mass source is \( w_i, \rho_i, c_i \), \( h_i \) (\( i = 1,2, \ldots, 7 \)) represent the density, mass fraction and enthalpy of component \( i \) in unit mass, respectively. Moreover, \( \rho D_i \) is defined by:

$$ \rho D_i = \frac{1 - X_i}{1 - c_i} \left( \frac{\mu_i}{S_i} + \frac{\mu_T}{S_{ci}} \right) $$  \hspace{1cm} (4)

Where laminar Schmidt number and turbulent Schmidt number are represented by \( S_i \), and \( S_{ci} \), respectively. The mole fraction is defined as \( X_i, \mu_i \) and \( \mu_T \) represent the laminar viscosity and turbulent viscosity, respectively. Where \( \mu \) of gas mixture is calculated by Lennard-Jones method[8] which is shown by Eq. (5):
\[ \mu_i = \sum_{i=1}^{7} X_i \mu_i, \phi_i = \sum_{j=1}^{2} X_j \left(1 + \frac{\mu_i M_j}{\mu_j M_i} (\frac{\mu_i}{\mu_j})^{\frac{1}{2}} \right) \]

The universal gas constant \( R_u \) is used to calculate the gas mixture pressure, which is given by:

\[ p = \sum_{i=1}^{7} \rho_i R_u T \]

The Newton iteration method (Eq. (7)) is employed to calculate the \( T \) (temperature).

\[ \rho E - \frac{1}{2} \rho (u^2 + v^2 + w^2) = \sum_{i=1}^{7} \rho_i (T_{298} C_{pi} dT + h_{i298}^T) - \rho_i R_u \sum_{i=1}^{7} \frac{T_{298}}{M_i} \]

Where, \( h_{i298} \) is the heat of formation enthalpy of component \( i \) at 298 K.

The specific heat at constant pressure of component \( i \) \( (C_{pi}) \) could be calculated by:

\[ C_{pi} = a_i + a_2 T + a_3 T^2 + a_4 T^3 + a_5 T^4 \]

In which the parameter \( a_i \) (\( k=1, 2, 3, 4, 5 \)) can be found in the chemical kinetics package [9].

2.2. Governing equation of solid domain

The governing equation of solid domain is written in the following form [10]:

\[ \rho_s c_s \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left( \lambda_s \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( \lambda_s \frac{\partial T}{\partial y} \right) + \frac{1}{\gamma} \left( \lambda_s \frac{\partial T}{\partial y} \right) + \rho_s \frac{\partial \bar{h}_{s}}{\partial y} \]

Where, the density is represented by \( \rho_s \), energy of unit mass of HDPE is \( h_s \), heat capacity is \( c_s \), and \( \lambda_s \) represents the thermal conductivity. In Eq. (9) \( \rho, \rho_s, \partial \bar{h}_s/\partial y \) represents the change of energy in solid phase caused by chemical reaction.

2.3. Chemical reaction model

The combustion of HDPE is very complex, which is very difficult to describe. Thus, according to Ref. [11], to simplify the combustion process of HDPE, an assumption is proposed that the only pyrolysis product of polyethylene is \( C_2H_4 \). As paper [11] described, the main products in the chamber are \( N_2, CO, H_2O, CO_2, O_2 \). And the reaction model of gas phase [12] is shown in Table 1.

| reaction | \( A/(cm^2 \cdot mol^{-1} \cdot s^{-1}) \) | n | \( E_j/(j/mol) \) |
|----------|---------------------------------|---|-----------------|
| \( C_2H_4+O_2 \rightarrow 2CO+2H_2 \) | 2.10E14 | 0 | 149779.2 |
| \( 2CO+O_2 \rightarrow 2CO_2 \) | 3.48E11 | 2 | 84261.5 |
| \( 2H_2+O_2 \rightarrow 2H_2O \) | 3.00E20 | -1 | 0.0 |

2.4. Computational conditions and models

In this study, to investigate the combustion characteristic affected by the length of the SFRJ combustor, two cases with combustor length of 300mm and 500mm are adopted. (see Table 2)

| case | \( s \) | \( d_p/mm \) | \( d_w/mm \) | \( L \) | \( d/mm \) | \( \dot{m}_{in}/(kg/s) \) |
|------|------|-------|-------|-----|-------|------------------|
| 1    | 0.6  | 90    | 40    | 300 | 24.2  | 0.3              |
| 2    | 0.6  | 90    | 40    | 500 | 28.5  | 0.3              |
The physical model of SFRJ used in this investigation is expressed in Figure 1. The HDPE grain is represented by the shaded part. And the boundary conditions at walls are set to no-slip adiabatic boundary condition, the axial gradient quantities are set to zero at pressure outlet. Moreover, distributions of the axial and tangential velocities at the inlet are defined by profiles, which is obtained by the experimental result of Dellenback [13].

![Physical model of simulation](image)

**Figure 1. Physical model of simulation**

2.5. Model validation

In this paper, the in-house code written in FORTRAN has been validated by many of our previous works, the performance of SFRJ has been validated by the experiment conducted with connected pipe facility, the chemical reactions model, heat transfer code and swirl model are validated by the classical benchmark cases, respectively. See Ref. [6] for more information.

3. Results and discussion

The streamlines of cases 1 and 2 are shown in Figure 2. It can be seen from Figure 2 that there is no significant difference in the area of recirculation zone between the two cases, which indicates that the area of recirculation zone does not change with the length of the chamber. Figure 3 shows the temperature contours of cases 1 and 2. It could be seen from the figure that the high temperature zone near the backward-facing step of 300mm length case is lower than that of 500mm length case. The temperature distribution in after burning chamber of case 1 is lower than that of case 2, this may be because that the 300mm length case has smaller burning surface compared with 500mm length chamber.

![The streamlines for case 1 and 2](image)

**Figure 2. The streamlines for case 1 and 2**

![The contours of temperature](image)

**Figure 3. The contours of temperature**

Figure 4 shows the regression rate of cases 1 and 2 at different time ranges, at the period of 0.1s-0.4s, the regression rate increases rapidly due to the ignition gas. At the time of 0.5s, the ignition quenched, which lead to the decreasing of regression rate. When the combustion developed to 1s, the stable self-sustain combustion of case 1 and case 2 is established.
Figure 4. Regression rate of different cases at different time.

The simulation results of local regression rate of different cases are shown in Figure 5, it could be seen from Figure 5, the profiles of the regression rate reach the max value around the reattachment point and decrease in the redevelopment zone.

The heat flux of all the cases is shown in Figure 6. It is worth to be noticed that the heat flux of the case with 500mm length combustor is a little higher than that of 300mm length combustor, which indicates that the heat transfer at reattachment point is more sufficient.

The thrust of case 1 and case 2 is calculated, the thrust of case 1 is 125N, the thrust of case 2 is 190N, the larger thrust is owing to the larger burning surface.

4. Conclusions

In this paper, combustion characteristics affected by the length of the combustion chamber of solid-fuel ramjet has been investigated through numerical methods. The in-house code is developed to simulate the unsteady swirling reacting flow in SFRJ. The main conclusions are presented as follows:

- The temperature near the backward-facing step is increased with the increasing of combustor length.
- The temperature of the afterburning chamber is decreased with decreasing of combustor length. Owing to the smaller burning surface of 300mm length chamber.
- The investigation of local regression rate indicates that the trend of local regression rate has no obvious difference between the two cases. However, as for the heat flux result, the heat flux for the case of 500mm length chamber around the reattachment point is a little higher than that of 300mm length combustor.

5. References

[1] T. Liou, P. Hwang, Y. Li, C. Chan, Flame stability analysis of turbulent nonpremixed reacting flow in a simulated solid-fuel ramjet combustor, J. Mech. 18 (1) (2002) 43–51.
[2] D. Rhode, D. Lilley, D. McLaughlin, On the prediction of swirling flowfields found in axisymmetric combustor geometries, J. Fluids Eng. 104 (3) (1982) 378–384.
[3] D. Lilley, J. Samples, D. Rhode, Prediction of swirling reacting flow in ramjet combustors, in: AIAA, SAE, and ASME, 17th Joint Propulsion Conference, Colorado Springs, p. 1981.
[4] Musa, Omer, et al. Effect of Inlet Conditions on Swirling Turbulent Reacting Flows in a Solid Fuel Ramjet Engine. Applied Thermal Engineering 113(2016):186-207.

[5] Musa, Omer, X. Chen, and C. Zhou. Experimental and numerical investigation on the ignition and combustion stability in solid fuel ramjet with swirling flow. Acta Astronautica 137(2017):157-167.

[6] Li, W., Chen, X., Cai, W., & Musa, O. (2019). Numerical Investigation of the Effect of Sudden Expansion Ratio of Solid Fuel Ramjet Combustor with Swirling Turbulent Reacting Flow. Energies, 12(9), 1784.

[7] Kuo, Kenneth K. Principles of Combustion. (1986).

[8] J. Chen, Combustion Fundamental of Solid Rocket, Nanjing University of Science and Technology Press, Nanjing, 2011 (in Chinese).

[9] J. Kee, F.M. Rupley, E. Meeks, J.A. Miller, CHEMKIN-III: a FORTRAN Chemical Kinetics Package for the Analysis of Gas-phase Chemical and Plasma Kinetics, Technical Report, Sandia National Labs, 1996.

[10] Stoliarov, S. I., Walters, R. N. (2008). Determination of the heats of gasification of polymers using differential scanning calorimetry. Polymer Degradation & Stability, 93(2), 422-427.

[11] G. Schulte, R. Pein, A. HOgl, Temperature and concentration measurements in a solid fuel ramjet combustion chamber, J. Propul. Power 3 (2) (1987) 114–120.

[12] R.A. Baurle, T. Mathur, M.R. Gruber, K.R. Jackson, A numerical and experimental investigation of a scramjet combustor for hypersonic missile applications, in: 34th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 1988. AIAA 1998–3121.

[13] P. Dellenback, D. Metzger, G. NEITZEL, Measurements in turbulent swirling flow through an abrupt axisymmetric expansion, AIAA J. 26 (6) (1988) 669–681.