Numerical Analysis of Solid Fuel Regression Rate Distribution Characteristics in Solid-fuel Ramjet with Different Fuel Types

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Abstract. This paper proposes and examines numerically a new design of solid-fuel ramjet motor. Multi-physics coupling code is developed using FORTRAN and parallel computing to solve the problems of multi-physics coupling of fluid mechanics, solid pyrolysis, heat transfer, thermodynamics, and chemical kinetics. Simulations are carried out for the proposed design then the results are compared with the classic design of the solid-fuel ramjet. It is found that the proposed design has improved the regression rate significantly; besides, the amount of released solid fuel is increased for the same size.

1. Introduction

The combination of range and speed is the most needed feature in the warfighters. Traditional rocket motor requires carrying an oxidizer which makes the rocket heavier and then decreases its flight range. For the same size of rocket motor, solid-fuel ramjet (SFRJ) could flight for longer range with much higher speed since it uses its forward motion to draw in oxygen from the surrounding atmosphere. Therefore, the larger fuel store allows SFRJ to sustain high speed during flight. Besides, SFRJ is a simple air-breathing engine, in design, that contains no moving parts. Thus, the internal design of the SFRJ determines its performance.

However, low fuel regression rate is the main disadvantage of the SFRJ, usually less than one mm/sec [1], which is the key parameter in the design and operation of SFRJs that is primarily depend on the heat transfer from the flame to the fuel surface. The classical design of SFRJ basically consists of air intake system, combustion chamber, and nozzle in which the combustor contains flame-holder and cylindrical solid fuel grain (see Fig. 1 - upper). However, in order to overcome the disadvantage of SFRJ and enhances its combustion characteristics and performance we proposed and studied a new SFRJ design which contains additional solid fuel (rod) at the center of the tubular grain (see Fig. 1 - lower). The idea is to increase the solid fuel surface area contacting with incoming air to enhance the heat transfer to the solid fuel and then the regression rate. Besides, maintaining the amount of solid fuel released during flight which makes the thrust stable. In this paper, the proposed SFRJ design is investigated numerically using an in-house CFD code. The code is written by FORTRAN with parallel computing to solve the problems of multi-physics coupling of fluid mechanics, solid pyrolysis, heat transfer, thermodynamics, and chemical kinetics.

In open literature, few studies are available regarding different solid-fuel ramjet combustor’s designs. However, complex configurations have been investigated extensively in hybrid rocket motors. Lee et al.
[2] studied the regression rate characteristics of helical grain. A higher regression rate is achieved when the pitch number is small, and the combination of helical grain with a large pitch number and a moderate inlet swirl may produce the maximum regression rate. Li et al. [3] investigated numerically the regression rate distributions for tube, star, and wagon wheel grains. The regression rates of star and wagon wheel grains were generally higher than that of tube grain under the same oxidizer mass flux.

Figure 1. The classic (upper) and proposed (lower) design of solid-fuel ramjet.

2. Mathematical Modeling

2.1. Governing Equations.

The flow field considered is essentially three dimensional (3-D) for which all velocity and Reynolds stress components are included with regard to the simplifying condition of symmetry, whereas the flow is still angular symmetry \((\partial/\partial \theta=0)\). Therefore, the 3-D Reynolds-average Navier-Stokes equations with angular symmetry condition in integral form, which are representing the conservation of mass, momentum, energy, and species equations, can be written as:

\[
\frac{\partial}{\partial t} \iint_U \rho \mathbf{U} dV + \iiint \left( \mathbf{F} \cdot n_x + \mathbf{G} \cdot n_y \right) ds - \iiint \left( F_v \cdot n_x + G_v \cdot n_y \right) ds = \iiint (H + H_v) \varepsilon dV + S
\]

where \(n = n_x i + n_y j\) is the unit normal vector in outward direction of the boundary surface \(s\); \(t\) is the time, \(\varepsilon = 0\) for two-dimensional plane flow, \(\varepsilon = 1\) and for axisymmetric flow. The conservative vector \(\mathbf{U}\), convective flux vectors \(\mathbf{F}, \mathbf{G}\), viscous flux vectors \(F_v, G_v\), axisymmetric source terms \(H, H_v\), and chemical reactions source term \(S\) can be found elsewhere [4].

Arrhenius formula (Eq. 2) is adopted to determine reaction rate constants.

\[
\dot{n}_k = A_k T_w^{n_k} \exp \left[ -\frac{E_a}{R_w T_w} \right]
\]

where \(A_k\) is the pre-exponential factor, \(n_k\) is the temperature exponent, \(E_a\) is the activation energy, and \(T_w\) is the solid-fluid interface wall temperature. In order to model the solid fuel pyrolysis in the solid-fluid interface the zeroth order \((n_k = 0)\) Arrhenius equation is used. The mass rate of fuel freed by pyrolysis is determined using:

\[
m = \rho_{sol} \dot{\rho}_{sol} A_{sol} \exp \left[ -\frac{E_{sol}}{R_w T_w} \right]
\]

The subscript “sol” indicates the solid fuel. The solid fuel has been used in this work is the high-density Polyethylene (HDPE) grain. The gas-phase chemical reactions kinetic of HDPE [5] can be written as in Table 1.

Table 1. Chemistry Model of Ethylene.

| Chemical reaction | \(A/(cm^2/mol \cdot s)\) | \(n\) | \(E_a(J/mol)\) |
|-------------------|-----------------|-----|--------|
| \(2C\text{H}_4 + O_2 \rightarrow 2CO + 2H_2\) | 2.00E20 | -1 | 0.0 |
| \(2CO + O_2 \rightarrow 2CO_2\) | 3.48E11 | 2 | 84261.5 |

where the number of reactions are three \((I=3)\) with six species \((N=6)\).
2.2. Numerical Solution.
The prescribed governing equations have been solved simultaneously by means of cell-centered, finite-volume method with structured grids, multi-block, and density-based approach. At each cell of the SFRJ flow field meshes (104982 cells) the governing equations are discretized and numerically solved in which AUSMPW+ [6], third-order upwind-based MUSCL [7], and Van Albada limiter function [8] are employed to evaluate inviscid fluxes with the second-order central differences for viscous fluxes. The turbulence is treated by Menter’s shear-stress transport (SST) turbulence model [9].

Finite rate model is employed to determine the chemical source terms. In this model the flame is treated as laminar flame with neglecting the effect of turbulent fluctuating (turbulence-chemistry interaction), at which Arrhenius expression is used to determine the mean reaction rate. Since we considered unsteady simulations, the lower-upper symmetric Gauss-Seidel (LU-SGS) implicit dual time-stepping algorithm is selected for fluid domain and backward Euler method for solid domain [10].

In this work, two cases are simulated with different combustor designs, the proposed design and the classic one. The total temperature is set to be 540K and the mass flow rate is fixed at 0.6 kg/s. Other boundary conditions are treated as follows; no-slip adiabatic boundary condition at walls, axisymmetric boundary condition at axis, all axial gradient quantities are set to zero at exit, and at solid-fluid interface the solid and fluid domains are coupled by direct coupling approach in which the wall temperature is determined by energy balance equation.

3. Model Verification and Validation
An extensive verification and validation study has been performed on the base code in our previous work [11], including uncertainty and numerical errors. In addition, the base code has been also validated using swirl benchmark cases in the previous work [12]. Furthermore, the extended code with combustion model needs to be validated on combustion cases, to do so; additional two cases have been studied as well in the previous works [4, 13, 14].

4. Results and Discussion
This section presents the numerical results obtained for the cases prescribed in previous sections. The ignition process is achieved by using hot gas flowing together with the incoming air into the combustor. The ignition gas flows with 0.4 kg/s, total temperature of 2500 K and contains N2, H2O2, and CO2. The ignition gas is produced through combustion of double-based propellant and only the gas components are considered in the model. After 0.35 second the ignition gas has stopped and only the incoming air flow is continued.

![Figure 2. Axial distributions of local regression rate for solid fuel surface at different time intervals.](image_url)

Normally, ignition delay time includes; heating (gasification) time delay, mixing time delay, and chemical processes time delay; but mixing time is very small and can be ignored. Fig. 2 shows the ignition and combustion processes during the whole simulation for the proposed design. Fig. 2a presents...
the local regression rates for outer surface of the rod solid fuel. As can be seen, the pyrolysis starts for the end of the combustor (0.3m) due to the effect of incoming air jet. As time progresses the pyrolysis moved towards the inlet till the distance 0.17 m. For sustained combustion, the regression rate is significantly much higher than tubular grain surface regression. Fig. 2b shows the local regression rates of inner surface of the tubular solid fuel.

On comparing the regression rates of the classical and the new designs, the proposed designs has higher regression rate with a new trend. In which, the peak is shifted into the end of the combustor due to the high temperature offered by the combustion of the outer grain (see Fig. 3). This can be seen clearly in Fig. 4, where the temperature contour represents the flams (high temperature) produced near to each surface.

![Figure 3. Regression rates along axial direction for the proposed and the classic design.](image)

![Figure 4. Temperature contours of the proposed (upper half) and the classic design (lower half) [K].](image)

5. Summary
A new design of solid-fuel ramjet is proposed and examined numerically in this paper. CFD code is developed using FORTRAN and parallel computing. The developed code is structured, finite-volume, density-based, cell-centered flow solver that simulates the axisymmetric, unsteady, turbulent, reacting flows. It has been shown that the proposed design has improved the local regression rate and increased the amount of solid fuel inside the motor for the same size compared to the classical solid-fuel ramjet.

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