Stabilization of solid fuel combustion in a ramjet engine

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Abstract. Combustion stability problem for solid fuel ramjet engine is considered. Stabilization is achieved due to the presence of a wider section in the combustion channel near the air inlet. In this part, playing the role of flame holder, a recirculation zone develops which increases the residence time of combustion products in contrast to the straight part of the channel. In this work, numerical modeling of solid fuel ramjet engine is carried out for PMMA as a fuel. A simple model for gasification rate is used in order to describe the solid fuel decomposition under the incident heat flux. Reacting multicomponent gas equations are solved by a low-dissipation numerical scheme suitable for a wide range of Mach numbers, with Eddy Break-Up model for turbulent combustion. Simulation results are presented for subsonic conditions in the ramjet inlet.

1. Introduction

Solid fuel ramjet engines (SFRE) are considered to be promising propulsion systems of unmanned aerial vehicles. A feature of the workflow in these engines is that the used solid fuels contain a minimum quantity of oxidizing components and incapable to self-sustained combustion. Solid fuel combustion occurs in a forced mode: due to heat supplied from the high-speed flow in the grain channel, the gasification (decomposition) of solid fuel occurs; the products of gasification enter the flow and burn out there, providing the thrust.

Solid fuel ramjet engines are being developed and tested in different countries for over 40 years [1-4]. Despite the high expectations associated with these engines, they have not yet received wide distribution. This is mainly due to instability of their operation and with a very narrow range of operating parameters in which stable combustion of solid fuel is possible. A lack of understanding of the processes occurring in SFRE, and, above all, of the mechanism of instability of the solid fuel forced combustion in the high-speed flow prevent to the wide use of SFRE.

In order to stabilize the solid fuel combustion in SFRE, the solid fuel grains with a profiled channel are used (figure 1). For this purpose, a ledge is formed in the inlet part of the grain channel that acts as a flame holder. It was established experimentally that steady combustion of solid fuel in SFRE is possible only at certain shapes and sizes of the flame holder, but the detailed mechanism of stabilization of combustion is not completely clear; moreover there are no methods for selection of the appropriate size and shape of the flame holder.

Qualitatively, the mechanism of stabilization of combustion in SFRE can be explained as follows. When air, entering the ramjet combustor, flows around the ledge in the grain channel, the recirculation zone occurs, in which the mixing of air with the products of decomposition of the solid fuel, combustion of the mixture and the formation of the high temperature gas mixture occur. The resulting high-temperature gas mixture flows out of flame holder into the grain channel and provides the
gasification of solid fuel and combustion of the products of gasification in the channel. In order to provide stable combustion of whole grain, the energy of high-temperature gas mixture in the flame holder should be large enough. This is provided by the flame holder sizes and as long as possible residence time of the particles of the gas mixture, which is also determined by the sizes and shape of the flame holder.

Recently, a number of papers appeared in which attempts were made to investigate numerically the processes in SFRE. In particular, the influence of the shape and the sizes of the flame holder on the flow structure was studied numerically in [5], where the influence of the ratio of the flame holder length to its depth and the angle of slope of the wall at the exit of the flame holder were analyzed. A steady-state gas-dynamic model and steady-state combustion model of solid fuel was used in [5]; it does not allow simulating the occurrence and development of SFRE operation instability. In [6], self-ignition of solid fuel in a ramjet was investigated, but stability of combustion of solid fuels and connection of the stability with the parameters of the flame holder were not considered.

In this paper, we propose a non-stationary model of solid fuel combustion in SFRE and present some screening results of numerical simulation for several inlet parameters of a solid fuel ramjet combustor.

2. Mathematical model

2.1. Solid fuel
Polymethylmethacrylate (PMMA) was taken as the solid fuel because it is quite widespread in current experimental studies [7]. While gasification of PMMA, as a complex polymer, produces whole spectrum of gas components, in this study we take a simple model that PMMA, upon thermal decomposition, gives rise just to gaseous methylmethacrylate (MMA) represented by chemical formula $C_5H_8O_2$.

The mass rate of gasification corresponding to the incident heat flux $q_i$ is described by a simple model taking into account the heating of solid material from its initial temperature $T_0$ to the boiling temperature $T_s$ which is assumed to be maintained on the surface of decomposing material, as well as the gasification heat $\Delta H_G$:

$$m = \frac{q_i}{c_s(T_s - T_0) + \Delta H_G}$$

(1)

Here, $c_s$ is the specific heat capacity of solid fuel. The heat flux $q_i$ can generally include the radiation part, but here it is not taken into account due to small sizes of combustor considered. The following properties of PMMA are chosen: density $\rho_s = 1.18$ g/cm³, boiling temperature $T_s = 200$ °C, specific heat capacity $c_s = 1500$ J/(kg K), heat of gasification $Q_s = 1591$ kJ/kg.

Combustion of MMA in the gas phase is described by a single irreversible gross reaction [7]

$$C_5H_8O_2 + 6O_2 \rightarrow 5CO_2 + 4H_2O + \Delta H_c$$

(2)

with heat of combustion per unit mass of fuel $\Delta H_c = 25.6$ MJ/kg.

2.2. Reacting gas mixture
The multicomponent gas mixture is described by the Reynolds-averaged Navier-Stokes equations (RANS) in the fully compressible formulation. Five mixture components are considered: $C_5H_8O_2$, $O_2$, $CO_2$, $H_2O$, $N_2$. Each component is described by the ideal gas equation of state, the thermal properties (specific heat, internal energy, enthalpy) as functions of temperature are described by polynomials. The temperature of gas mixture was determined from its total energy and composition by solving a corresponding nonlinear equation.

Turbulence is described by the standard $k-\varepsilon$ model, the gas-phase combustion rate is described by the Eddy Break-up (EBU) model [8] which assumes that reaction rate is controlled by the rate of
turbulent mixing of fuel and oxidizer. Namely, the rate of combustion reaction (2) is calculated from the following formula [8]:

\[ \dot{w} = \rho A \frac{\varepsilon}{k} \min \left( Y_{\text{C}_3\text{H}_8\text{O}_2}, \frac{Y_{\text{O}_2}}{s}, B \frac{Y_{\text{CO}_2} + Y_{\text{H}_2\text{O}}}{1 + s} \right) \]

where \( A = 4 \), \( B = 0.5 \) are model constants, \( \rho \) is the gas density, \( k \) and \( \varepsilon \) are the turbulent kinetic energy and its dissipation rate, \( Y \) are mass fractions of corresponding species, \( s = 6.32/100 = 1.92 \) is the mass stoichiometric coefficient of oxygen (i.e., mass of oxygen consumed per unit mass of fuel) in reaction (2).

On the channel boundaries, injection of gaseous fuel occurs due to solid fuel decomposition. The injection mass flux was taken equal to that of solid fuel decomposition (see (1)), i.e., possible incomplete gasification due to charring is not taken into account. The density of gas produced on the walls was determined for the equation of state for pure fuel, assuming the local gas pressure; the temperature of the injected gas was taken equal to the boiling temperature \( T_s \) for PMMA. As a result, the linear local injection velocity was obtained and used as the boundary condition for the normal velocity component on the wall. For the tangential component of gas velocity, standard wall functions were applied which implies the turbulent log-law velocity profile. The heat flux from the gas phase onto the fuel surface, \( q_s \), required in (1) for calculation of gasification rate, was also determined from wall functions for the temperature.

3. Numerical implementation
The governing equations (4) are solved in the axisymmetric framework by an explicit finite-volume high-resolution scheme on a uniform Cartesian grid. The “inviscid” fluxes are approximated by a scheme HR-SLAU2 [9] belonging to the AUSM family of numerical schemes. In order to calculate the cell face flux from the state variables defined in the cell centers, the “left” and “right” states on the boundary are first obtained by second-order monotonic interpolation with MINMOD flux limiter, after which the fluxes are found by solving the Riemann problem. An important feature of HR-SLAU2 scheme is that it falls into the category of “all-speed” numerical schemes owing to special control of numerical dissipation depending on the local Mach number. This is a must for internal flow problems where high-speed (including supersonic) zones can coexist with low-speed (subsonic) zones.

Viscosity, diffusion, and heat conduction terms are approximated by standard second-order central difference scheme. Chemical reactions are taken into account at a separate substep, with Strang splitting to maintain the second-order approximation in time: at each time step chemistry is advanced by half-step, then the gas dynamics solver is called to advance the solution by full time step, after which the chemistry solver is called again to integrate the kinetic equations by another half-step.

The solid fuel surface, generally, does not coincide with cell boundaries of Cartesian grid. Also, the shape of the surface can change with time due to fuel burnout. In this work, we apply the “embedded” sharp interface approach [10] in which the internal boundary is described by a level-set of a distance function. In the cells located away from the boundary, normal approximations are used, however, in the near-boundary cells operators are modified to take into account that cells are cut by the surface.

Implementation of wall functions in \( k - \varepsilon \) turbulence model bears difficulties because embedded boundaries can cut cells randomly, in contrast to body-fitted grids where the size of near-wall cell can be controlled. To overcome this difficulty, wall functions were implemented not for the cut cells, but for one-dimensional grids extended from the surface into the flow along a normal to the surface, with subsequent interpolation of boundary layer variables onto the Cartesian mesh [11].

4. Geometry, initial and boundary conditions
Numerical simulations were carried out for the geometry which resembles closely the one used in the experiments [1, 2]. The geometry is shown in figure 1, with the main geometrical parameters listed in table 1.
Figure 1. Geometry of solid fuel combustor: air in injected through the inlet of diameter $D_1$ into the main channel (of diameter $D_3$) via a flow expansion chamber (of diameter $D_2$) serving as flame holder due to development of recirculation zone.

Table 1. Combustion chamber measurements.

| Parameter | Value (mm) |
|-----------|------------|
| $D_1$     | 10         |
| $D_2$     | 30         |
| $D_3$     | 15         |
| $L$       | 100        |
| $L_1$     | 5          |
| $L_2$     | 45         |
| $L_3$     | 5          |

The inlet conditions corresponded to air with normal oxygen contents (21% vol.) supplied at a given linear velocity $v_{in}$, temperature $T_{in}$ and pressure $P_{in}$. At the initial instant, the channel was filled with air at the same pressure and temperature as in the inlet. The initial axial velocity was set to 50% of the inlet velocity $v_{in}$ in order to provide some gas flow through the channel. Since the cross-section area of the channel varies with distance, the initial flowrate did not correspond to steady-state conditions, rather, some time was required for the system to adjust the initial flow.

Due to strong feedback between the surface reaction and gas flow, solver instability could develop during this initial stage. Therefore, the initial period of 1 ms was simulated with the surface reaction (1) calculated from an artificial constant heat flux $q_s = 1 \text{ kW/m}^2$, which was sufficient to initialize the gasification, but did not lead to development of high temperature in the combustor. After this period, the heat flux was gradually ramped up to its actual local values, and simulations were carried on without any further intervention.

Note that in the adopted here combustion model (EBU) chemical kinetics of gas-phase reaction (2) is not taken into, and ignition occurs as soon as the fuel is mixed with oxidizer. Further improvement of the combustion model will be performed in the future, so that ignition or extinction of combustion will be addressed. Here, we are interested mostly in the features of reacting flow in an already started SFRJ.

Numerical simulations were carried out in four cases listed in table 2. Results obtained are presented in the next section.
Table 2. Parameters of simulations.

| Case | Pressure $P_{in}$ (atm) | Velocity $v_{in}$ (m/s) | Temperature $T_{in}$ (K) |
|------|--------------------------|-------------------------|--------------------------|
| 1    | 1                        | 100                     | 500                      |
| 2    | 1                        | 200                     | 500                      |
| 3    | 2                        | 100                     | 500                      |
| 4    | 2                        | 200                     | 500                      |

5. Results

In figure 2a-d, the temperature, concentrations (of fuel and oxidizer), and reaction rate spatial distributions obtained in Case 1 (see table 2) are plotted. In figure 2a, streamlines demonstrating the flow field developing in the combustion chamber are also shown. One can see that a recirculation zone develops in the flame holder due to abrupt change in the cross-section area.

In the recirculation zone, the gas consists of a mixture of fuel (MMA) emitted at the solid surfaces, and hot combustion products. The reaction zone revealed by the distribution of volumetric heat release rate (figure 2b) separates the fuel-containing zones near the solid surfaces (figure 2c) from the oxygen-rich core flow (figure 2d). Thus, combustion in the solid-fuelled ramjet is of diffusion type.

In figure 3a-d, similar results are shown in Case 2, with the injection velocity increased twice. In figures 4a-d and 5a-d, distributions are shown in Cases 3 and 4 (table 2) for higher pressure in the combustor. Increase in the pressure or inlet velocity results in the increase in the mass inflow of air (i.e., oxidizer) into the combustion chamber. However, this also increases the turbulence level and heat release rate, so that, generally, the distributions of flow parameters in the solid-fuelled ramjet presented in figures 2–4 are featured by similarity.

Figure 2. Temperature (a), volumetric heat release rate (b), volume fractions of $\text{C}_3\text{H}_4\text{O}_2$ (c), and $\text{O}_2$ (d) for $P_{in} = 1$ atm, $v_{in} = 100$ m/s, $T_{in} = 500$ K (Case 1 in table 2).
Figure 3. Temperature (a), volumetric heat release rate (b), volume fractions of \( \text{C}_5\text{H}_8\text{O}_2 \) (c), and \( \text{O}_2 \) (d) for \( P = 1 \text{ atm} \), \( v = 200 \text{ m/s} \), \( T = 500 \text{ K} \) (Case 2 in table 2).

Figure 4. Temperature (a), volumetric heat release rate (b), volume fractions of \( \text{C}_5\text{H}_8\text{O}_2 \) (c), and \( \text{O}_2 \) (d) for \( P = 2 \text{ atm} \), \( v = 100 \text{ m/s} \), \( T = 500 \text{ K} \) (Case 3 in table 2).
Figure 5. Temperature (a), volumetric heat release rate (b), volume fractions of $C_2H_5O_2$ (c), and $O_2$ (d) for $P_{in} = 2$ atm, $v_{in} = 200$ m/s, $T_{in} = 500$ K (Case 4 in table 2).

Compare now the time histories of temperature and total combustion power obtained in the four cases listed in table 2. In figure 6, corresponding results are shown, with the curves numbered in accordance with table 2. One can see that initial stage is featured by rapid rise in the combustion power, followed by gradual decrease to steady-state levels. The maximum temperatures are not too sensitive to the inlet parameters, while the combustion powers differ according to the mass flow of oxygen through the ramjet.

Figure 6. Time histories of the maximum temperature in the combustor (a) and total combustion power (b). (Curves correspond to cases 1–4 in table 2).

6. Conclusions
The results presented in this work demonstrate the capability of the mathematical model and software developed to simulate internal flows in the combustion chamber of a solid fuel ramjet. A more challenging problem which will be tackled in the follow-up work is to run coupled simulations of combustion and fuel burnout, i.e., consider flow with variable shape of the channel. The approach of
“embedded” internal boundaries adopted in the numerical implementation provides a tool for describing the shape change without the need to rebuild the mesh each time the solid fuel shape changes.

Another challenging issue is to tackle the problem of ramjet ignition and extinction (flame blow-off). In order to treat this problem, the model of turbulent combustion must be enhanced, so that kinetics of chemical reaction (either global, or detailed) is taken into account.

The main research directions in which this work is going to evolve are to consider much wider range of operating conditions, including subsonic and supersonic ones. The ultimate goal is to find the conditions under which the stabilizer is efficient, study the effect of flame holder shape and perform parameters optimization.

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