Combustion stability in a solid-fuel ramjet engine

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Abstract. A computational model is presented for a solid-fuel ramjet engine with an axisymmetric combustion channel in a fuel grain containing a wider section near the air inlet. The latter part of the channel serves as a flame holder where a recirculation zone develops providing necessary combustion stabilization. The model is based on RANS equations, with finite-rate chemistry in the turbulent gas phase flame taken into account. Reacting multicomponent gas equations are solved by a low-dissipation numerical scheme suitable for a wide range of Mach numbers. Solid fuel is gasified at the surface, and gasification products react in the core flow. Combustion of PMMA is studied numerically in the subsonic flow regime for different pressures, inlet velocities, and flame holder geometry parameters. It is shown that under certain conditions combustion in the engine becomes unstable, with flame blown off either in the main channel, or in the flame holder as well. Different combustion regimes are plotted as stability maps in the parameters space.

1. Introduction
Solid-fuelled ramjet (SFRJ) engines are quite promising for unmanned aerial propulsion vehicles, and interest to their development and application has been increasing over the past few decades [1-3]. In SFRJs, thrust is created by reacting gas flow in the grain channel, with fuel supplied into the reacting zone by decomposition of grain material, and oxygen taken from the atmospheric air. Unlike the rocket engines, the fuel in SFRJ contains only a small fraction of oxidizer and is not capable of self-sustained combustion. SFRJs can also be used as a part of hybrid propulsion systems where the hot gases in the grain channel are created by burning a rocket fuel [4].

An important issue in the design of solid-fuel ramjet engines is to make sure that combustion in the fuel grain channel is stable in a wide range of flight conditions. One approach to the solution of this problem relies on the specially profiled channel geometry: a ledge (wider section) is formed in the inlet part of the grain channel, which acts as a flame holder due to development of recirculation zone. In the hot recirculation zone, the incoming air is mixed continuously with the gas fuel to burn and maintain the high temperature necessary for steady ignition of the main grain channel.

Combustion in SFRJs was studied experimentally and numerically in a number of papers [1-6]. In particular, numerical study on the effects of the shape and sizes of the flame holder on the flow was carried out in [5]. The influence of the ratio of flame holder length to its depth and the slope angle of the wall at the exit of the flame holder was analysed by a steady-state model, which does not allow simulation of SFRJ operation instability. In [6], self-ignition of solid fuel in a ramjet was investigated,
but stability of combustion of solid fuels and connection between the stability and geometry of the flame holder was not considered.

In a recent paper [7], a non-stationary numerical model for simulation of combustion processes in solid-fuel ramjet engines was developed, and some screening results of numerical simulation for several inlet parameters of a solid fuel ramjet combustor were presented. Then, the model was further enhanced to include finite-rate turbulent combustion in order to provide the capability of simulating ignition and extinction of fuel-air mixture [8, 9]. Here, we present extensive numerical simulations of combustion in SFRE carried out for subsonic flow regimes, with emphasis on the stability of combustion and its dependence on the inlet flow velocity, pressure, and flame holder geometry.

2. Mathematical model

2.1. Gas flow

Multicomponent reacting mixture consisting of five components is considered: C₃H₆O₂ (fuel), O₂, CO₂, H₂O, and N₂. 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 [10]. The temperature of gas mixture is determined from its internal energy and composition by solving a corresponding nonlinear equation.

The gaseous fuel is methylmethacrylate (MMA) resulting from decomposition of the solid fuel, polymethylmethacrylate (PMMA). Being a complex polymer, PMMA produces, upon gasification, a whole spectrum of gas components, however, in this study we take a single simple-product model of its gasification (see review, e.g., in [4]). More detailed kinetics schemes will be taken upon in the future work.

In the cylindrical coordinates \((r, z)\), gas flow is described by the Reynolds-averaged Navier-Stokes equations (RANS) in the fully compressible formulation:

\[
\frac{\partial \mathbf{Q}}{\partial t} + \frac{\partial \mathbf{F}}{\partial r} + \frac{\partial \mathbf{G}}{\partial z} + \frac{S}{r} = \frac{\partial \mathbf{F}^D}{\partial r} + \frac{\partial \mathbf{G}^D}{\partial z} + \frac{S^D}{r} + \mathbf{R}
\]

(1)

where \( \mathbf{Q} \) is the vector of state variables, \( \mathbf{F} \) and \( \mathbf{G} \) are inviscid fluxes in the \( r \)- and \( z \)-directions, and \( S \) is the source term, while \( \mathbf{F}^D \), \( \mathbf{G}^D \), and \( S^D \) are corresponding dissipation terms; \( \mathbf{R} \) is the chemical reaction source term, subscript \( i \) denotes a chemical component \((i = 1, \ldots, N_c)\).

\[
\mathbf{Q} = \begin{pmatrix} \rho \\ \rho u \\ \rho v \\ E \\ \rho Y_i \end{pmatrix}, \quad \mathbf{F} = \begin{pmatrix} \rho u \\ \rho u^2 + p \\ \rho uv \\ (E + p)u \\ \rho Y_i u \end{pmatrix}, \quad \mathbf{G} = \begin{pmatrix} \rho u \\ \rho uv \\ \rho v^2 + p \\ (E + p)v \\ \rho Y_i v \end{pmatrix}, \quad S = \begin{pmatrix} \rho u \\ \rho u^2 \\ \rho uv \\ (E + p)u \\ \rho Y_i u \end{pmatrix}
\]

(2)

\[
\mathbf{F}^D = \begin{pmatrix} 0 \\ \tau_{rr} \\ \tau_{rz} \\ ut_{rr} + \nu_{rr} + \lambda T_r \\ \rho D Y_{i,r} \end{pmatrix}, \quad \mathbf{G}^D = \begin{pmatrix} 0 \\ \tau_{rz} \\ \tau_{zz} \\ ut_{rz} + \nu_{rz} + \lambda T_z \\ \rho D Y_{i,z} \end{pmatrix}, \quad S^D = \begin{pmatrix} 0 \\ \tau_{rz} - \tau_{\theta\theta} \\ \tau_{\theta\theta} \\ ut_{rz} + \nu_{rz} + \lambda T_r \\ \rho Y_{i,r} \end{pmatrix}, \quad \mathbf{R} = \begin{pmatrix} 0 \\ 0 \\ \rho \Delta H_c \\ \dot{w} \end{pmatrix}
\]

(3)

where

\[
\tau_{rr} = \mu \left( 2u_r - \frac{2}{3} \text{div} \mathbf{U} \right), \quad \tau_{rz} = \tau_{rz} = \mu (\nu_z + \nu_r), \quad \tau_{zz} = \mu \left( 2u_z - \frac{2}{3} \text{div} \mathbf{U} \right), \quad \tau_{\theta\theta} = \mu \left( \frac{2u_r}{r} - \frac{2}{3} \text{div} \mathbf{U} \right)
\]

(4)
are components of the stress tensor with \( \text{div} \mathbf{U} = u_r + v_r + u / r \) (here, for brevity, \( u_r, u_t, v_r, v_t, T_r, T_t, Y_r, \) and \( Y_t \) denote the partial derivatives of velocity components, temperature and mass fractions of components with respect to the corresponding coordinate). The effective viscosity \( \mu = \mu_r + \mu_t \), heat conductivity \( \lambda = \lambda_r + \lambda_t \), and diffusivity \( D = D_r + D_t \), are the sums of laminar and turbulent values, the latter obtained from the standard \( k-\varepsilon \) turbulence model.

2.2. Reactions and combustion model

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 \( T_s \) on the surface of decomposing material and further gasification:

\[
\dot{m} = \frac{q_i}{c_s(T_s - T_0) + \Delta H_G} \quad (5)
\]

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 was not taken into account due to small sizes of the combustor considered. The properties of PMMA are: density \( \rho_s = 1.18 \text{ g/cm}^3 \), boiling temperature \( T_s = 200^\circ \text{C} \), specific heat capacity \( c_s = 1500 \text{ J/(kg K)} \), heat of gasification \( \Delta H_G = 1591 \text{ kJ/kg} \).

Combustion of MMA in the gas phase is described by a single irreversible gross reaction [11]

\[
\text{C}_3\text{H}_6\text{O}_2 + 6\text{O}_2 \rightarrow 5\text{CO}_2 + 4\text{H}_2\text{O} + \Delta H_e \quad (6)
\]

with the heat of combustion per unit mass of fuel \( \Delta H_e = 25.6 \text{ MJ/kg} \) and kinetics

\[
\dot{\omega}_k = B \cdot T \cdot \frac{s_k}{W_{O_2}} \rho^2 Y_r Y_{O_2} \exp\left(-\frac{E_k}{RT}\right) \quad (7)
\]

Here, \( B = 6.6 \cdot 10^6 \text{ [m}^3/\text{mol s K]} \) is the pre-exponential factor, \( E_k = 144 \text{ kJ/mole} \) is the activation energy, \( s_k \) is the mass stoichiometric coefficient of \( k \)-th species (for fuel \( s_r = -1 \)), \( W_{O_2} \) is the molar mass of oxygen.

The turbulent combustion rates for all species on the right-hand side of conservation equations (3) are evaluated as \( \dot{\omega}_k = s_k \dot{\omega} \), where the reaction rate \( \dot{\omega} \) is obtained from the corresponding turbulent combustion model. In the previous work [7], the Eddy Break-up (EBU) model [12] was used in which assumes that infinitely fast chemistry, so that the reaction rate is controlled by the rate of turbulent mixing of fuel and oxidizer. In the current work, this turbulent combustion model was substituted by the Eddy Dissipation Concept (EDC) [13] which takes into account the finite-rate kinetics in turbulent flame. EDC considers combustion as occurring in fine structures occupying a fraction of volume, each fine structure described as a perfectly stirred reactor with the flow rate and residence time related to the turbulent quantities, and reaction rate described by the kinetical formula (7). In this way, turbulence-kinetics interaction is taken into account, which, importantly, allows us to model flame ignition/extinction without any additional assumptions on the critical temperature or strain rate.

2.3. Initial and boundary conditions

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 \( P_{in} \).

The mass flux of fuel gas (MMA) at the channel boundaries is described by equation (5) which relates the decomposition rate of PMMA with the heat flux incident on the wall. The temperature of gaseous fuel at the wall was taken equal to the boiling temperature \( T_s \); the density was then obtained from the equation of state using the local pressure near the wall (possible incomplete gasification due
to charring is not taken into account). The normal velocity component at the wall was obtained from the mass flux and density, for the tangential velocity component the wall functions implemented in the \( k - \varepsilon \) turbulence model were used, implying the universal logarithmic wall law; thermal wall functions were used to evaluate the incident heat flux \( q_s \).

In a working ramjet engine, combustion is maintained due to feedback between the hot burning zone and solid fuel gasification at the channel walls. In order to establish the working regime, some ignition procedure (external heating or hot gas flow from a gas generator) is necessary. Studying the ignition stage was outside the scope of the current paper, which focuses on the simulation of reacting flows in a working ramjet engine and evaluation of combustion stability. Therefore, an “artificial” ignition procedure was followed. Simulations were started with gas flow parameters corresponding to the inlet conditions throughout the domain; during short initial time (1 ms), the heat flux in the gasification formula (5) was set to \( q_s = 1 \text{ kW/m}^2 \), which was sufficient to initialize the gasification, but did not lead to development of high temperature in the combustor. Then, simulations were run for another 4 ms with infinite reaction rate in the EDC model (equivalent to EBU model), which was sufficient for obtaining steady combustion. At time 5 ms, the combustion model was switched to finite-rate EDC (imitating switching off the igniter), and further evolution of gas flow and combustion zone was simulated.

3. Numerical implementation

The governing equations (1) – (4) were solved in the axisymmetric coordinates by an explicit finite-volume high-resolution scheme on a uniform Cartesian grid. The “inviscid” fluxes are approximated by a scheme HR-SLAU2 [14] belonging to the AUSM family of numerical schemes. HR-SLAU2 scheme is an “all-speed” numerical scheme applicable to wide range of Mach number flows. Viscosity, diffusion, and heat conduction terms are approximated by the second-order central difference scheme; chemical reactions are solved on a separate substep, prior to the solution of gas dynamics equations.

The solid fuel surface is described on the Cartesian grid by the “embedded” sharp interface approach [15] in which the internal boundary is the zero level set of a signed distance function. In the near-boundary cells, fluxes and finite-volume operators are modified to take into account that cells are cut by the surface. The wall functions of \( k - \varepsilon \) turbulence model were implemented for the embedded boundaries by extending a normal from the surface into the flow, setting the wall laws along this normal, and subsequent interpolation of the boundary layer variables back onto the Cartesian grid [16].

4. Results

4.1. Geometry and inlet conditions

Numerical simulations were carried out for the geometry similar to that used in the experiments [1, 2]. The geometry is shown in figure 1, with the main geometrical parameters listed in table 1. The same geometry was studied in our previous works [7–9]; here, a wider range of geometrical parameters and operating conditions is covered.

![Figure 1](image-url)  
**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.
Table 1. Combustion chamber dimensions.

| Parameter | Value (mm) |
|-----------|------------|
| $D_1$     | 10         |
| $D_2$     | 26 – 40    |
| $D_3$     | 15         |
| $L$       | 100        |
| $L_1$     | 5          |
| $L_2$     | 20 – 60    |
| $L_3$     | 5          |

Simulations were carried out for two values of operating pressure, $P = 1$ and 2 atm, the inlet velocity was varied in the range of $V_{in} = 100 – 400$ m/s, the inlet temperature was fixed at $T_{in} = 500$ K. It was found that five main operating regimes are possible: 1) stable combustion, 2) short-duration combustion instability with eventual reignition; 3) oscillatory regime; 4) flame extinction in the channel; 5) total flame extinction. In the following sections, we demonstrate the flow and combustion zone structure corresponding to these regimes, after which maps of possible regimes in the parameter space will be shown.

4.2. Stable combustion
In figure 2, steady-state distributions corresponding to $P_{in} = 2$ atm and $V_{in} = 300$ m/s are presented; the flame holder dimensions are $D_2 = 30$ mm, and $L_2 = 45$ mm. On the temperature field, streamlines demonstrating recirculation in the flame holder are shown. It can be seen that hot gases recirculating in the flame holder cause fuel gasification in the absence of oxygen near the surface (see plates c) and d)). Gaseous fuel produced in the wide section mixes near the inlet with the incoming air, however, temperature there is low, and ignition occurs later on, as the fuel-air mixture travels towards the main channel. As a result, a “hanging” combustion zone is formed in the flame holder (see plate b)). Hot gases from the burning flame holder ignite the channel, and a near-surface combustion zone is stabilized there along the channel walls. These distributions are typical of all cases where steady-state combustion was observed.

Figure 2. Temperature (a), volumetric heat release rate (b), volume fractions of MMA (c) and oxygen (d) for steady combustion regime: $P_{in} = 2$ atm, $V_{in} = 300$ m/s, $T_{in} = 500$ K.
4.3. One-time extinction and reignition in main channel
The sequence of events in this case is shown in figures 3 and 4. The flame is blown down the channel by the time 8 ms, however, after that the main channel is reignited by the hot gases from the flame holder, and steady combustion is established by 16 ms.

![Temperature distribution](image1.png)

**Figure 3.** Temperature for $P_{in}=1$ atm, $v_{in}=100$ m/s, $T_{in}=500$ K, $D_2=30$ mm and $L_2=20$ mm at $t=5$ ms (a), $t=8$ ms (b), $t=11$ ms (c) and $t=16$ ms (d).

![Volumetric heat release rate](image2.png)

**Figure 4.** Volumetric heat release rate for $P_{in}=1$ atm, $v_{in}=100$ m/s, $T_{in}=500$ K, $D_2=30$ mm and $L_2=20$ mm at $t=5$ ms (a), $t=8$ ms (b), $t=11$ ms (c) and $t=16$ ms (d).
4.4. Periodic extinction and reignition in main channel

In figures 5 and 6, the case where partial extinction of combustion in the main channel occurs, however, the flame is not blown out of the channel because of fast fuel reignition. This process is periodic, as will be demonstrated below on time histories of the total power (see figure 8).

**Figure 5.** Temperature for $P_{in} = 2$ atm, $v_{in} = 200$ m/s, $T_{in} = 500$ K, $D_2 = 30$ mm and $L_2 = 20$ mm at $t = 5$ ms (a), $t = 12$ ms (b), $t = 17$ ms (c) and $t = 25$ ms (d).

**Figure 6.** Volumetric heat release rate for $P_{in} = 2$ atm, $v_{in} = 200$ m/s, $T_{in} = 500$ K, $D_2 = 30$ mm and $L_2 = 20$ mm at $t = 5$ ms (a), $t = 12$ ms (b), $t = 17$ ms (c) and $t = 25$ ms (d).
4.5. Total extinction in main channel

In some cases extinction in the main channel occurred without subsequent reignition, however, combustion in the flame holder was stable. The steady temperature and volumetric heat release rate distributions corresponding to such a case are shown in figure 7.

Figure 7. Temperature (a) and volumetric heat release for \( P_m = 1 \text{ atm}, \ v_m = 300 \text{ m/s}, \ D_2 = 40 \text{ mm}, \) and \( L_2 = 30 \text{ mm}. \)

4.6. Total combustion power

In figure 8, typical time histories are plotted, demonstrating the regimes of flame blow-off and reignition in the main channel (a), oscillatory combustion mode (b), total extinction (c), and stable combustion (d).

Figure 8. Time histories of total power for \( P_m = 1 \text{ atm}, \ v_m = 100 \text{ m/s} \) (a) and \( P_m = 2 \text{ atm}, \ v_m = 200 \text{ m/s} \) (b) with the geometry \( D_2 = 30 \text{ mm}, \ L_2 = 20 \text{ mm}; \) \( P_m = 1 \text{ atm}, \ v_m = 400 \text{ m/s} \) (c) and \( P_m = 2 \text{ atm}, \ v_m = 400 \text{ m/s} \) (d) with the geometry \( D_2 = 30 \text{ mm}, \ L_2 = 45 \text{ mm}. \)
4.7. Map of combustion regimes

A number of simulations were performed in which the flow parameters and flame holder geometry were varied. It was found that combustion regimes observed in the whole parameter space covered by the simulations fall into the categories demonstrated in the previous sections. An overview of the results is given in figures 9 and 10, where color maps of combustion regimes are given for flame holder of the diameter $D_z = 30$ mm. On each map, rows correspond to different flame holder lengths $L_z$, whereas columns correspond to different inlet velocities. Figure 10 shows the map obtained for pressure $P_{in} = 1$ atm, while figure 11 corresponds to a higher pressure $P_{in} = 2$ atm. Different flow regimes obtained for each combination of flame holder length and inlet velocity are shown by colours, with the following colour key:

- **Stable combustion**
- **Extinction/regeneration in channel**
- **Extinction in channel**
- **Periodic extinction/regeneration**
- **Total extinction**

![Color Map Example](image)

**Figure 9.** Combustion regime map for pressure $P_{in} = 1$ atm.

![Color Map Example](image)

**Figure 10.** Combustion regime map for pressure $P_{in} = 2$ atm.

One can see that combustion stability deteriorates with the increase in the flow velocity. Short flame holders are incapable of providing necessary combustion stabilization. Also, with the increase in pressure combustion becomes more stable, which can be attributed to the increase in the burning rate proportional to the square of density (second-order reaction, see (7)).
Effect of flame holder geometry is also demonstrated in figure 11 corresponding to a single value of inlet velocity $V_{in} = 300$ m/s, $P_{in} = 1$ atm, with the colour keys given in the legend.

**Figure 11.** Effect of flame holder geometry.

| $D_2/L_2$ | 30 | 45 | 60 |
|-----------|----|----|----|
| 26        |    |    |    |
| 35        |    |    |    |
| 40        |    |    |    |

Stable combustion
Extinction in channel
Total extinction
No ignition

5. Conclusions
Numerical simulations performed in this work show that stability of combustion in a solid fuel ramjet engine depend on a number of parameters, so that optimization of flame holder geometry is vital for achievement of stable operation of SFRJ in wide range of conditions.

In the subsonic regime considered here, at higher velocities combustion in the fuel channel becomes unstable, the instability manifests itself first via oscillations with periodic extinction and reignition near the boundary between the flame holder and main channel; further increase in the velocity may result in complete flame extinguishment in the channel, possibly followed by secondary ignition. Combustion in the flame holder is more stable due to the presence of recirculation zone; the “hanging” combustion zone is located at the periphery of the recirculation vortex providing necessary ignition source for the main channel. However, at high velocities complete extinguishment was observed in the whole SFRJ.

Further work will be focused on the extension of the model to supersonic flow conditions, typical of scramjets. Other planned improvements include implementation of a more detailed model for solid fuel gasification. Validation of the computational model against the data on supersonic tests will also be performed.

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