Numerical investigation of heat flux structure on the surface of a fuel grain during operation of solid fuel ramjet combustor

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Abstract. To investigate the features of the processes inside the ramjet subsonic combustion chamber, a numerical model is used. The model is based on Reynolds-averaged Navier–Stokes equations along with turbulence, radiation and combustion models and considers solid fuel pyrolysis. Available in literature experimental data was used to validate the model. The dependences of the heat flow structure on the air flow are obtained. The effect of radiation heat transfer on the regression rate is shown.

1. Introduction

Simplicity, high stored fuel density and high specific impulse at high flight speed make solid fuel ramjet (SFRJ) an attractive design for supersonic propulsion systems. Typically, such an engine consists of an air inlet, a combustor with a solid fuel grain inside and a nozzle (figure 1).

During the flight of the aircraft with a SFRJ the incoming air is decelerated by shock waves in the inlet, yielding an increase of pressure and temperature. At the combustion chamber inlet, a flame stabilizer creates a sudden expansion of the incoming air, originating a recirculation zone, which provides flame stabilization. Inside the chamber the solid fuel grain is pyrolyzed by the heat flux from gas phase where reactions between gasified fuel and oxygen occur. Combustion of gasified fuel increases the internal energy of the flow which is converted to kinetic energy in the nozzle, yielding thrust. Polymers, solid hydrocarbons and their compositions with metal and boron particles are considered [1] as solid fuels for ramjets. Since the flow rate of solid fuel is influenced by the flow parameters of the incoming air, predicting the rate of regression of solid fuel is important in the study of SFRJ characteristics. Various works employ computational fluid dynamics [2–8] in order to evaluate SFRJ performance parameters. The modeling requires to employ turbulence and combustion models and to consider solid fuel gasification.

Most solid fuel combustion work in SFRJ or similar hybrid rocket engines does not take into account radiation heat transfer, as it is usually not expected to have a large impact on the work process. Despite there are some works [9–11] which employ a radiation model, influence of radiative heat transfer on combustion in SFRJ has not been thoroughly investigated.

The aim of the present work is to investigate the structure of heat flux on the surface of a solid fuel grain inside typical SFRJ combustor under different conditions and to evaluate influence of radiative heat transfer on working process.

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2. Model description

2.1. Case setup

This work deals with the processes inside a typical SFRJ combustion chamber, which consists of solid fuel grains and a flame stabilizer (figure 2). The solid fuel grain is a hollow cylinder made of polyethylene (PE)—a typical solid fuel. The flame stabilizer is a diaphragm placed before the fuel grain. The grain and the flame stabilizer form a step which allows a detached flow to appear during combustor operation. A two-dimensional axisymmetric case is considered.

Parameters of the air flow at the combustor inlet, e.g., temperature \( T_0 \), static pressure \( P_0 \) and air mass flux \( \rho V_0 \) are the entry data of the model and are used to state Dirichlet boundary conditions there. It is assumed that solid fuel pyrolysis takes place at the grain surface consuming all the heat supplied from the gas phase and yielding monomer \( C_2H_4 \). Only subsonic flows are considered in this work.

2.2. Flowfield calculation

The flow is governed by mass, momentum, energy and species conservation equations. These equations can be written as

\[
\frac{\partial Q}{\partial t} + \frac{\partial F_i}{\partial x_i} = \frac{\partial G_i}{\partial x_i} + S,
\]

where \( Q, F, G, S \) are vectors of conserved variables, convective fluxes, viscous fluxes and source terms respectively:

\[
Q = \begin{pmatrix} \rho \\ \rho v_j \\ \rho E \\ \rho Y_n \end{pmatrix}, \quad F_i = \begin{pmatrix} \rho v_i \\ \rho v_i v_j + P \delta_{ij} \\ (\rho E + P) v_i \\ \rho v_i Y_n \end{pmatrix}, \quad G_i = \begin{pmatrix} 0 \\ \tau_{ij} \\ -\frac{\rho D}{\rho D} \frac{\partial Y_n}{\partial x_i} \end{pmatrix}, \quad S = \begin{pmatrix} S_{\text{mass}} \\ 0 \\ S_{\text{energy}} + \nabla q_{\text{rad}} \\ S_n \end{pmatrix},
\]

where \( \rho \) is density, \( v \) is flow velocity, \( P \) is static pressure, \( E \) is the sum of the specific internal energy and specific kinetic energy, \( \tau_{ij} \) is the shear-stress tensor, \( T \) is temperature, \( Y_n \) is the mass fraction of the \( n \)-th specie, \( S_{\text{mass}} \) and \( S_n \) are source terms for mass (due to fuel gasification) and for \( n \)-th specie (due to chemical reactions), \( S_{\text{energy}} \) is source term for energy due to chemical reactions and \( q_{\text{rad}} \) is local radiative flux. These equations are closed by equation of state of a perfect gas:

\[
P = \frac{\Sigma Y_n M_n}{M_p} \rho RT.
\]

Since the flow inside SFRJ combustor is characterized by high Reynolds numbers \( (\text{Re} > 10^5) \) a turbulence must be considered. In the present work, \( k-\Omega \) shear stress transport [12] two-equation turbulence model was employed to deal with the turbulence. This model was proven [8,13] to be reliable in simulating flows inside SFRJ combustors.
A well validated [14, 15] Chandrasekhar’s discrete ordinate method [16] is used to simulate radiative heat transfer. In this method the radiative transfer equation

$$\frac{dI}{ds} = a(\sigma T^4 - I)$$

is approximated by a set of $N$ equations for radiation intensities for each of $N$ chosen directions [17]. Grey body emissivity and absorption of gases are taken into account. Absorption coefficient $a$ is calculated from

$$a = \frac{P}{\Sigma Y_n \Sigma a_n \frac{Y_n}{M_n}},$$

where $a_n$ are the Planck mean absorption coefficients estimated using polynomial temperature approximations [18] for each specie except $N_2$ and $O_2$, which are considered as transparent. It is considered that boundaries of the computational domain diffusely emit gray body thermal radiation. According to [19] emissivity of the grain surface was taken as 0.9. After this set of equations is solved, radiative heat flux $q_{rad}$ is calculated from

$$q_{rad} = \sum_{i=1}^{N} w_i I_i s_i,$$

where $w_i$ is weight of $i$-th direction, $I_i$ is radiation intensity along $i$-th direction, $s_i$ is a direction vector for $i$-th direction. A set of 8 directions is considered in the present work.

A non-premixed flame is known [1–11, 13] to take place inside subsonic SFRJ combustor. Combustion rates in such flames are [20] usually limited by reactants supply rate. It was shown in [6] that combustion model employed for modeling SFRJ combustor performance hardly influences computation results for solid fuel regression rates and heat fluxes at the fuel grain surface. In this work combustion processes are taken into account by using the laminar finite chemical reaction rate model. A combustion process is described by a set of chemical reactions. A source term of each species is the sum of its production rates in each reaction. Mass production rate of an $i$-th specie in a $j$-th reaction obeys the law of mass action and the Arrhenius law [20]:

$$r_{ij} = M_i s_{ij} [A][B] k_j T^n \exp \left( -\frac{E_j}{RT} \right).$$

In the present work, simplified gas-phase kinetic scheme taken from [13] is employed to describe combustion of PE.

Numerical results were obtained on a rectangular mesh (figure 3) by using the OpenFOAM [21] CFD toolbox which is based on the finite volume method of solving partial differential
equations. Mesh cells were clustered near the grain surface in order to ensure the resolution of the viscous sublayer there and to ensure independence of fuel gasification rate and corresponding heat consumption on cell sizes.

2.3. Boundary conditions

Dirichlet boundary conditions are set at the combustor inlet for the most of flow parameters at \( x = -l \):

\[
T = T_0, \quad v_x = v_0, \quad v_y = 0, \quad Y_i = 0, \quad Y_{O_2} = 0.23, \quad Y_{N_2} = 0.77.
\]

On the central line and exit from the combustion chamber, for each variable, a zero gradient condition is specified. It is assumed that the surface of flame stabilizer is impermeable, inert and do not conduct heat. Hence, a no-slip boundary condition is specified for velocity and zero gradient condition is used for other flow parameters. It is too assumed that the grain surface is impermeable for every specie and heat. The approach employed to deal with fuel injection and corresponding heat consumption will be described further.

2.4. Modeling of solid fuel gasification

In order to calculate the temperature of the grain surface and fuel injection rate one must couple energy balance equation of the grain surface with kinetic law of fuel pyrolysis. Solid fuel pyrolysis is governed by the Arrhenius law. Hence, solid fuel regression rate can be obtained from [22]:

\[
U = A \exp \left( -\frac{E_A}{RT_s} \right),
\]

where \( E_A \) is the activation energy of solid fuel pyrolysis, \( A \) is the pre-exponential factor, \( R \) is universal gas constant and \( T_s \) is temperature of the grain surface. In the present work, the solid fuel gasification is dealt with by introducing additional corresponding source terms for energy, mass and fuel transport equations in cells adjacent to the grain surface:

\[
S_{\text{energy}} = -\frac{F_{\text{sur}}}{V_{\text{cell}}} \left[ H_{\text{pyr}} + C_p(T - T_{\text{in}}) \right] \rho_{\text{fu}} A \exp \left( -\frac{E_A}{RT} \right),
\]

\[
S_{\text{mass}} = S_{\text{fu}} = \frac{F_{\text{sur}}}{V_{\text{cell}}} \rho_{\text{fu}} A \exp \left( -\frac{E_A}{RT} \right).
\]

In these formulations \( F_{\text{sur}} \) is area of the cell face which belongs to the grain surface, \( V_{\text{cell}} \) is cell volume, \( H_{\text{pyr}} \) is standard specific enthalpy of pyrolysis, \( C_p \) is specific heat of gasified fuel and \( T_{\text{in}} \)
is temperature inside the grain, which is considered constant and equal to 298 K, $\rho_{fu}$ is density of solid fuel.

In the formulation of the final volume, such an approach for the mass conservation equation and for the fuel transfer equation is equivalent to applying the corresponding mass flow through the gas–solid interface. For the energy conservation equation, this is equivalent to stating heat balance equation of gas–solid interface as a boundary condition.

Parameters of solid fuel pyrolysis are taken from [23]: $E_A = 125.05$ kJ/Mole, $A = 4780$ m/s.

With the calculated temperature field, the longitudinal distribution of the linear regression rate of solid fuel was obtained using (1). With this distribution known the average regression rate is obtained by

$$U = \frac{1}{L} \int_0^L U \, dx.$$

3. Verification of the numerical model
To validate the numerical model and the computational algorithm let us compare numerical results with experimental regression rate data from [8]. In figure 4 there are shown calculated fuel regression rate longitudinal distribution in comparison with experimental data. Data was obtained for combustion of cylindrical grains of PE with $L = 0.3$ m, $r = 0.035$ m, $h = 0.0175$ m in air flow with inlet temperature $T_0 = 540$ K, static pressure $P = 0.66$ MPa and mass flow rate $G_{air} = 0.3$ kg/s. It can be seen that calculated results are in agreement with experimental data and do capture main features of the processes under investigation. Local regression rate drastically grows along the grain behind the flame stabilizer where the recirculation zone occurs, reaching maximum at the flow reattachment point and then it slowly decreases.

4. Results and discussion
A working process inside the combustion chamber of a SFRJ was simulated for different air flow rates. The combustor under consideration (see figure 2) has following parameters: the length of
Figure 5. Temperature field, distribution of oxygen and gasified fuel mass fractions inside a SFRJ combustor with grain of PE.

![Temperature field and species distributions](image)

Figure 6. Longitudinal distributions of overall (a) and radiative (b) heat fluxes at the surface of a fuel grain for different air flow rates. In both parts, blue, yellow, green and red curves are distributions for $(\rho V)_0$ of 20, 100, 200 and 300 kg/(m²s), respectively.

![Heat flux distributions](image)

The grain $L = 0.5$ m, inner radius of the grain $r = 0.05$ m and the height of the flame stabilizer $h = 0.025$ m. The incoming air has temperature 500 K, static pressure 5 atm and mass flux varying between 10 and 400 kg/(m²s). Such parameters can be encountered during the flight of an aircraft with SFRJ.

A typical for SFRJ temperature distribution can be observed in figure 5. Air mass flux here is 100 kg/(m²s). A flame is forming above the grain surface behind flame stabilizer and divides the flow into an oxygen-rich region and a fuel-rich region below the flame. Fractions of these species become thinner when closing to the flame as they consumed by the combustion process while fraction of fuel is highest near the grain surface where it yields during solid fuel pyrolysis. The temperature is highest near the flame and drops near the grain surface due to endothermicity of solid fuel pyrolysis.

Distributions of heat fluxes are shown in figure 6. It can be seen that overall surface heat flux grows along the grain reaching maximum at flow reattachment area. After reattachment point the flux gradually decreases due to growth of boundary layer thickness and decrease of cross section averaged mass fraction of oxygen.

Radiative heat flux grows along recirculation zone which can be attributed to development of the flame above grain surface. Beyond flow reattachment point radiative heat flux does not changes significantly since radial distribution of temperature stays almost the same.

In general, under conditions considered magnitudes of convective heat fluxes are significantly greater than magnitudes of radiative fluxes.
Average overall heat flux grows with air supply growing [figure 7(a)] as well as radiative heat flux. The fraction of radiative heat flux, however, decreases drastically with air supply growing [figure 7(b)]. As can be seen in figure 8, the difference between average regression rates calculated without and with radiation taken into account decreases with air supply growing which is in accordance with radiative heat flux behavior [see figure 7(b)]. Hence, during simulations of SFRJ performance under low air flow rates it is advisable to consider radiative heat transfer in gas phase.
5. Conclusion

A structure of heat flux on the surface of the solid fuel grain during SFRJ operation has been investigated numerically. It is shown that radiative heat transfer does not influence solid fuel regression rate significantly within wide range of air flow rates. Fraction of convective heat flux as well as overall heat flux grows with air flow rate growing while fraction of radiative heat flux drastically decreases.

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