Heat exchange in the back lip cavity of the large solid-propellant rocket motor

B Ya Benderskyi and A A Chernova

Kalashnikov Izhevsk State Technical University, 426000, 7 Studencheskaya Street, Izhevsk, Russia

E-mail: alicaaa@gmail.com

Abstract. Issues of numerical modeling of spatial gas dynamics and heat exchange in the back lip cavity of the combustion chamber of a large solid-propellant rocket motor (SRM) are considered. Topological features of the flow structure and thermophysical parameters near the nozzle cap in the back lip cavity are analyzed. Distribution of the heat transfer coefficient over the nozzle bottom surface in the back lip cavity is obtained by the radial coordinate. The obtained dependences fairly correlate with the known experimental data.

1. Introduction

In order to prevent possible deformations of the charge and casing, the layout of a large solid fuel rocket engine provides [1-5] unloading cavities not filled with the fuel between the bottom of the combustion chamber and the case-bonded charge. The presence of such back lip cavities leads to, on the one hand, stress reduction of the deformation mode in the engine charge and, on the other hand, to formation of return flow zones [5-11]. The location of back lip cavities near the bottoms is connected with the necessity of solving the issues of additional thermal protection of structural elements; for this purpose, information about peculiarities of heat exchange processes in the back lip cavity is required.

Issues of numerical modeling of the conjugate problem of heat exchange in the flow paths, the pre-nozzle volume (PV) and the back lip cavity of SRM are considered.

2. Mathematical simulation

The problem of the spatial flow of compressible heat-conducting gas in flow paths and the back lip cavity of SRM was considered (Figure 1). The working body was the combustion products (CP) of a conventional solid fuel with the adiabatic index 1.2 and combustion temperature 3000 K. The temperature and flow rate of CP were assigned at mass supply surfaces. The conjugation condition at the solid/gas boundary was set [12]. At the nozzle outlet, non-reflecting boundary conditions were assigned.
Figure 1. Computational area.

For mathematical simulation of viscous compressed gas motion the equation system is solved, and it includes the additional condition equation:

$$
\begin{align*}
\frac{\partial \rho}{\partial t} + \nabla \rho \mathbf{u} &= 0, \\
\rho \frac{d \mathbf{u}}{dt} &= \rho \mathbf{F} - \nabla p + \text{Div} P, \\
\rho \frac{dE}{dt} &= \rho \mathbf{F} \mathbf{u} + \nabla (P \mathbf{u}) + \nabla \mathbf{q}, \\
\frac{\partial T}{\partial t} &= \lambda \nabla^2 T, \\
\frac{P}{T} &= \rho R.
\end{align*}
$$

(1)

where $\rho$ is the gas density, $p$ is the pressure, $\mathbf{u}$ is the vector of velocity, $P$ is the pressure, $\mathbf{F}$ is the external volume force, $T$ is the temperature, $E$ is the total specific energy, $\mathbf{q}$ is the heat flux vector, $R$ is the specific gas constant; and $\mu$ is the dynamic-viscosity coefficient.

Coefficients of molecular viscosity heat $\mu$ and conductivity $\lambda$ depend on the temperature as [6]. The system of equations (1) is averaged by Favre and Reynolds [11], and it is closed using the two-zone Menter turbulence model SST [13, 14].

The quasi-stationary problem was solved by the relaxation method (mass conservation law), based on the compliance with conditions of $\textit{RMS} < 10^{-6}$. Discretization of basic equations was carried out by the finite volume method taking into account the Rhie-Chow correction. The counter-flow scheme of the second degree of accuracy was applied in order to discretize non-viscous flows and the central scheme of the second degree of accuracy was applied for viscous ones. The difference equation system was solved algebraically by the multi-grid method with the conjugate gradient method applied for rapid convergence. Discretization of the computational area was made by means of hexagons with their total number of 4.3 mln elements including prismatic cells for near-wall flows.
3. Calculation results
As a result of numerical modeling the structure of gas flow (Figure 2) and instantaneous distributions of fields of physical quantities in the PV back lip cavity of the SRM combustion chamber were obtained.

![Figure 2](image1.png)

**Figure 2.** Flow pattern in the back lip cavity: a) experimental; b) calculated.

It is seen from Figure 2 that the flow in the back lip cavity is due to the inflow of some part of the supra-nozzle flow into the cavity. The calculations allowed for obtaining the resulting pattern of limit stream lines (Figure 2b) with a distinct development of specific points and lines that are confirmed by experimental data [5] (Figure 2a).

The detailed pattern of the flow represented as velocity field vectors is shown in Figure 3.

![Figure 3](image2.png)

**Figure 3.** Flow structure in the back lip cavity.

Figure 3 shows that the interaction of the flow with the armored end of the charge is characterized by the presence of distinct lines of dripping, spreading and several "specific" points. In Figure 3 the dripping lines are marked as L1, focus points as f1, node points as U1, and saddle points as S1.

In Figure 3 the central line of spreading is registered to form due to the interaction between the flow entering the pre-nozzle gap and the flow generated in the back lip cavity. Three "saddle" points are marked by the letter S in Figure 2. Letters L1 to L4 denote "node points". Groups of "specific"
points L3 and L4 are "focus" points, and they are close to the separating lines. Points L1 and L2 are "node" points, and they are characterized by the junction of spreading lines. Dripping lines are located between "focus" points L3 and L4. Thus, the number of "node" points is twice as high as the number of "saddle" points, which is fully consistent with the Davy - Lighthill law.

Figure 4 shows the distribution of the dimensionless heat transfer coefficient over the relative radial coordinate for the values of the angular coordinate 0, 45, 90, 180. The diagrams show the experimental results [5] which satisfactorily coincide with the calculated ones.

\[ \frac{\alpha}{\alpha_{\text{max}}} = \frac{\rho \cdot c_p \cdot \mu}{\alpha_{\text{max}}} = 0.21 \]

The analysis of Stanton numbers shows the insignificant influence of the angular coordinate on heat exchange processes at the predominant influence of the radial coordinate:

\[ St = -0.26 \cdot (r / R)^2 + 0.08 \cdot (r / R) + 0.24 \]
Table 1. The St number.

| Angular position | r/R       | St         |
|------------------|-----------|------------|
| 0                | 0.474605686 | 0.212242678 |
| 45               | 0.46066832  | 0.211583046 |
| 90               | 0.441611598 | 0.204280975 |
| 180              | 0.453637296 | 0.206252418 |

Conclusions
Conjugate problem of heat exchange in the back lip cavity of a large solid propellant rocket motor has been solved. Distributions of dimensionless heat transfer coefficient near the nozzle bottom surface by the radial coordinate are given, as well as Stanton number for local maxima and the polynomial dependence of the number by the radial coordinate. Comparison of the numerical data with the experimental results [5] gives a satisfactory correlation.

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