The influence of the charge shape on heat exchange of a recessed nozzle

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Abstract. The paper deals with the numerical simulation of the flow of thermally conductive viscous gaseous combustion products in the flow paths of a power plant. The influence of the shape of the mass supply surface on the gas dynamics and heat exchange near the recessed nozzle of the power plant is investigated. The coupled problem of heat exchange is solved by the method of control volumes. It is shown that the compensator geometry determines the localization of both the topological features of the flow near the recessed nozzle and the position of local maximums of the heat transfer coefficient. It has been revealed that The use of a channel with a star-shaped cross section and a triangular form of compensator rays leads to an intensification of heat exchange processes near a recessed nozzle.

1. Introduction
The design of power plants (PP) requires information on intrachamber processes [1, 2] including the intensity of heat fluxes in flow paths of the combustion chamber. Experimental studies of heat exchange processes in the PP combustion chamber are challenging and are performed using the "heat flux reversal" method [3] on model stands with air as the working body. The results of such studies are generalized in the form of criterial equations [4], the application of which for engines with a charge shape different from the experimentally studied one [5] requires additional research.

When designing PP [6], the choice of the mass supply surface shape is determined from the conditions of providing the required mass supply [2]. There are various shapes of channels mass supply [1], which depend on the type of the developed PP [7]. At the same time, the thermal mode in the combustion chamber (CC), including the pre-nozzle volume (PV), is largely determined by the combustion product flow (CPF) [4] coming from the mass supply surface. The internal gas dynamics in flow paths of PP is substantially determined here by the geometry of these flow paths [8,9]. There are individual works [10, 11] devoted to the study of thermo-physical processes occurring in the combustion chamber of PP for specific assemblies. However, studies of the relationship between the type of the mass supply surface and thermo-physical processes in PV implemented for this design scheme are not currently presented in publications.

Thus, the work is devoted to mathematical modeling of heat exchange processes in flow paths of PP with charges of various cross-sections and a recessed nozzle in the quasi-stationary mode of engine operation.
2. Mathematical simulation
Numerical modeling of the problem of conjugate heat exchange in flow paths of PP with a recessed nozzle and a case-bonded channel charge of various cross-sections (Figure 1) is considered.

![Figure 1. Shape of mass supply surface: six-beam cross-section (a); twelve-beam cross-section (b); six-beam star cross-section (c); three-blade cross-section (d); four-blade cross-section (e); saw-toothed channel (f); groove channel (g).](image)

In general, the computational domai under consideration is a system of flow paths of the combustion chamber of a PP with a recessed nozzle (Fig. 2).

![Figure 2. Computational domain.](image)

The working body is the combustion product (CP) of a conditional solid propellant with the adiabatic index 1.2 and the combustion temperature $T = 2500$ K. The temperature, pressure, and velocity of combustion products are set for mass supply surfaces, and non-reflective boundary conditions are set at the nozzle outlet. Conditions for adhesion and impermeability are set for solid impermeable surfaces. The boundary condition of the IV-th type is set at the boundary of the solid and CP, and boundary conditions at outer boundaries are set in accordance with [12]. Since the Reynolds number on the channel outlet has the order of $10^3 \div 10^6$ and the Mach number in the critical cross-section area of the recessed nozzle can reach the value $M = 1$ or more, the viscous compressible gas model is used. For a mathematical description, the model of viscous heat-conducting compressible gas is given by the following system of equations:

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_i}{\partial x_i} = 0$$  \hspace{1cm} (1)

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial \rho u_i u_j}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_i} \left( \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} \mu \frac{\partial u_i}{\partial x_k} \delta_{ik} \right) + F_i$$ \hspace{1cm} (2)
\[
\frac{\partial \rho E}{\partial t} + \frac{\partial \rho E u_j}{\partial x_j} = -\frac{\partial \rho u_i}{\partial x_j} + \frac{\partial \rho u_j}{\partial x_i} + F_j u_i + \frac{\partial q_i}{\partial x_j} + \frac{\partial q_j}{\partial x_i} + F_j u_i \tag{3}
\]

\[
cp \frac{\partial T}{\partial t} = \lambda \nabla^2 T \tag{4}
\]

\[
p = \rho RT \tag{5}
\]

where \( \rho \) is the gas density, \( p \) is the pressure, \( u_i \) is the velocity components, \( F_i \) is the external volume force, \( T \) is the temperature, \( q_j \) is the component of heat flux density vector, \( R \) is the specific gas constant; \( \mu \) is the dynamic viscosity, \( \lambda \) is the heat conductivity factor, \( E = C_i T + 0.5u_i^2 \) is the total specific energy, \( H = E + p / \rho = C_i T + 0.5u_i^2 = h + 0.5u_i^2 \) is the total specific enthalpy; \( \tau_{ij} = 2\mu S_{ij} - 2\mu \frac{\partial u_i}{\partial x_j} \delta_{ij} \) is the viscous stress tensor; \( S_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \) is the strain velocity tensor.

Coefficients of the molecular viscosity heat \( \mu \) and conductivity \( \lambda \) depend on the temperature.

In literature, there is no substantiation for the application of turbulence models for fluxes in flow paths of the PP combustion chamber; besides, experimental confirmation of the model correctness is also missing. So, with account of implementing the mode with a significant difference in the transfer of individual components of the Reynolds stress tensor and based on the analysis of physical models for the flux in the PP flow paths, it is the most reasonable to use the model of transfer of Reynolds stress components within the Mentor model. Initial equations are averaged in accordance with [11, 12, 13]. The Navier-Stocks averaged system is closed by the model of the Reynolds stress component transfer within the Mentor model [13, 14]. All constants of the Mentor model [13] are calculated in accordance with [12, 13, 14, 15] with values from standard models \( k - \varepsilon \) and \( k - \omega \) as \( \alpha = \alpha_F + \alpha_{1-} \), etc. The constants of this model are \( \beta = 0.09 \), \( \alpha_{1+} = 5/9 \), \( \alpha_{2+} = 0.44 \), \( \beta_{1+} = 3/40 \), \( \beta_{2+} = 0.0828 \), \( \sigma_{1+} = 0.85 \), \( \sigma_{1-} = 1 \), \( \sigma_{2+} = 0.5 \), \( \sigma_{2-} = 0.856 \), \( \alpha_{1+} = 0.31 \).

The grid convergence was estimated from the SAR flow rate through the critical section relative to the grid power (Fig. 3). Since increasing the grid dimension above 3mln cells has no effect on the changes in the flow rate through the critical, but increases the computational resource requirements, the optimal one, based on the analysis of the convergence curve (Fig. 3), is the dimension of 3 mln cells.

![Figure 3](image.png)

**Figure 3.** Dependence of the mass flow rate on the number of elements of the calculation domain.

The computational domain discretization is performed on hexagonal mesh, and the overall number of cells does not exceed 3.1 million cells, including prismatic cells to resolve near-wall flows. The quasi-stationary problem is solved by the relaxation method (mass conservation law), based on the compliance with conditions \( RMS < 10^{-6} \). Basic equations are discretized by the finite-element method.
with account of the Rhie-Chow correction. Non-viscous flow discretization is performed with a counter-flow scheme of the 2nd order accuracy, and the central scheme of the 2nd order accuracy is used for viscous flows. A system of equations is solved by an algebraic multigrid method, which applies the conjugate gradient method to accelerate the convergence.

3. Calculation results
As a result of the realized calculations, distribution fields of physical quantities in the PP PV for different types of charges are obtained. The structure of the PV flow in the form of velocity vectors in the longitudinal section of the CC implemented near the inlet part of the recessed nozzle is shown in Figure 4.

Figure 3 shows that under the same conditions of gas injection from the surface, due to the difference in areas of mass feed surfaces in the channel, different modes of flows [16] are implemented near the inlet surface of the recessed nozzle (Fig. 4). For all channels with different shapes of compensators (Fig.1, a-e) formation of braking points on the inlet surface of the recessed nozzle is noted (Fig.4, 5 a-e). The location of braking points on the inlet surface of the recessed nozzle is conditioned by the geometry of the mass feed channel, which corresponds to the experimental data [16].

It should be noted that for charges with different numbers and shapes of compensators (Fig.1, a-e) the formation of flow breakaway zones in the area of the supra-nozzle gap (Fig.4, 5 a-e) is also specific. Localization of these zones, as can be seen from Fig. 4a,b,c,e, is determined by the flow mode implemented in the PV. For the saw-toothed shape of the mass feed channel (Fig.1,f), as well as for the channel with the ring bore (Fig.1,g) the mode with penetration of the supra-nozzle flow into the nozzle (Fig.4,f,g) and formation of zones of flow mixing in the pre-nozzle volume of CC is implemented.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure4.png}
\caption{Velocity vectors in the longitudinal section channels (a) with six-beam cross-section; (b) twelve-beam cross-section; (c) six-beam star cross-section; (d) three-blade cross-section; (e) four-blade cross-section; (f) saw-toothed channel and (g) groove channel.}
\end{figure}

It should be noted that local maximums of the heat flux coincide with the identified topological features (braking points on the inlet surface of the nozzle, spreading lines, Fig. 6).
Figure 5. The limiting streamline structure near recessed nozzle surface with (a) six-beam cross-section; (b) twelve-beam cross-section; (c) six-beam star cross-section; (d) three-blade cross-section; (e) four-blade cross-section; (f) saw-toothed channel and (g) groove channel.

It is shown that in transition from the trapezoidal to triangular shape of compensators, for the star-type charge, there is an increase in the intensity of the heat flux near the inlet surface of the recessed nozzle (Fig. 7, a) which is caused by the previous CP flow in the charge channel.

Figure 6. Distribution of the heat transfer local coefficient on the recessed nozzle inlet surface for (a) six-beam cross-section; (b) twelve-beam cross-section; (c) six-beam star cross-section; (d) three-blade cross-section; (e) four-blade cross-section; (f) saw-toothed channel and (g) groove channel.

Distribution of the relative heat transfer coefficient along the generating line of the recessed nozzle for the considered channel charge types is shown in Figure 7, b.

The obtained distributions of the heat transfer coefficient show that the use of a channel with the star-shaped cross-section and triangular shape of compensator beams leads to intensification of heat exchange processes near the recessed nozzle (Fig. 7, b). In this case, local maximums of the heat transfer coefficient correspond to the position of special points determined by the geometry of compensators.
Figure 7. Distribution of the dimensionless heat transfer coefficient along the generating nozzle: (a) for the ratio of the heat transfer coefficient to the local maximum for a particular charge and (b) for the ratio of the heat transfer coefficient to the maximum for all charges, where: 1 is the six-beam cross-section; 2 is the twelve-beam cross-section; 3 is the six-beam star cross-section; 4 is the three-blade cross-section; 5 is the four-blade cross-section; 6 is the saw-toothed channel, and 7 is the groove channel.

Conclusions
Studies have shown that for the star-shaped channel with trapezoidal compensators, the channel with the saw-shaped cross-section, lobe-shaped compensators, as well as the channel with the ring bore, heat fluxes are smaller by more than 47% than for other studied channels (Fig. 7, b).

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