Numerical simulation of the regime and geometric characteristics influence on the pressure loss of a low-flow aerothermopressor

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In this paper, a study of gasdynamic processes that occur in a low-flow aerothermopressor has been done. The aerothermopressor is a two-phase jet apparatus for contact cooling, in which, due to the removal of heat from the air flow, the air pressure is increased (thermogasdynamic compression) and its cooling is taken place. Highly effective operation of the aerothermopressor is influenced by primarily the flow part design and the water injected method in the apparatus. Constructive factors that influence energy costs to overcome friction losses and local resistances on the convergent-divergent sections of the aerothermopressor are exerted a significant impact on the working processes in the apparatus. In this paper, a study of a number of typical low-flow aerothermopressor models has been conducted by using computer CFD modeling. Determination of the main parameters of the air flow (total pressure, dynamic pressure, velocity, temperature, etc.) has been carried out for a number of taper angles of a confuser α and a diffuser β, as well as for a number of values of the relative air velocity in the working chamber M = 0.4-0.8. Comparison of the obtained data with experimental data has been carried out. The deviation of the calculated values of local resistances coefficients in the confuser and in the diffuser from those obtained by computer CFD modeling does not exceed 7–10%. The recommended angles were determined: confuser convergent angle – 30° and diffuser divergent angle – 6°, corresponding to the minimum pressure loss is 1.0 – 9.5 %, and therefore also to the maximum pressure increase as a result of the thermogasdynamic compression that occurs during injection and evaporation of liquid in the working chamber. Thus, analytical dependences are obtained for determining the local resistance coefficients for the confuser (nozzle) and the diffuser, which can be recommended to use in the design methodology for low-flow aerothermopressors.

Keywords: Aerothermopressor, Coefficients of local resistance, CFD modeling

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1. Introduction

Jet devices have long taken their place in the technical area and are widely used, both as individual devices, and as part of power plants to improve cooling systems and to increase fuel and energy efficiency. An aerothermopressor is one of such devices, it is a two-phase jet apparatus for contact cooling, in which, due to the removal of heat from the air flow, the air pressure is increased (thermogasdynamic compression) and its cooling is taken place.

The aerothermopressor effectiveness depends on the values of total pressure losses due to the following factors: surface and internal friction of the air, aerodynamic resistance of the injection system, resistance of the injected liquid, the process of heat and mass transfer at a finite temperature difference and partial pressure. Such losses can be quite significant and amount to 10-40%, depending on the design features of the apparatus flow-through part.

Therefore, taking this into account, the actual development of the aerothermopressor type jet technology is the determination of rational parameters of the workflow organization with the corresponding development of the flow part design. At the same time, it is necessary to have an opportunity for the analytical determination of losses associated primarily with friction in the confuser (nozzle) and diffuser of the aerothermopressor.

Use of the low-flow aerothermopressor in the cycle air cooling system of low-power gas turbines (micro-turbines) is highly topical issue.
2. Literature Review

The aerothermopressors using as contact heat exchangers is possible for a wide range of power plants, namely for cooling the cycle air of gas turbines of various nominal capacities [1], cooling the charge air of internal combustion engines [2], for removing superheating of vapor in industrial ammonia two-stage refrigeration plants of moderate cold [3], etc. Due to the evaporative cooling in the aerothermopressor, the effect of thermogasdynamic compression takes place, that is, an increase in air pressure, as a result of the instantaneous evaporation of water, which is injected into the accelerated hot air flow. The heat that goes to the evaporation of water is taken from the air flow, thereby cooling it.

To ensure the highly efficient operation of the aerothermopressor, it is necessary to determine the technological requirements for the flow part design and the water injected method in the apparatus. A significant influence on the working processes in the aerothermopressor is exercised by design factors that influence energy costs to overcome the friction losses and local resistances on the convergent-divergent sections of the aerothermopressor.

The air velocity at the minimum cross-section of the aerothermopressor should be $M = 0.5-0.9$ to ensure a positive increase in pressure. At such a velocity, the total pressure loss is increased rapidly [4].

Pressure losses due to aerodynamic resistance in the flow-through part of the aerothermopressor are determined by the local resistance coefficients: conserver (nozzle) – $\zeta_c$; working chamber (evaporation area) – $\zeta_{ch}$; diffuser – $\zeta_d$.

The well-known classical methods of hydrodynamics and fluid flow mechanics are used to calculate losses from the total resistance [5, 6, 7, 8]. So to determine the coefficients of the total hydraulic resistance of the conserver (1) and diffuser (2) the following dependencies are used [5, 6, 8]:

$$\zeta_c = \left(\frac{\lambda_c}{8\sin^2\alpha_2}\right) \left[1 - \left(\frac{d_{ch}^2}{d_f^2}\right)\right],$$

$$\zeta_d = \left(\frac{\lambda_d}{8\sin^2\frac{\beta}{2}}\right) \left[1 - \left(\frac{d_{ch}^2}{d_f^2}\right)\right] + \sin\beta \left[1 - \left(\frac{d_{ch}^2}{d_f^2}\right)\right]^2,$$

where $\lambda_c$ – average value of hydraulic friction coefficients at the beginning and at the end of the conserver; $\alpha_2$ – conserver taper angle, °; $d_f$ – conserver diameter, m; $d_{ch}$ – working (evaporation) chamber diameter, m; $\lambda_d$ – average coefficient of hydraulic friction at the beginning and at the end of the diffuser; $\beta$ – diffuser taper angle, °; $d_f$ – diffuser diameter, m.

When the air velocity is $M = 0.5-0.7$, the resistance coefficient for the working chamber $\zeta_{ch}$ resides in the region of the self-similar air flow according to the Reynolds number (Re) and the Mach number (M). Depending on the degree of roughness of the walls, $\zeta_{ch}$ can be defined as [4]:

$$\zeta_{ch} = (0.01-0.02)\frac{L_{ch}}{D_{ch}}$$

$L_{ch}/D_{ch}$ – caliber or relative diameter - the ratio of the length of the mixing chamber to its diameter.

To determine the coefficient of local resistance of the diffuser $\zeta_d$, there are two main methods: semi-empirical and based on the boundary layer theory.

The disadvantage of the semi-empirical method is that it does not take into account the effect of gas compressibility, operating parameters in the minimum cross section and the conditions of entry and the initial stage of flow turbulence. This, in turn, gives the value of $\zeta_d$ several times different from the real (experimental) value [4, 9].

In the method of determining $\zeta_{ch}$, on the basis of the theory of the boundary layer, the integral characteristics of the boundary layer are determined and, on their basis, analytical dependences are obtained for the calculation. The disadvantage of this method is the need to satisfy the condition of uniformity of the velocity field at the entrance, which is very difficult to obtain in practice [9].

The above methods for determining local resistance coefficients do not provide accurate data on losses in the diffuser, which, in turn, makes it necessary to use the data obtained during the experiment [4] in studies in a wide range of geometric and regime parameters.

It should be noted that with Reynolds numbers $Re \leq 2 \cdot 10^3$ the local resistance coefficient does not depend on the Reynolds Re number and the Mach number M (in the range of values $M = 0.1-0.9$) and is determined only by geometrical parameters (for example, the angle of tapering and the ratio of the diameters of the input and output $D_i/D_o$). Considering the above, it has been established that the value of the local resistance coefficient resides in the region of the self-similar flow regime for Re and M [4], that is, the air flow remains mechanically similar to itself when one or several parameters determine this flow change.

The smallest value $\zeta_d = 0.06-0.08$ corresponds to the angle of the diffuser expansion $\beta = 5-7$ ° and the degree of expansion $n = 10$. The above data are valid provided that the velocity field at the input [4] is uniform. If there is a working chamber in front of the diffuser with a sufficiently large caliber value $(L_{ch}/D_{ch})$, the velocity distribution field will be substantially uneven. The value of $\zeta_d$ can be calculated by the following equations [5]:
\[ \zeta_{\text{lm}} = K \cdot \zeta_d, \]  

(4)

K – correction factor.

When \( \text{Re} > 10^5 \) \( (L_{ch}/D_{ch}) = 5 \text{-} 15 \), the value of the correction factor can be taken \( K = 1.3 \text{-} 1.6 \). Thus, the value of the local resistance coefficient will be \( \zeta_d = 0.08 \text{-} 0.15 \).

A study was made [10] of the aerothermopressor operation on the exhaust gases of a gas turbine. The authors designed and investigated an experimental jet apparatus, 7.5 meters long, an initial flow velocity was equal to 31 m/s, the gas flow rate was equal to 11.5 kg/s. The data on pressure loss through local and hydraulic resistance in different parts of the aerothermopressor were obtained, the total pressure resistance without fluid injection reached 14%.

In the works [1, 11] it is shown that the positive effect from the thermogasdynamic compression use in the aerothermopressor (increasing the air pressure during cooling) is greater, then the friction loss is smaller. Losses due to friction according to the classical method of calculation are up to 5-8%.

The discrepancy of theoretical data, based on classical dependencies, and experimental data indicates inaccuracy in determining local coefficients of pressure loss, which is especially important with small diameters of the flow-through part of the aerothermopressor, that is, with low air flow.

Obviously, to determine losses from the total resistance in the low-flow aerothermopressor (air flow \( G_{\text{air}} \) is up to 1 kg/s), it is necessary to clarify the empirical dependences to determine the coefficients of total aerodynamic resistance through the small diameters of the apparatus flow part. The establishment of such dependences or a range of specific values for local coefficients of pressure loss will allow choosing the optimal structural characteristics of the aerothermopressor, which will correspond to the achievement of the maximum pressure increase value as a result of thermogasdynamic compression.

The study purpose is to obtain analytical dependencies for determining the local resistance coefficients for the confuser and the diffuser of the low-flow aerothermopressor.

3. Research Methodology

To determine the optimal design parameters of the experimental aerothermopressor (Fig. 1) at various air flow rates in the working chamber \( (M = 0.4 \text{-} 0.8) \), a hydrodynamic analysis of typical models was carried out by using CFD modeling software ANSYS Fluent [12].

The experimental aerothermopressor was developed to study the working processes with the thermogasdynamic compression emergence in order to determine the optimal geometrical and regime parameters. The working medium is humid air with initial parameters of pressure \( P_{\text{atp}} \), temperature \( T_{\text{atp}} \) and relative humidity \( \varphi_{\text{atp}} \), corresponding to the parameters of the cycle air of gas turbines and charge air of internal combustion engines (Table 1).

![Figure 1 – The design of the experimental aerothermopressor](image)

**Table 1 – Technical characteristics of the experimental aerothermopressor**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet air pressure ( P_{\text{atp}} ), 10^5 Pa</td>
<td>3.0</td>
</tr>
<tr>
<td>Inlet air temperature ( T_{\text{atp}} ), K</td>
<td>453</td>
</tr>
<tr>
<td>Relative inlet humidity ( \varphi_{\text{atp}} ), %</td>
<td>30</td>
</tr>
<tr>
<td>Air velocity at the inlet confuser (nozzle) ( w_{\text{air}}, \text{m/s} )</td>
<td>35</td>
</tr>
<tr>
<td>Mach number at the inlet working chamber ( M )</td>
<td>0.40 – 0.80</td>
</tr>
<tr>
<td>Relative velocity of injected fluid ( (w_{\text{air}}/w_{\text{air}}) )</td>
<td>0.3</td>
</tr>
<tr>
<td>Temperature of injected fluid ( T_{\text{w}}, \text{K} )</td>
<td>293</td>
</tr>
<tr>
<td>Air mass flow ( G_{\text{air}}, \text{kg/s} )</td>
<td>0.34</td>
</tr>
<tr>
<td>Relative mass flow rate of injected fluid ( g_{\text{w}}, % )</td>
<td>5</td>
</tr>
</tbody>
</table>

To build a three-dimensional solid model, AutoCAD graphic program was used (Fig. 2). The input and output sections of the geometric model were elongated to eliminate the influence of edge effects in the computational model. The geometrical characteristics of the aerothermopressor were given in Table 2.

![Figure 2 – 3D model of the experimental aerothermopressor](image)
The computational grid (Fig. 3) was constructed by using the Automatic Method, the grid elements are tetrahedrals. The maximum size of each element does not exceed 3 mm. Wall layers are specified in the amount of 4 pieces (Table 3).

**Table 2 – Flow part geometric characteristics of the experimental aerothermopressor**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerothermopressor length $L_{\text{atp}}$, mm ($L_{\text{ch}}/D_{\text{ch}} = 5$)</td>
<td>341</td>
</tr>
<tr>
<td>Confuser</td>
<td></td>
</tr>
<tr>
<td>Inlet diameter $D_{c1}$, mm</td>
<td>64</td>
</tr>
<tr>
<td>Outlet diameter $D_{c2}$, mm</td>
<td>22</td>
</tr>
<tr>
<td>Angle $\alpha$, °</td>
<td>30; 35; 40; 45; 50</td>
</tr>
<tr>
<td>Length $L_{c}$, mm (at $\alpha = 30$ °)</td>
<td>36</td>
</tr>
<tr>
<td>Diffuser</td>
<td></td>
</tr>
<tr>
<td>Inlet diameter $D_{d1}$, mm</td>
<td>22</td>
</tr>
<tr>
<td>Outlet diameter $D_{d2}$, mm</td>
<td>65</td>
</tr>
<tr>
<td>Angle $\beta$, °</td>
<td>6; 8; 10; 12</td>
</tr>
<tr>
<td>Length $L_{d}$, mm (at $\beta = 6$ °)</td>
<td>208</td>
</tr>
<tr>
<td>Working chamber at $(L_{ch}/D_{ch}) = 5$</td>
<td></td>
</tr>
<tr>
<td>Diameter $D_{ch}$, mm</td>
<td>22</td>
</tr>
<tr>
<td>Length $L_{ch}$, mm</td>
<td>108</td>
</tr>
</tbody>
</table>

**Figure 3 – Computational grid for modeling of the experimental aerothermopressor**

**Table 3 – Calculation grid parameters for modeling of the experimental aerothermopressor**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amount of nodes</td>
<td>70575</td>
</tr>
<tr>
<td>Amount of elements</td>
<td>290890</td>
</tr>
<tr>
<td>Thickness of the first wall layer, mm</td>
<td>0.5</td>
</tr>
<tr>
<td>Amount of wall layers</td>
<td>4</td>
</tr>
<tr>
<td>Maximum mesh size, mm</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Numerical simulation of the airflow process in the aerothermopressor was carried out using the finite volume method in the ANSYS Fluent software package. A calculation method was defined based on the Pressure-Based solvers, a turbulence model was selected, a calculation was made taking into account the convergence of results, and the output data were processed and visualized in Postprocessing in the form of graphs, fields and streamlines for the main parameters of the workflow. The calculation of the air flow parameters (total pressure, dynamic pressure, velocity, temperature, etc.) in the aerothermopressor was carried out for a number of confuser and diffuser taper angles, as well as for a number of relative air velocity values in the working chamber $M = 0.4-0.8$.

To study of the air flow behavior, $k-\varepsilon$ Realizable two-parameter turbulence model was used from the group of models Reynolds-Averaged Navier-Stokes (RANS). This model is recommended for axisymmetric flows in jet devices and makes it possible to predict the behavior of the flow propagation velocity and has proven itself in solving engineering problems [13, 14, 15, 16].

To determine the local resistance coefficients for the diffuser and confuser, classical dependences of fluid dynamics [5, 6] were used.

The energy equation (Bernoulli equation for airflow, taking into account mechanical specific losses):

$$\rho g z_1 + p_1 + N_1 \frac{w_1^2}{2} = \rho g z_2 + p_2 + N_2 \frac{w_2^2}{2} + \Delta p_1, \quad (5)$$

where $\rho g z_1$, $\rho g z_2$ – geometric pressure, Pa; $p_1$, $p_2$ – static pressure, Pa; $\Delta p_1$ – total losses of total pressure, Pa; $N_1 \frac{w_1^2}{2}$, $N_2 \frac{w_2^2}{2}$ – dynamic pressure, Pa.

Dividing by $\rho g$:

$$z_1 + \frac{p_1}{\rho g} + N_1 \frac{w_1^2}{2g} = z_2 + \frac{p_2}{\rho g} + N_2 \frac{w_2^2}{2g} + \Delta h_1, \quad (6)$$

$\Delta h_1$ – total head losses, m.

The equation for total pressure is:

$$p_1 = p_1 + N_1 \frac{w_1^2}{2} \quad (7)$$

Taking into account the fact that $z_1 = z_2$ and Eq. (7), the total head losses $\Delta h_1$:

$$\Delta h_1 = \frac{p_1 - p_2}{\rho g} \quad (8)$$

The local resistance coefficient $\zeta$ is:

$$\zeta_i = \frac{2\Delta p_i}{\rho w_i^2} \quad (9)$$

To check the adequacy of the obtained analytical dependencies for the local resistance coefficients, the experimental data given in [4, 9, 17] were used. The experimental data were compared with those ob-
tained during CFD modeling and their relative discrepancy was determined.

4. Results and Discussions

According to the results of computer CFD modeling of models of the aerothermopressor, the value of local resistance coefficients for the diffuser (divergent angle $\beta = 6; 8; 10; 12^\circ$) and confuser (convergent angle $\alpha = 30; 35; 40; 45; 50^\circ$). Initial data at the confuser part inlet of the aerothermopressor: $P_1 = 3 \cdot 10^5$ Pa; $T_1 = 453$ K, $w_{air} = 35$ m/s. It should be noted that the nature of the change in air velocity $w_{air}$ along the length of the flow part is fairly uniform (Fig. 4), and the velocity profiles change almost proportionally (Fig. 5).

![Figure 4](image)

**Figure 4** – Velocity field distribution in the flow part of the aerothermopressor at the inlet velocity to the working chamber $M = 0.4$ (a) and $M = 0.8$ (b).

In addition, the value of local resistance coefficients, both for the confuser $\zeta_c$ and for the diffuser $\zeta_d$, practically do not change when the velocity in the working chamber $M = 0.4-0.8$ (Fig. 6) and Re average value change (Fig. 7). At the same time, for confuser $\zeta_c = 0.02-0.08$, where lower values correspond to the convergent angle $\alpha = 30^\circ$. The influence of the diffuser resistance is more significant $\zeta_d = 0.08-0.32$, where the diffuser with the divergent angle $\beta = 6^\circ$ has a smaller value. The absence of the influence of Re and M on $\zeta_c$ and $\zeta_d$ indicates that there is a self-similar flow regime both in the confuser and in the diffuser of the aerothermopressor, that is, the value of the local resistance coefficient depends only on the geometric parameters (opening angle $\alpha$ and $\beta$, expansion $n_d$ and contraction $n_c$ ratio) of the corresponding channel.

![Figure 5](image)

**Figure 5** – Velocity diagrams distribution over the sections of the flow-through part of the aerothermopressor: $\alpha = 30^\circ$; $\beta = 6^\circ$; $M = 0.6$; $n_c = 6.6$; $n_d = 6.8$; $G_{air} = 0.34$ kg/s; $x$ - distance from the inlet part aerothermopressor

Considering the above, the equation determination for the coefficient of local resistance of the confuser $\zeta_c$ was carried out by the method of approximation depending on the geometric parameters in accordance with a number of equations. In this case, the equations of a paraboloid of rotation were chosen (Fig. 8):
\[ z = y_0 + ax + by + cx^2 + dy^2 \] (10)

or

\[ \zeta_c = \sin(0.3287\sin \alpha - 0.2421) + n_c(7 \cdot 10^{-4} n_c - 0.0063) + 0.0858 \] (11)

parameters, the nature of the flow velocity field, and the prerequisites for the boundary layer separation phenomenon.

**Figure 6** – Dependence of local resistance coefficients \( \zeta \) on the velocity \( M \) at the inlet to the working chamber:

- diffuser: \( \odot \)- 6°; \( \triangle \)- 8°; \( \square \)- 10°; \( \diamond \)- 12°; confuser divergent angle: \( \blacktriangle \)- 30°; \( \bullet \)- 35°; \( \times \)- 40°; \( \bullet \)- 45°; \( \blacksquare \)- 50°.

**Figure 7** – Dependence of local resistance coefficients \( \zeta \) on the average value of \( Re \)

This equation (regression coefficient – \( R = 0.9857 \); \( R^2 = 0.9715 \)) is obtained for the following flow characteristics of the confuser:

\[ 1.2 \cdot 10^5 < Re < 3.4 \cdot 10^5; \]
\[ \alpha = 30-50 \degree; \]
\[ M = 0.4-0.8; \]
\[ n_c = 5.6-8.5. \]

The deviation of the calculated values of the coefficient \( \zeta_c \) from those obtained in the numerical CFD simulation of \( \zeta_{c,c} \) is \( \delta_c = \pm 7 \% \) (Fig. 9).

Determining the local coefficient of resistance of the diffuser \( \zeta_d \) is more difficult due to the influence of ambiguously interconnected geometric and operating

**Figure 8** – Dependence of the coefficient of local resistance of the confuser \( \zeta_{c,c} \) on \( \sin \alpha \) and contraction \( n_c \) ratio (distribution over the surface in accordance with equation (10, 11))

**Figure 9** – Comparison of experimental local resistance coefficients \( \zeta_{c,c} \) in confuser with calculated \( \zeta_c \)

It should be noted that the prerequisites for the occurrence of the separation of the boundary layer occur in almost all modes of operation of the aerothermo-pressor. So, for example, when \( M \geq 0.4 \), additional flow turbulence occurs in the boundary layer of the diffuser (Fig. 10, a), at a diffuser divergent angle \( \beta \geq 12 \degree \) (Fig. 10, b) the flow turbulence increases so that in the near-wall zone reverse air flow occurs. As a result, a flow separation occurs in the boundary layer (Fig. 11), which, in turn, leads to a sharp increase in the value of the local drag coefficient \( \zeta_d \).

Considering the above, the equation determination for the coefficient of local resistance of the diffuser \( \zeta_d \)
was carried out by the method of approximation depending on the geometric parameters in accordance with a number of equations. In this case, the equations of a paraboloid of rotation were chosen (Fig. 12):

\[ \zeta_d = \sin \beta (0.428 + 6.4174 \sin \beta) + n_d (0.0142 - 7 \times 10^{-4} n_d) \cdot 0.0794 \]  

(12)

This equation (regression coefficient – R = 0.9828; \( R^2 = 0.9659 \)) is obtained for the following flow characteristics of the diffuser:

- \( 1.2 \cdot 10^5 < \text{Re} < 3.4 \cdot 10^5 \);
- \( \beta = 4-12^\circ \);
- \( \alpha = 40^\circ \);
- \( M = 0.4-0.8 \);
- \( n_d = 4.4-8.7 \).

The deviation of the calculated values of the coefficient \( \zeta_d \) from those obtained in the numerical CFD simulation of \( \zeta_{e,d} \) is \( \delta = \pm 10\% \) (Fig. 13).

When comparing the calculated data obtained by equation (12) with the experimental data obtained in [9, 17], one can see (Fig. 14) that the equation given for the diffuser gives a value with an allowable error (\( \delta = \pm 20\% \)) in the range of angles disclosures \( \beta = 6-12^\circ \). At \( \beta = \geq 12^\circ \), the calculated values of \( \zeta_d \) significantly exceed the experimental ones.
The total pressure losses in the aerothermopressor due to the aerodynamic resistance are determined by the equation:

$$\Delta P_{\text{loss}} = \Delta P_1 + \Delta P_2 = \left( \zeta_\text{a} + \zeta_\text{d} + \zeta_\text{diff} \right) \frac{\rho w_{\text{mix}}^2}{2},$$

(13)

$w_{\text{mix}}$ – flow velocity in the working chamber;
$\zeta_\text{a}$, $\zeta_\text{d}$ – coefficients of local resistance in the confuser and diffuser in accordance with the equations (11), (12); $\zeta_\text{diff} = \lambda_\text{fr} = \text{coefficient of friction losses in the working chamber}$, which can be determined by Blaussius [6, 8]:

$$\lambda_\text{fr} = \frac{0.3164}{\text{Re}^{0.25}},$$

(14)

**Figure 14** – Comparison of the experimental coefficients of local resistances $\zeta_d$ in the diffuser with the calculated ones depending on the angle of taper $\beta$:
- - - - - calculated curve according to equation (12)
■ - Experimental $\zeta_d$ with $n_d = 4$ and $M = 0.4$ according to the data given in [9, 17]

Analysis of the calculated data according to equation (14) shows that the total pressure loss in the "dry" aerothermopressor (without injection of liquid for evaporation) is $\Delta P_{\text{loss}} = 0.05\cdot100\cdot10^5 \text{ Pa} (2-31\%)$ at a fixed confuser convergent angle $\alpha = 40^\circ$ and variable diffuser angle $\beta = 4-14^\circ$ (Fig. 15). At a fixed divergent angle of the diffuser $\beta = 6^\circ$ and variable angles of the confuser is $\alpha = 30-50^\circ$ - $\Delta P_{\text{loss}} = 0.05\cdot0.40\cdot10^5 \text{ Pa} (1-12\%)$ (Fig. 16). It can be concluded that the effect of a change in the diffuser divergent angle is greater than the influence of the confuser convergent angle. At the same time, we can recommend angles $\alpha = 30^\circ$ and $\beta = 6^\circ$ for the low-flow aerothermopressor, corresponding to the minimum pressure losses $\Delta P_{\text{loss}} = 1.0-9.5 \%$, and therefore to the maximum pressure increase as a result thermosdynamic compression during injection and evaporation of fluid in the working chamber.

Numerical simulation to determine the total pressure losses in the aerothermopressor shows that with $M = 0.6$, $\alpha = 30^\circ$, $\beta = 6^\circ$ - $\Delta P_{\text{loss}} = 0.2\cdot10^5 \text{ Pa} (6.6\%)$ (Fig. 17). Thus, it can be seen that the calculated data fully correspond to the results of CFD modeling, and the obtained equations for determining the local resistance coefficients can be recommended for use in the low-flow aerothermopressor design method.

**Figure 15** – Dependences of total pressure loss $\Delta P_{\text{loss}}$ in the "dry" aerothermopressor in absolute (a) and relative (b) values on the air velocity $M$ in the working chamber at different diffuser divergent angles $\beta$
5. Conclusions

1. The empirical equations for determining the coefficients of local resistance of the confuser $\zeta_c$ and diffuser $\zeta_d$ of the low-flow aerothermopressor are determined. The given results correspond to the following mode and geometrical characteristics $1.2 \cdot 10^5 < Re < 3.4 \cdot 10^5$; $\alpha = 30-50^\circ$; $\beta = 4-12^\circ$; $M = 0.4-0.8$; $n_c = 5.6-8.5$; $n_d = 4.4-8.7$.

2. The numerical values of local resistance coefficients was determined by using computer CFD modeling at $M = 0.4-0.8$; $\zeta_c = 0.02-0.08$ and $\zeta_d = 0.08-0.32$.

3. The recommended angles were determined: confuser convergent angle $\alpha = 30^\circ$ and diffuser divergent angle $\beta = 6^\circ$, corresponding to the minimum pressure loss $\Delta P_{loss} = 1.0-9.5\%$, and therefore also to the maximum pressure increase as a result of the thermogasdynamic compression that occurs during injection and evaporation of liquid in the working chamber.

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Чисельне моделювання впливу режимних і геометричних характеристик на втрати тиску маловитратного аеротермопресора

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В роботі досліджуються гідрогазодинамічні процеси, які протікають в маловитратному аеротермопресорі. Цей струмінний апарат представляє собою двофазовий струмінний пристрій для контактного охолодження, в якому за рахунок відведення тепліз із газового потоку відбувається зменшення температури газу та його охолодження (термогазодинамічна компресія). Високоекофективна робота аеротермопресора залежить від конструкції проточної частини та способу розподілу потоку води в апараті. Конструктивні чинники, які впливають на втрати енергії для подолання сил тertia та місцевих опорів на звужувально-розширювальних ділянках аеротермопресора, здійснюють значний вплив на робочі процеси в апараті. В роботі проведено дослідження ряду типових моделей аеротермопресора маловитратного комп'ютерного CFD-моделювання. Визначення основних параметрів потоку повітря (повний тиск, динамічний тиск, швидкість, температура та ін.) проводилось для ряду кутів конусності конфузора і дифузора, а також для ряду значень відносної відкритості повітря в робочій камері $M = 0.4 – 0.8$. Проведено порівняння отриманих даних з експериментальними. Відхилення розрахункових значень коефіцієнтів місцевих опорів в конфузорі та в дифузорі від отриманих при комп'ютерному CFD-моделюванні не перевищує 7-10 %. Таким чином, отримані аналітичні залежності для визначення коефіцієнтів місцевого опору для конфузора (спол) і дифузора, які можна рекомендувати для використання в методиці проектування аеротермопресорів маловитратних.

Ключові слова: Аеротермопресор, Коефіцієнти Місцевих Опорів, CFD-моделювання

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