ISSN 0018-151X, High Temperature, 2014, Vol. 52, No. 1, pp. 12–18. © Pleiades Publishing, Ltd., 2014.
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Exploring Ways to Improve Efficiency of Gasdynamic Energy Separation

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Received February 22, 2013

Abstract—This work is devoted to research into ways to improve the efficiency of gasdynamic energy separation in the pipe Leontiev. It is shown that restoring the coefficient of temperature *r* depending on the Prandtl number Pr has the greatest impact on the magnitude of energy separation. The conducted analysis showed that for a gas with Pr = 0.7 the most promising ways to improve the efficiency of gasdynamic energy separation are the partial condensation of the working body and the use of regular relief that is deposited onto the wall of the supersonic channel in the pipe Leontiev. We have performed a modification of the calculation method and its verification using experimental data obtained on natural gas. The results of numerical modeling have shown that the use of regular relief (dimples) in this class of devices is effective.

DOI: 10.1134/S0018151X14010064

INTRODUCTION

It is known that the intensity of heat exchange between gas and streamlined surface is proportional to the magnitude of temperature difference between the wall and the gas flow. In the case of a compressible gas, this magnitude is equal to the difference between the restoring temperature on the wall and the initial temperature of the wall.

The restoring temperature on the wall for a gas with constant heat capacity is given by [1]

$$T_W^* = T + r\frac{W_0^2}{2C_p} = T\left(1 + r\frac{k-1}{2}\mathrm{M}^2\right) = T^*\left[1 - (1-r)\frac{k-1}{k+1}\lambda^2\right]. \quad (1)$$

In (1), $T^* = T + \frac{W_0^2}{2C_p}$ is the braking temperature of the flow; $r = \frac{T_W^* - T}{T^* - T}$ is the restoring coefficient of temperature; W_0 is the velocity of the flow; C_p is the isobar heat capacity; T is the static (thermodynamic) temperature; k is the adiabatic index; $\mathrm{M} = W_0/a_\mathrm{s}$ is the Mach number (a_s is the local velocity of sound); $\lambda = W_0/a_\mathrm{cr}$ is the reduced velocity and a_cr is the critical velocity.

The restoring coefficient of temperature r determines the share of kinetic energy that is transformed into heat on the wall [1]. When the intensity of heat release owing to the work of frictional force on the wall exceeds the intensity of heat removal from the wall in the flow of gas at a given temperature, we have $\mathrm{Pr} > 1$ and $r > 1$, while in the opposite case when heat removal dominates, we have $\mathrm{Pr} < r$ 1 and $r < 1$.

A particular distribution of the restoring coefficient of temperature over the thickness of the boundary layer in the case of compressible gas flowing around a thin plate was already noted in 1942 [2]. The method for temperature separation by Leontiev is based on this effect. He also proposed a device to implement this method which is referred to as "Leontiev's" tube (LT) [3, 4].

The limiting estimations of the maximum possible increase in the braking temperature of the flow were discussed in [5]. In [6, 7], a method for calculating the effect of gasdynamic temperature separation in Leontiev's tube was proposed on the base of one-dimensional gasdynamic equations.

The impact of different factors on the effect of gasdynamic temperature separation was discussed in [8–11]. In these works, it was shown that the strongest influence on the effectiveness of operation of this class of devices is exerted by restoring temperature coefficient *r*. When gas flows around an impermeable body with a given shape, this coefficient is a function of five variables: the Prandtl number and the turbulent Prandtl number, the adiabatic index, the Reynolds and the Mach numbers, while the strongest impact on the flow is exerted by the Prandtl number [4–11].

The data numerically calculated by the method from [6, 7] were compared to the data obtained on natural gas in [12]. Later, the calculation method was modified and verified in [13, 14] using experimental data corresponding to natural gas and water.

The conducted analysis showed [4–14] that for the majority of gases and mixtures (at $\mathrm{Pr} \approx 0.7$) the most promising ways to improve efficiency of gasdynamic stratification are partial condensation of working body and the use of rational wall shape of the supersonic

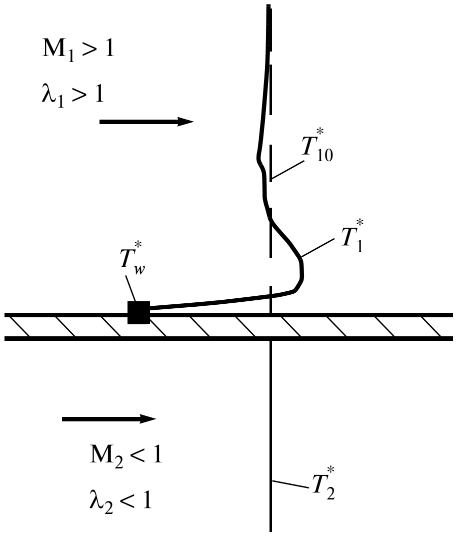

Fig. 1. Scheme of the effect of gasdynamic temperature separation.

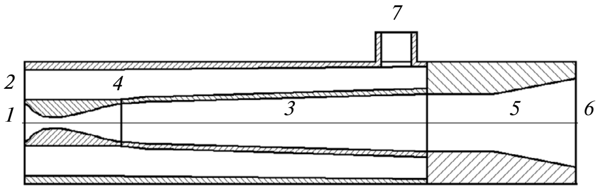

Fig. 2. The principal scheme of the device for gasdynamic temperature separation (LT): *1*, entrance to the supersonic channel; *2*, entrance to the circular subsonic channel; *3*, supersonic channel; *4*, circular subsonic channel; *5*, diffuser; *6*, output from the supersonic channel; *7*, output from the subsonic channel.

channel, and regular relief (dimples) infliction onto the wall. To date, there are many works devoted to numerical and physical (see [15–19] for example) investigations of the effect of regular relief on the temperature restoration and thermal conductivity coefficients. Moreover, the temperature gradient that appears on the surface with dimples can additionally stimulate the formation of vortex structures [20, 21] causing additional intensification of the heat exchange.

The aim of this work is to reveal ways to increase the effectiveness of the devices in which the mechanism of gasdynamic temperature separation is used and to improve the calculation methods.

WAYS TO IMPROVE THE EFFICIENCY OF ENERGY SEPARATION

The principal scheme of gasdynamic temperature separation is shown in Fig. 1. Two gas flows are separated by a wall. The supersonic and subsonic gas flows are shown respectively on the top and bottom sides of the figure, and their parameters are designated by subscripts 1 and 2. Initially, the braking temperatures of the flows are assumed to be equal. In the initial section from the side of the subsonic flow, the epure of braking temperature T_2^* is constant, while from the side of the supersonic flow the epure of braking (restoring) temperature T_1^* is modified. In this case, the mean integral braking temperature T_{10}^* in the boundary layer is constant. In this situation, provided that the initial braking temperatures are equal ($T_{10}^* = T_2^* = T^*$), on the separating wall arises temperature load given by

$$\begin{aligned}\Delta T = T_2^* - T_W^* = T^* - T^*\left[1-(1-r)\frac{k-1}{k+1}\lambda_1^2\right] \\ = T^*(1-r)\frac{k-1}{k+1}\lambda_1^2.\end{aligned} \tag{2}$$

One can see from (2) that an increase in the reduced subsonic flow velocity λ_1 leads to increasing temperature difference between the subsonic and supersonic flows of gas. However, for the flows in the channel with a given braking pressure at the input, growth of the velocity of the supersonic flow leads to a decrease in static pressure and, accordingly, thermal conductivity coefficient from the side of supersonic flow. In other words, there is an optimal velocity of the supersonic flow at which the amount of heat transferred from the subsonic to the supersonic flow takes maximum value.

Figure 2 shows the principal scheme of the device implementing the effect of gasdynamic temperature separation [3, 4].

Let us write the system of equations reported in [6 7] to describe gasdynamic temperature separation in LT. This system was derived under the condition of a constant cross-sectional area of a subsonic channel (*4* in Fig. 2). Parameters with indexes 1 and 2 correspond to the supersonic and subsonic flows, respectively. The lower index H corresponds to the initial section (parameters before LT), and index F corresponds to the final section; index 0 corresponds to standard conditions.

$$\begin{gathered}\left(\frac{\lambda_1^2-1}{\lambda_1^2}\right)\frac{d\lambda_1}{\lambda_1}+\left(\frac{\lambda_1^2+1}{\lambda_1^2}\right)\frac{d\theta_1}{2\theta_1} \\ =\left(\frac{1}{\lambda_1^2}-\frac{k-1}{k+1}\right)\frac{dF_1}{F_1}-\xi_1\frac{k}{k+1}\sqrt{\frac{F_{1H}}{F_1}}d\overline{x}, \\ \left(\frac{\lambda_2^2-1}{\lambda_2^2}\right)\frac{d\lambda_2}{\lambda_2}+\left(\frac{\lambda_2^2+1}{\lambda_2^2}\right)\frac{d\theta_2}{2\theta_2}=-\xi_2\frac{k}{k+1}d\overline{x}, \\ \frac{d\theta_1}{\dfrac{K}{\alpha_1}\left[(m+1)-\theta_1\left(\dfrac{T_W^*}{T_1^*}+m\right)\right]}=\sqrt{\frac{F_{1H}}{F_1}}\frac{\xi_1}{2}f(\mathrm{Pr})\,d\overline{x},\end{gathered} \tag{3}$$

Table 1. Natural gas composition used in numerical studies

Component	Mass fraction of component, %
Methane	97.693
Ethane	0.415
Propane	0.573
Isobutane	0.147
Normal butane	0.165
Isopentane	0.018
Normal pentane	0.009
Hexane	0.037
Nitrogen	0.944

$$d\theta_2 = m d\theta_1,$$

$$d\bar{F}_1 = 2\left[1+\left(\sqrt{\frac{F_{1H}}{F_{1F}}}-1\right)\frac{x_1}{L}\right]\frac{D_{1H}\left(\sqrt{\frac{F_{1F}}{F_{1H}}}-1\right)}{L}d\bar{x},$$

where $\lambda_1 = W_1/a_{\text{cr}1}$ and $\lambda_2 = W_2/a_{\text{cr}2}$ $\lambda_1 = W_1/a_{\text{cr}1}$ and $\lambda_2 = W_2/a_{\text{cr}2}$ are the reduced velocities of the supersonic and subsonic gas flows; $\theta_1 = T_1^*/T_{1H}^*$ and $\theta_2 = T_2^*/T_{2H}^*$ are the corresponding braking temperatures; T_{1H}^* and T_{2H}^* are the braking temperatures of the supersonic and subsonic gas flows at the input of LT; F_{1H}, F_{1F}, F_1 are the initial, final, and current cross-sectional areas of the supersonic channel in LT; $\xi_1 = \xi_{10}\sqrt{1-\frac{k-1}{k+1}\lambda_1^2}$ and $\xi_2 = \xi_{20}\sqrt{1-\frac{k-1}{k+1}\lambda_2^2}$ are the drag coefficients of the supersonic and subsonic channels under standard conditions; ξ_{10}, ξ_{20}; $\bar{x} = x_1/D_{1H}$ and x_1 are the relative and absolute longitudinal coordinates of the supersonic channel in LT; D_{1H} and L are, respectively, the initial diameter and the length of the supersonic channel in LT; $m = G_1/G_2$ is the ratio of the mass flow rates of the supersonic and subsonic gas flows; $f(\text{Pr})$ is the correction to the Prandtl number (see [22] for more detail); and K/α_1 is the ratio of the coefficient of heat transfer from the subsonic to the supersonic flow to the convective heat transfer coefficient from the side of the supersonic flow. Following [22], this ratio can be represented in the form

$$\frac{K}{\alpha_1} = \frac{1}{1+m^{0.8}\frac{D_2^2-(D_1+2h)^2}{D_1^{1.8}(D_1+2h)^{0.2}}\left(\frac{T_1}{T_2}\right)^{0.15}\left[\frac{D_1}{b(D_1+h)}+\frac{D_1}{D_1+2h}\right]},$$

where D_1 and D_2 denote the current diameters of the supersonic and subsonic channels in LT; T_1 and T_2 are the corresponding static temperatures of the supersonic and subsonic gas flows; h is the wall thickness separating the supersonic and subsonic gas flows; and b is the correction factor to account for thermal conductivity of the wall [22].

Let us analyze the possible ways to increase the energy separation efficiency. In system (3) that was obtained in [6, 7], the restoring coefficient of temperature r is set explicitly when calculating T_W^*. When carrying out numerical studies, this value is set from the beginning of the calculation and does not vary later.

Among factors affecting the magnitude of the restoring coefficient of temperature that were not taken into account in this calculation method, one can point to the possibility of deposition of the condensate in a supersonic channel. One more factor is the creation of regular vortex-forming relief (dimples) on the wall of the supersonic channel, which may change the magnitude of the restoring coefficient of temperature and has considerable impact on the magnitude of friction and heat transfer coefficients.

By using the data on the influence of regular relief on the magnitudes of heat transfer and temperature restoring coefficients [15–19], one can estimate an increase in the amount of heat transferred from subsonic to supersonic gas flow due to the increasing convective heat transfer coefficient and the decreasing restoring coefficient of temperature.

Let us estimate the impact of condensation in a supersonic channel on the restoring coefficient of temperature with verification according to the experimental data [12–14], obtained on natural gas (upon condensation of higher hydrocarbons).

We will perform the calculation for the Leontiev's tube in the case of natural gas flow under conditions close to the conditions of exploitation of the devices proposed in [23–25]. In our calculations of gasdynamic separation, the natural-gas composition corresponds to the data [12] (see Table 1), while the thermal-physical properties of its components are determined as in [26]. The effect of a second phase on the hydrodynamics of an axisymmetric flow can be estimated using the data of [27].

MODIFICATION OF THE METHOD OF LT CALCULATION

We will adopt the assumption of mutual independence of the above factors, as well as the fact that condensation occurs within the condensation shock. The modernization of the calculation procedure is carried out under the assumption that all the calculations are carried out for the equilibrium parameters, whereas the thermo-physical and transport properties of the mixture are recalculated to the new composition of the gaseous medium.

Since it is difficult to account properly the effect of condensation in the supersonic channel on the restoring coefficient of temperature from the very beginning, this is performed by an iterative procedure. On the first iteration, the calculation is carried out by the method of [6, 7], when the parameters of distribution in the supersonic channel are computed with allowance for the condensation of components of the gaseous mixture flowing in the supersonic channel. Moreover, the magnitude of the restoring coefficient of temperature is taken as recommended in [8–11] without allowance for condensation.

Further on, the intensity of mass flow of the condensate onto the wall and the corresponding decrease in the restoring coefficient of temperature in the supersonic channel are computed. After that, the calculation of energy separation with allowance for condensate evaporation on the wall and a decrease in the concentration of condensed gaseous components in the flow are performed using a new value of the restoring coefficient of temperature. Finally, the restoring coefficient of temperature is corrected once again and a new calculation is carried out.

The effect of condensation of some components in the working mixture on the value of the restoring coefficient of temperature is taken into consideration by the methodology described below.

Assessing the Mass Flow of the Condensate on the Wall

Write the equation for the Stanton diffusion number

$$\mathrm{St}_D = \frac{j_W}{\rho_0 W_0 (C - C_W)} = \frac{\xi}{8}, \tag{4}$$

where j_W is the mass flow of the condensate onto the wall; ρ_0 is the density of gas flow; C and C_W are the mass concentrations of the condensate in the gas flow and on the wall, and ξ is the friction coefficient. In further calculations, we assume that the drops of condensate adhere to the wall when they fall on it (i.e., the condition $C_W = 0$ is fulfilled).

Assume that the supersonic channel has a cylindrical cross section with a diameter D_1 in the limits of the integration domain (the value of D_1 varies when we pass to the next domain of integration [6, 7]). We perform the estimation for the laminar regime of the flow assuming that the friction coefficient is given by [6]

$$\xi = \frac{64\mu_0}{\rho_0 W_0 D_1}\sqrt{1 - \frac{k-1}{k+1}\lambda^2}, \tag{5}$$

where μ_0 is the kinematic viscosity of gas.

By transforming Eq. (5) and using the values $k = 1.31$ and $\lambda \approx 1.8$ (the conditions that are close to the data [12–14]), the friction coefficient is given by

$$\xi = \frac{64\mu_0}{\rho_0 W_0 d}\sqrt{1 - \frac{k-1}{k+1}\lambda^2} \approx \frac{48\mu_0}{\rho_0 W_0 D_1}. \tag{6}$$

With allowance for Eq. (6), Eq. (4) takes the form

$$j_W = \frac{\xi}{8}\rho_0 W_0 C \approx \frac{6\mu_0 C}{D_1}. \tag{7}$$

The amount of condensate m_1, deposited onto the wall per unit time within the length x_1 can be determined by the formula

$$m_1 = \int_0^x \pi D_1 j_W dx_1. \tag{8}$$

For the estimation we assume that the mass concentration of condensate in the flow of gas is constant, i.e., $C = C_0 = \mathrm{const}$ and the film of the condensate is not evaporated from the surface. Then, substituting (7) into (8) and integrating yields

$$m_1 = 6\pi\mu_0 C_0 x_1. \tag{9}$$

Assessment of the Restoring Coefficient of Temperature with Allowance for Condensation

Assume that the temperature of drops is equal to the thermodynamic temperature of gas in the given cross section. The condensate mass m_2, (which is deposited per unit time) that is necessary for the formation of a continuous film of condensate with thickness h_1, can be determined by the formula

$$m_2 = \pi D_1 h_1 \rho_L W_L, \tag{10}$$

where ρ_L and W_L are the density and velocity of the film of condensate.

Combining Eqs. (9) and (10), we estimate the length of the channel necessary for the formation of a continuous film of condensate on the surface of supersonic LT channel

$$x_1 = \frac{D_1 h_1 \rho_L W_L}{6\mu_0 C_0}. \tag{11}$$

When considering the Nusselt problem (for high velocities of gas flow), one can write the equation for the flow of the condensate film in the form

$$\tau \approx \frac{\xi}{8}\rho_0 W_0^2 = \tau_W, \tag{12}$$

where τ is the tangential stress, $\tau_W = \mu_L dW_L/dy$ is the tangential stress on the wall, μ_L is the kinematic viscosity of condensate, and y is the transverse coordinate.

By rewriting Eq. (12) with allowance for (6), we obtain

$$\frac{dW_L}{dy} = \frac{6W_0}{d}\frac{\mu_0}{\mu_L}.$$

Integrating and transforming this equation yields

$$W_L = 6\frac{h_1}{D_1}W_0\frac{\mu_0}{\mu_L}. \tag{13}$$

After substituting (13) into (11) and transforming, we obtain

$$x_1 = \frac{\rho_L W_0 h_1^2}{\mu_L C_0}.$$

This expression represents a limiting estimation for the lower-bound length of a supersonic channel in LT, which is necessary for the formation of a continuous condensate film. The necessary length can be larger provided that the concentration of a condensed component in the flow of gas decreases and the film evaporates from the surface of the channel. An analogous assessment can be carried out in the case of a turbulent regime of the flow, but it is impossible to obtain an analytical solution.

The average value of the restoring coefficient of temperature can be determined by integrating distribution *r* over the area of the wall of the supersonic channel and assuming that the restoring coefficient of temperature equals zero within the domains with continuous film of condensate. In the absence of the film, the average restoring coefficient of temperature is determined as recommended in [8–11].

As follows from the calculations, a rather good agreement with experimental data [12–14] is obtained at drops diameter of 50 μm and the same minimal thickness *h* of the film.

Accounting for the Effect of Regular Relief

As the analysis of works on the studies of heat exchange and friction on the surfaces with regular relief shows (see [15–19], for example), the results of numerical study of the intensification of heat exchange on the surfaces with relief are controversial to some extent and depend strongly on the calculation methods and models of turbulence that are implemented. The use of experimental data cannot give an unambiguous result since the data are fragmentary and do not allow us to obtain empirical dependences to describe the friction and heat exchange for the surfaces with regular vortex-forming relief in the supersonic flow.

We improve the method of LT calculation by introducing empirical corrections that take into account the influence of regular relief in the supersonic channel of LT on the coefficients of the thermal conductivity, friction, and restoring coefficient of temperature. Moreover, we neglect the impact of the change in the surface area due to the introduction of regular relief.

For a correct account of the effect of regular relief on the intensification of heat exchange and friction, we will accept the corrections obtained using the experimental data [17]. For a surface with regularly arranged shallow hemispherical dimples (with depth of 1 mm, diameter of 7 mm, and corridor arrangement with steps of 20 and 11.5 mm along the flow and across it, respectively) [17], the increase in the drag coefficient is ~1.7 times in comparison with a smooth surface when the surface is streamlined by the supersonic flow. In this case, one can note an increase in the intensity of heat transfer by ~1.2 times and a decrease in the restoring coefficient of temperature by 3% as compared to a smooth surface. These corrections will be taken into consideration in the form of correcting empirical coefficients.

THE RESULTS OF RESEARCH USING AN IMPROVED CALCULATION METHOD

We set the initial and boundary conditions in numerical calculations using the data taken from [12–14]: the Mach numbers at the entrance to the working section of the supersonic and subsonic channels of LT are 3 and 0.1, respectively; the absolute pressures at the entrance and exit points of LT are 4 and 0.4 MPa, respectively; the friction coefficient under the standard conditions is $\xi_0 = 0.01$; and the Prandtl number is 0.7. Additionally, we accept the condition that the mass flows in subsonic and supersonic channels are equal and the length of the working part of the supersonic channel cannot exceed 1500 nm.

All the calculations are carried out under the condition that braking of the gas flow at the end of the supersonic channel occurs in a direct compression shock. This leads to considerable losses in the total pressure (a greater degree of pressure decrease in the supersonic channel). The calculation showed that the longitudinal effect of thermal conductivity of the walls of the supersonic channel can be neglected in our device.

By analogy with [12–14], we represent numerical results in the form of the dependence of the change of natural gas enthalpy in the supersonic channel of LT (Δh_1) versus the degree of pressure decrease in the supersonic channel with allowance for the losses in the direct compression shock in the diffuser (π_Σ). The analysis of the increase in natural gas enthalpy is more correct than that of temperature owing to the throttling effect that is observed when decreasing the natural gas pressure. Correspondingly, the temperature of natural gas in the supersonic channel of LT is affected by the heat input from the subsonic channel of LT and the temperature change due to the Joule-Thomson effect, since the latter leads to a decrease in the temperature for a given range of parameters.

Figure 3 shows the graph of the change of natural gas enthalpy in the supersonic channel of LT depending on the degree of pressure decrease involved. Curve corresponds to the calculation performed by the method of [6, 7] for the natural gas composition listed in Table 1. Curve *2* shows the calculation result for the same natural gas composition using an improved method with allowance for the effect of condensation of higher hydrocarbons. Experimental values were taken in accordance with [12, 13] and correspond to the curves *1* and *2*. Curve *3* shows the calculation using an improved method with allowance for the effect of condensation of higher hydrocarbons and relief (as in [17]) on the wall of the supersonic channel of LT.

As we can see from these data, the increase in the natural gas entropy (curve *2* in Fig. 3) obtained using the improved method with allowance for the condensation of higher hydrocarbons is higher than the experimental one [12, 13]. This deviation can be explained by the presence of a system of oblique compression

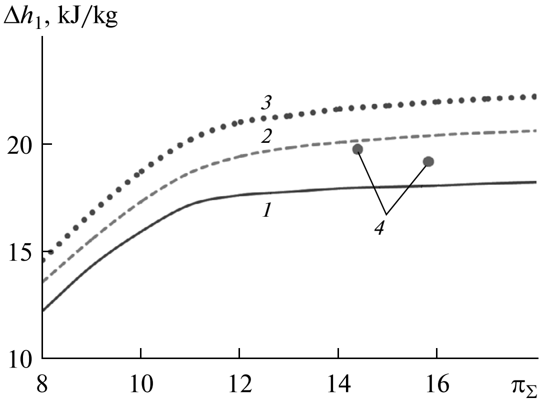

Fig. 3. The effect of the total decrease of pressure in a supersonic channel on the increase of natural gas enthalpy for a "thick" plate: *1*, calculation [6, 7]; *2*, calculation with allowance for condensation; *3*, calculation with allowance for condensation and relief on the wall of supersonic channel; *4*, experiment [12, 13].

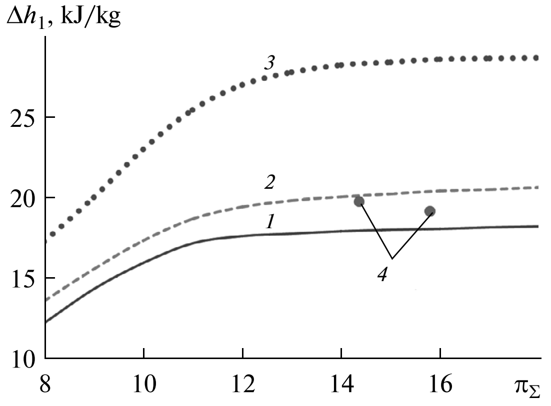

Fig. 4. The effect of total decrease of pressure in the supersonic channel and the thickness of the wall of the supersonic channel upon an increase in the natural gas enthalpy: *1*, *2*, the same as in Fig. 3; *3*, the same as for *2*, but with reduced thickness of the wall of the supersonic channel; *4*, experiment [12, 13].

shocks in the supersonic channel that was observed in the course of experimental studies. An analogous picture is obtained for the other initial data sets taken in accordance with works [12–14]. From this we can conclude that the improved method of LT calculation is correct.

Intensification of heat exchange by creating regular relief (dimples) on the surface of the wall of the supersonic channel (curve *3* in Fig. 3) resulted in a slight growth in the LT efficiency. This can be explained by the fact that a considerable contribution in the heat transfer coefficient of the device tested on the polygon [12–14] stems from the thermal resistance of the wall of the supersonic LT-channel.

This assumption is confirmed by the results of studying the analogous device made of 12Cr18Ni10T steel and tested on a polygon [12–14] having a smaller thickness of the wall of the supersonic channel.

The results of these investigations are shown in Fig. 4. Curves *1*, *2* and experimental points *4* correspond to those shown in Fig. 3. Curve *3* in Fig. 4 was plotted at an average thickness of the wall of the supersonic channel of 4 mm (which ensures the necessary safety factor), made of 30CrMnSiA steel. In our calculations for 12Cr18Ni10Ti and 30CrMnSiA steels, the thermal conductivities are given in Table 2.

As we can see from the data in Fig. 4, a decrease in the thickness of the wall of the supersonic channel of LT and the use of material with higher thermal conductivity allows one to increase considerably the amount of heat transferred from subsonic to supersonic gas flow.

Figure 5 shows the results of numerical studies of the effect of thickness and thermal conductivity of a material of the wall of the supersonic channel and the presence of intensifiers of heat exchange (dimples) on the increase in natural gas enthalpy in the supersonic channel. The use of heat exchange intensifiers in the form of hemispherical dimples allows us to increase the amount of heat transferred from the subsonic to the supersonic gas stream by 10–15% at a given length of the channel. This is caused by two factors: a decrease in the restoring coefficient of temperature and an increase in the convective heat transfer coefficient from the side of the supersonic flow.

In addition, it is necessary to note that the influence of regular relief in the form of hemispherical dimples proves to be considerably stronger upon a decrease in the thickness of the supersonic channel wall and the use of material with a higher thermal conductivity than in the experiments [12–14]. On the basis of these calculations, we can reach a conclusion on the feasibility of application of regular relief in the form of hemispherical dimples on the wall surface of the supersonic channel in devices that use the gasdynamic effect of temperature separation [22–25].

CONCLUSIONS

We have improved the calculation scheme of gasdynamic temperature separation, allowing us to take into consideration the impact of higher hydrocarbons on the restoring coefficient of temperature for gas flows in

Table 2. Thermal conductivity of steels used in calculations

Material	Material properties	T, °C			
		20	100	200	300
12Cr18Ni10Ti	λ, W/(m °C)	15	16	18	19
30CrMnSiA		38	38	37	37

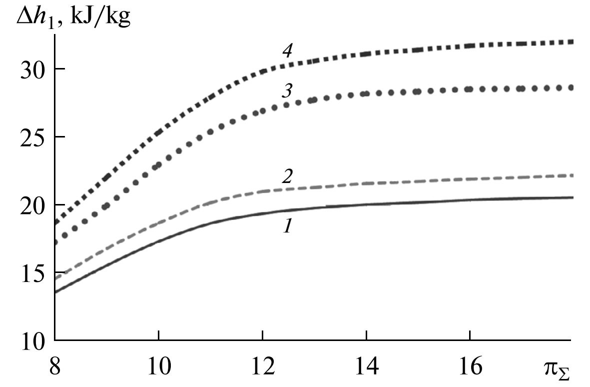

Fig. 5. The impact of the total decrease of pressure in the supersonic channel, the wall thickness of the supersonic channel and the presence of intensifiers upon the increase of natural gas enthalpy: *1*, *2*, the same as in Fig. 3; *3* the same as for *2* but with reduced thickness of the wall of the supersonic channel; *4*, the same as for *2* but with a reduced thickness of the supersonic channel wall and presence of the relief.

a supersonic channel. Empirical correction coefficients were introduced in the method of calculation, which allowed us to take into account the effect of regular relief in the form of hemispherical dimples on the growth of the heat transfer and drag coefficients, and the decrease in the restoring coefficient of temperature. Verification of the results of numerical calculation was carried out using the data obtained for natural gas.

Using the improved calculation technique, we studied a device for the gasdynamic temperature separation in the presence of intensifiers of heat transfer in the form of hemispherical dimples on the wall surface of a supersonic channel. We have shown that the use of intensifiers of heat transfer allows us to increase the amount of heat transferred from subsonic to supersonic gas flow.

ACKNOWLEDGMENTS

This work was supported by the Russian Foundation for Basic Research (project nos. 11-08-00152-a and 11-08-00750-a) and a Grant for Leading Scientific Schools (project no. NSH-6495.2012.8).

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Translated by G. Dedkov