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TECHNICAL PHYSICS

Intensification of Heat Exchange in a Device for Gas-Dynamic Energy Separation

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Abstract—The operating efficiency of a gas-dynamic energy-separation device is analyzed, and it is shown that it can be improved if we deposit a regular relief on the wall separating the supersonic and subsonic channels. To decrease the total pressure losses on the side of the supersonic channel, shallow spherical dimples (stampings) are deposited, creating spherical ledges in the subsonic channel because of the small thickness of the wall. The calculation technique is modernized, and modeling is carried out, which shows that by introducing intensified heat exchange, it is possible to improve the efficiency of this device by 1.2–1.4 times in air and in natural gas with a simultaneous decrease in the device size by 20–25%.

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In nature, it is possible to find various examples of the energy-separation process in gas flows. It can arise due to vortex motion, pressure pulsations, or an imbalance in the quantities of heat released and removed. Some of these phenomena have been applied in various technical devices intended for an instrumental (machine-free) method of obtaining energy separation [1].

A device for gas-dynamic energy separation is proposed in [2], and a schematic drawing of it is seen in Fig. 1. The operating principle of this device is based on the imbalance arising in compressed-gas flows between the quantity of heat released near the wall due to the work of friction forces and the quantity of heat that can be removed into the gas flow by the heat-conduction mechanisms at this temperature.

In [3, 4], the limiting estimates are established, which show that the efficiency of this device first of all is determined by the value of temperature-recovery coefficient r. The experimental works on natural gas [5], air [6], and inert-gases mixtures [7] made it possible to verify the results of the numerical investigations performed by the method described in [8]. However, the efficiency of this class of devices proved to be low for the majority of gases because the value of the energy separation is determined significantly by the temperature-recovery coefficient r.

For gases with a value of the Prandtl criterion in the range of 0.6–2.0, the temperature-recovery coefficient is described well by the expression $r = \sqrt{\text{Pr}}$ for the laminar mode of flow and by $r = \sqrt[3]{\text{Pr}}$ for turbulent flow in the range of 0.5–2.0. In this case,

$$\text{Pr} = \frac{\mu C_p}{\lambda},$$

where C_p is the heat capacity of gas at constant volume, μ is the coefficient of kinematic viscosity, and λ is the coefficient of heat conductivity.

Analysis showed that it is possible to improve the efficiency of the device either by using a mixture with a low value of the Prandtl criterion [9] as the working body or by using in addition the mechanism of vortex energy separation [10].

A third way of improving the efficiency of the energy-separation device could be deposition of a vortex-forming regular relief (dimples) on the surface separating supersonic channel *3* from the circular subsonic channel *4* (Fig. 1) because this relief provides smaller pressure losses [12] at a comparable (with

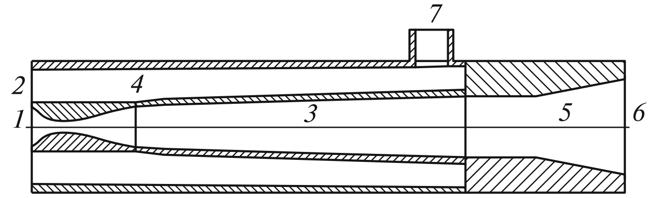

Fig. 1. Schematic drawing of the gas-dynamic energy-separation device: *1,* input into the supersonic channel, *2*, input into the circular subsonic channel, *3,* supersonic channel, *4,* circular subsonic channel, *5,* diffusor, *6,* output from the supersonic channel, and *7,* output from the subsonic channel.

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intensification of heat exchange) increase in the heat exchange instead of only a decrease in the temperature-recovery coefficient r [11].

In addition, it is necessary to take into account that the thickness of the wall separating subsonic gas channel *4* from supersonic gas channel *3* in the energy-separation device is small (from 1 to 5 mm) and the diameter of a dimple stain is 7–20 mm at depths of up to 3 mm. The deposition (indentation) of dimples on the side of the supersonic channel (even for dimples with a relative depth of $(0.10–0.15)D$) causes the formation of a regular relief in the form of hemispherical ledges in the subsonic channel, which also intensifies the heat exchange in it.

The experimental investigations showed the possibility of intensification of heat exchange with the help of the dimples for gas velocities corresponding to Mach number M = 3 [13] and the high thermal and hydraulic efficiency of the dimples [14]. The opposite situation, i.e., depositing spherical dimples in the subsonic flow and obtaining spherical ledges in the supersonic flow, gives a clear picture of heat-exchange intensification but results in an incomparably greater increase in the pressure losses [13].

To estimate the efficiency of the use of relief surfaces in the energy-separation device, we write the set of equations presented in [8]. The parameters of the supersonic flow have the subscript 1, and those of the subsonic flow have the subscript 2. The subscript H refers to the initial cross section, and the subscript F, to the final cross section. The subscript 0 relates to the conventional conditions.

$$\left(\frac{\lambda_1^2-1}{\lambda_1^2}\right)\frac{d\lambda_1}{\lambda_1}+\left(\frac{\lambda_1^2+1}{\lambda_1^2}\right)\frac{d\theta_1}{2\theta_1} =\left(\frac{1}{\lambda_1^2}-\frac{k-1}{k+1}\right)\frac{dF_1}{F_1}-\xi_1\frac{k}{k+1}\sqrt{\frac{F_{1H}}{F_1}}d\bar{x},$$

$$\left(\frac{\lambda_2^2-1}{\lambda_2^2}\right)\frac{d\lambda_2}{\lambda_2}+\left(\frac{\lambda_2^2+1}{\lambda_2^2}\right)\frac{d\theta_2}{2\theta_2}=-\xi_2\frac{k}{k+1}d\bar{x},$$

$$\frac{d\theta_1}{\dfrac{K}{\alpha_1}\left[(m+1)-\theta_1\left(\dfrac{T_W^*}{T_1^*}+m\right)\right]}=\sqrt{\frac{F_{1H}}{F_1}}\frac{\xi_1}{2}f(\mathrm{Pr})\,d\bar{x},$$

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

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

where

$$\lambda_1 = W_1/a_{\mathrm{cr}1},\ \lambda_2 = W_2/a_{\mathrm{cr}2}$$

are the reduced velocities of the supersonic and subsonic gas flows; $\theta_1 = T_1^*/T_{1H}^*$, $\theta_2 = T_2^*/T_{2H}^*$ are the dimensionless total temperatures of the supersonic and subsonic gas flows; T_{1H}^*, T_{2H}^* are the total temperatures of the supersonic and subsonic gas flows at the input into the energy-separation device; F and D are the corresponding areas and diameters of the subsonic and supersonic channels; $m = G_1/G_2$ is the ratio of the mass flow rates of the supersonic and subsonic gas flows; and $f(\mathrm{Pr})$ is the correction for the Prandtl number. Other parameters are presented in detail in [8].

In comparison with [8], we modify the ratio of the heat-transfer coefficient from the subsonic to supersonic flow to the heat-release coefficient at the supersonic-flow side K/α_1 and the drag coefficients ξ_1 and ξ_2.

We write the relation K/α_1 in the form

$$\frac{K}{\alpha_1}=\frac{1}{1+\overline{St}_1 m^{0.8}\dfrac{D_2^2-(D_1+2h)^2}{D_1^{1.8}(D_1+2h)^{0.2}}\left(\dfrac{T_1}{T_2}\right)^{0.15}\left[\dfrac{D_1}{b(D_1+h)}+\dfrac{D_1}{D_1+2h}\right]},$$

where D_1 and D_2 are the current diameters of the supersonic and subsonic channels; T_1 and T_2 are the current values of static temperatures of the supersonic and subsonic flows; h is the thickness of the wall separating the supersonic and subsonic gas flows; and $\overline{St_1}$ is the correction coefficient taking into account the heat-exchange intensification on relief surfaces (for the particular surface shape, it can be obtained from experimental data).

The drag coefficients for supersonic and subsonic channels

$$\xi_1 = \overline{\xi_1}\xi_{10}\sqrt{1-\frac{k-1}{k+1}\lambda_1^2},\ \xi_2 = \overline{\xi_2}\xi_{20}\sqrt{1-\frac{k-1}{k+1}\lambda_2^2},$$

where ξ_{10}, ξ_{20} are the drag coefficients for smooth walls of the supersonic and subsonic channels under standard conditions; and $\overline{\xi_1}$ and $\overline{\xi_2}$ are the correction coefficients taking into account the effect of the relief.

Accepting the initial data at the input into the installation from the data of [5] and estimating the effect of the relief from the data of [13, 14] by the modified method, we investigate the effect of the ratio of the mass flow rates along the supersonic and subsonic contours. The calculation results for natural gas are

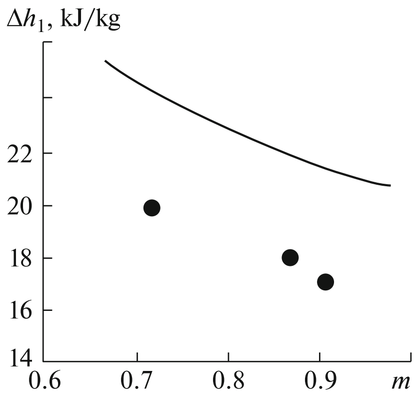

Fig. 2. Variation of enthalpy of natural gas. Points are the experimental data [5], and the line is the calculation in the presence of intensification of the heat exchange.

shown in Fig. 2. From these data, it can be seen that the intensification of heat exchange and the decrease in the temperature-recovery coefficient resulted in an increase in the quantity of the heat transferred by 20–25%. In this case, the alternative calculation showed that a decrease in the length of the supersonic and subsonic channels by 25% would result in a decrease in the quantity of the heat transferred of only 3%.

Similar calculations carried out for air for the same initial data and the 3-mm thickness of the wall separating the supersonic and subsonic channels showed that the use of regular relief on the wall separating the subsonic and supersonic channels allows us to increase the quantity of the heat transferred by 35–40% with a decrease in the length of the device of 20–25%.

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