Numerical simulation of energy separation of low-Prandtl gas mixture flowing in the finned single Leontiev tube

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Abstract. The paper presents results of numerical simulation of energy separation (temperature stratification) of helium-xenon gas mixture with low-Prandtl number, flowing in the finned single Leontiev tube. Only the inner surface of the central channel for subsonic part of the flow was finned by longitudinal fins. The influence of the flow rate of the cooling gas, flowing through the central channel, on the energy separation efficiency was analyzed in comparison with the efficiency of Leontiev tube with smooth walls. The method of efficiency enhancement by insulating the low-temperature area at the tube outlet was suggested.

1. Introduction

Interest in gas dynamics and heat and mass transfer in flows of gas mixtures with small Prandtl numbers is caused by the need to create a scientific and technical reserve necessary for the development of power plants for deep space expeditions [1]. In the most efficient configuration, such devices should be equipped with electrically powered systems based on a nuclear power source and a gas turbine unit. In [2, 3] studying closed gas turbine units operating on the Brighton cycle, it is shown that mixtures of noble gases, the best of which is helium-xenon, at certain compositions can increase the heat transfer intensity in the core by 7% and reduce the number of stages in the turbomachine by 24-30%. As a result, the use of helium-xenon mixture allows reducing the reactor mass by 7-10% with some loss of maximum efficiency due to the increase in hydraulic losses. In [1, 4-11] it is demonstrated that in high-speed (sonic and supersonic) flows of air and, in particular, gas mixtures with low-Prandtl numbers in ducts of power plants, there are thermal effects, changing the total energy of the flow or its part, even if channels are externally insulated. The effect of energy separation can be a negative factor, the nature of which has to be studied and taken into account in the design of power plants. This effect, on the contrary, may be treated as positive and used to build new types of power equipment. The operation principle of such a device of energy separation, i.e., Leontiev tube, was proposed in [4] and analyzed in detail in [1, 7]. In [9-11] the effect was confirmed in experiments in air, and limit values of the total temperature of the cooled (subsonic) flow and those of the supersonic flow were obtained. Authors of [12] proposed and analyzed the method for increasing the energy separation efficiency in laminar flow regime by injecting water in the form of aerosol into the near-wall boundary layer from the side of a supersonic flow. A significant decrease in the adiabatic braking temperature in the heat-insulated channel and a decrease in the temperature of the cooled gas were demonstrated. As in any heat exchangers, to which the energy separation device may be attributed, the efficiency of heat transfer from one medium to another depends on the thermal resistance of the
dividing wall and those of the wall boundary layers. In work [12] due to evaporation of water droplets, the gas temperature in the boundary layer decreases, the heat transfer coefficient increases, and the thermal resistance of the near-wall boundary layer from the supersonic flow decreases. The paper [13] theoretically analyzes the effect of the dividing wall finning on the reduction of the total thermal resistance and the increase in heat flux from subsonic to supersonic part of the flow. It is shown that effective finning can lead to a two- and three-fold increase in the intensity of heat transfer through the dividing wall, and, as a consequence, to an increase in the efficiency of energy separation.

This paper presents results of numerical simulation of energy separation in Leontiev tube with a finned dividing wall, confirming the conclusions of [13]. Since high-speed (supersonic) flows are sensitive to various obstacles on the streamlined surface, and the presence of supersonic flow is a necessary condition for energy separation in the Leontiev tube, only the longitudinal finning of the dividing wall from the subsonic flow side is considered. The influence of the flow rate of cooling gas, flowing through the central channel, on the energy separation efficiency is analyzed in comparison with the efficiency of Leontiev tube with smooth walls. The method of efficiency parameters enhancement by insulation of low-temperature area at the tube outlet is suggested.

2. Problem statement and solution method

In figure 1, the scheme of energy separation in the Leontiev tube (center), the computational domain and mesh (bottom) are presented. In the upper part of the figure, the form of finned dividing wall is shown.

![Figure 1](image)

*Figure 1. The problem statement and calculation domain for simulating energy separation in the Leontiev tube with finned dividing wall.*

The supersonic channel was a 100 mm long Laval annular nozzle with an expanding conical part of 150 mm, over which energy separation mainly occurred. The outer diameter of the dividing wall was 10.4 mm, the diameter of the supersonic nozzle at the inlet was 30 mm and at the critical section it was...
12.5 mm; then there was a 20 mm long section with a diameter of 16 mm at the outlet, expanding according to the law of cubic parabola. The estimated Mach number at the outlet of this section for the helium-xenon mixture ($\gamma = 1.68$) was 3.07, and the actual one was 2.7.

The conical part expansion allowed compensating for the decrease of the hydraulic diameter, caused by the growth of boundary layers, and keeping nearly constant Mach number over the length in the flow core, with the exception of the outlet sections, where the flow decelerated in a series of pseudoshock waves, immersed in viscous boundary layers. The latter effect is associated with some drop in the efficiency of energy separation at low flow rates of the cooled gas, which will be discussed later. The geometry and parameters of the flow in the supersonic channel were the same for all calculation variants. The geometries of the inner channel and dividing wall changed. Three options were considered: smooth copper tube with an inner diameter of 3.5 mm (wall thickness $\delta = 3.45$ mm and thermal resistance $\delta/\lambda = 8.9 \times 10^{-4}$ m$^2$K/W), tube with an inner diameter of 7.5 mm and 24 longitudinal fins with a height of 2 mm (wall thickness $\delta = 1.45$ mm, thermal resistance $\delta/\lambda = 3.7 \times 10^{-4}$ m$^2$K/W, and efficiency of fins $\eta = 4.7$) and tube with an inner diameter of 8.5 mm with the same number of fins with a height of 3.25 mm (wall thickness $\delta = 0.95$ mm, thermal resistance $\delta/\lambda = 2.4 \times 10^{-8}$ m$^2$K/W, and efficiency of fins $\eta = 7.4$). Here and after designations of physical quantities correspond to the designations given in [13].

At the channel inlet, constant pressure and braking temperature were set at 7.5 atm and 295 K, respectively. The pressure at the outlet of the central subsonic channel decreased from 7.495 to 1 atm, thus changing the gas flow rate in the channel. The pressure at the outlet of the supersonic channel was assumed to be 1 atm. Properties of helium-xenon mixture, used for calculations, are presented in table 1. Density is calculated using the model of ideal gas. Ebonite, the properties of which are given in table 2, was used as the insulating insert material applied in a number of calculations at low gas flow through the subsonic channel.

### Table 1. Properties of He-Xe mixture

| $K_w$, % | $\mu$, $\mu$Pa·s | $c_p$, J/kg·K |
|---------|-------------------|---------------|
| 5.0     | 24.50             | 410.0         |

| $\lambda$, mW/m·K | $M$, g/mole | $Pr$ |
|-------------------|------------|-----|
| 45.0              | 50.0       | 0.223 |

### Table 2. Properties of ebonite

| $\rho$, kg/m$^3$ | $\lambda$, mW/m·K | $c_p$, J/kg·K |
|------------------|--------------------|---------------|
| 1300             | 0.16               | 1465.0        |

Numerical simulation was carried out using the CFD package ANSYS Fluent within the frameworks of IT SB RAS license. The Spalart–Allmaras model was used to model turbulence. The calculations were performed by an implicit scheme of the second order of accuracy for all variables. The strategy of obtaining a stationary solution with the necessary accuracy of calculating the integral mass and energy balances included three steps. The first step was a hybrid initialization and URANS simulation with linear pressure reduction at the outlet of a supersonic channel from 6.5 to 2 atm for 0.1 second, then with a linear reduction of pressure from 2 atm to 1 atm for 0.1 sec, and further calculation at the outlet pressure of 1 atm. At this step, it is possible to achieve gas-dynamic stabilization of the flow in the supersonic channel. The dividing wall remains insulated. The second step was RANS simulation of the flow on a heat-conducting dividing wall. At this step, for 3000 iterations, one can obtain the stationary temperature field and achieve the accuracy of the calculation of the total temperature, weighted by mass flow rate in the channels at the outlet from the Leontiev tube, that is not worse than 0.05% or 0.15 degrees. This makes up no more than 3% of the change of the total temperature of the supersonic flow, obtained due to the energy separation effect. The third step was the change of pressure at the subsonic channel outlet and RANS simulation up to achieving the required accuracy, which is usually 1500-2000 iterations.
3. Results and discussion

Let us consider the results of modeling the average mass temperature of flow braking $\overline{T}$ in different cross sections along the length of the annular nozzle (figure 2 top) and the central channel (figure 2 bottom), obtained in Leontiev tubes with smooth and finned walls. For convenience of analysis, the data are presented as a difference between $\overline{T}$ in the corresponding channel and $T^*$, the total temperature at the tube inlet. Thus, the positive temperature difference is the degree of heating of the supersonic (heated) flow $\overline{T}_h - T^*$, and the negative one is the degree of cooling of the subsonic (cooled) flow $\overline{T}_c - T^*$. The difference between the degrees of heating and cooling is the effect of energy separation $\overline{T}_h - \overline{T}_c$. As can be seen from the graph, the energy separation effect for the helium-xenon mixture can reach 50 degrees, and the energy separation increases both along the tube length and with an increase in the efficiency of the dividing wall finning. An increase in finning efficiency leads to an increase in the rate of the subsonic flow cooling in the area beyond the critical section, which, in general, leads to a deeper cooling of the flow at the tube outlet.

![Figure 2](image1.png)

**Figure 2.** The degree of heating of the supersonic flow (on top) and the degree of cooling of the subsonic flow (at the bottom) in different sections of the considered Leontiev tube with a smooth dividing wall (red lines), with a finned wall at $\eta_i = 4.7$ (blue lines) and at $\eta_i = 7.4$ (black lines).

![Figure 3](image2.png)

**Figure 3.** The degree of the subsonic flow cooling in different sections of the considered Leontiev tube with a finned wall at $\eta_i = 7.4$ and at different pressures at the outlet from the central channel; the arrow shows the insulation of the dividing wall.

Figure 3 presents data on the degree of cooling in a tube with a finned dividing wall at $\eta_i = 7.4$ for different pressures at the outlet of the subsonic channel. It is seen that the decrease in pressure, and, hence, in the gas flow rate through the subsonic channel, leads to an increase in the degree of cooling. However, it may be noted that for the smallest pressure drops in the output sections, the total temperature of the cooled flow increases sharply. This effect is due to the supersonic to subsonic flow transition on pseudoshock waves in the annular nozzle. The gas temperature in the annular nozzle increases significantly, which leads to dividing wall heating at the tube outlet. This is clearly seen in figure 4, showing pressure and temperature fields in the longitudinal sections and at the tube outlet. For high flow rates through the central channel, this effect practically does not affect the average mass temperature, since the gas does not have time to warm up enough for the time of interaction with the outlet section of the dividing wall. For low flow rates, the impact of the output section is significant. Thus, at the braking pressure drop along the central channel of 0.005 atm, the loss of cooling efficiency at the tube outlet is 14 degrees, which is 25% of the maximum degree of cooling.
Figure 4. The total pressure field (a), the thermodynamic temperature field (b) and the total temperature field (c) of the flow in the considered Leontiev tube with finned wall at $\eta_2 = 7.4$ and at pressure at the outlet from the central channel of 7.495 atm.

Thermal insulation of the output section of the dividing wall leads to the return of cooling efficiency in the central channel and at low flow rates allows for deeper cooling compared to the tube without an insulating insert. For an insulating insert with a length of 70 mm, the results of calculations of the degree of cooling of the subsonic flow are shown in figure 4 by dotted lines in comparison with the data for a tube without an insulating insert (solid lines). The arrow on the graph shows the area of insulation of the dividing wall. Figure 5 presents generalized data on the degree of cooling and parameters of energy separation efficiency in the Leontiev tube with smooth and finned walls, depending on the ratio of flow rates in the central channel to the total gas flow through the tube.
As can be seen, a decrease in the dividing wall thickness and its finning, on the one hand, lead to an increase in the flow section of the central channel, and, on the other hand, to an increase in the area of the wall, streamlined by the coolant. Increasing the flow section leads to an increase in gas flow rate through the central channel, the parameter $\mu$ grows, and the thermal power of the tube increases as well. Increasing the heat transfer area allows cooling the increased gas flow even deeper than in a tube with smooth walls. Deeper cooling of the gas in the central channel at the same pressure losses in the supersonic nozzle leads to an increase in the temperature efficiency coefficient (figure 5b) and adiabatic COP (figure 5c). At low flow rates $\eta_T$ can reach 45%. This means that in the externally adiabatic Leontiev tube, the device with machine-free energy separation where the gas does not produce mechanical work, part of the gas can be cooled as in much more complex gas-expansion machine with internal efficiency of 45%. The temperature efficiency of the tube working on helium-xenon mixture is 3.5–4 times higher than in the tube working on air. The development of the heat exchange surface and the increase in gas flow rate in the central channel lead to an increase in adiabatic COP. In the best of the considered cases $\eta_T$ reaches 3.1%. Since the maximum adiabatic efficiency falls on the range of relative flow rate from 0.2 to 0.4, the presence of an insulating insert does not significantly change this efficiency parameter.

Figure 5. Degree of cooling (a), temperature efficiency (b) and adiabatic COP (c) for Leontiev tube with smooth separation wall, operating on air (black dots), operating on helium-xenon mixture (red dots); for the tube with finned wall operating on helium-xenon mixture at $\eta_T = 7.4$ (blue dots); effect of insulating insert (green dots).
Conclusions

Data of numerical simulation served to show that the decrease in the dividing wall thickness and its finning lead to an increase in the cooling efficiency of the coolant with a low Prandtl number and to an increase in efficiency parameters of the energy separation. The increase in the area of the flow section of the central channel at a finned wall increases the flow rate of the cooled gas and the thermal power of the Leontiev tube. It is shown that the supersonic flow decelerated in the annular nozzle at the tube outlet can have a significant impact on the degree of gas cooling. For the considered configuration, the loss in cooling efficiency was 25%. This effect can be avoided by using an insert, thermally insulating the supersonic part of the flow from the subsonic part at the tube outlet.

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References

[1] Zditovets A G, Vinogradov Yu A, Strongin M M, Titov A A and Kiselyov N A Bez mashinnoe ener gorazdelenie gazovyh potokov 2016 (In Russian)
[2] El-Genk M S and Tournier J M 2007 Journal of Propulsion and Power 23(4) 863–73
[3] Tournier J M P, El-Genk M S 2008 Energy Conversion and Management 49(3) 469–92
[4] Leont’ev A I High Temperature 1997 35(1) 155–7
[5] Leontiev A I and Lushchik V G and Yakubenko A E 2006 High Temperature 44 (2) 234–42
[6] Makarov M S and Makarova S N 2013 Thermophysics and Aeromechanics 20(6) 757–67
[7] Makarov M S, Makarova S N and Shibaev AA 2016 Journal of Physics: Conference Series 754 011002
[8] Zditovets A G, Vinogradov Yu A, Titov A A Proc. of the 15th Int. Heat Transfer Conference, August 10-15, 2014, Kyoto, Japan IHTC15-8965
[9] Leontiev A I, Zditovets A G, Vinogradov Y A, Strongin M M and Kiselev N A 2017 Experimental Thermal and Fluid Science 88 202–19
[10] Leontiev A I, Zditovets A G, Kiselev N A, Vinogradov Y A and Strongin M M 2019 Experimental Thermal and Fluid Science 105 206–15
[11] Azanov G M and Osiptsov A N 2017 International Journal of Heat and Mass Transfer 106 1125–33
[12] Makarov M S, Makarova S N and Naumkin V S 2018 Journal of Physics: Conference Series 1128 012018