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The influence of the supersonic nozzle length on the efficiency of energy separation of low-Prandtl gas flowing in the finned single Leontiev tube

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Abstract. The redistribution of the total temperature between the parts of the gas stream flowing through the Leontiev tube depends not only on the temperature recovery factor (Prandtl number) and the ratio of flows through the supersonic and subsonic channels of the tube (Mach numbers), but also on the thermal resistance of the separation wall. Earlier it has been shown that the reduction of thermal resistance due to the separation wall finning on the side of the subsonic flow leads to an increase in the efficiency of energy separation. It may be assumed that the intensification of heat exchange between channels, due to finning, reduces the length of the tube, which at the same intensity of heat exchange leads to a decrease in pressure losses and an additional increase in efficiency. This paper presents the results of numerical simulation of energy separation in Leontiev tubes with a finned separation wall and different lengths of supersonic nozzle. It is shown that the adiabatic efficiency of the energy separation in a short Leontiev tube with a finned wall increases when the outlet pressure decreases, while it does not change for smooth tubes.

1. Introduction

Gas-dynamic energy separation, the redistribution of the total temperature between the parts of the gas flowing through the energy separation device, depends on the nature of the temperature inhomogeneity in this flow (vortex effect, resonant effect, dissipative effect, etc. [1]) and is determined by various parameters. The principle of operation of the energy separation device in a supersonic flow (Leontiev tubes), in which temperature inhomogeneities occur due to dissipative effects, was proposed in [2] and analyzed in detail in [3, 4]. The effect was confirmed in experiments on air in [5-7] where the maximum differences in the total temperature of the cooled (subsonic) flow and the heated supersonic flow were obtained. In a Leontiev tube, the main parameters that determine the heat flux from the subsonic part of the gas flow to the supersonic part are the factor of temperature recovery from the supersonic flow (Prandtl number), the ratio of flow rates through the supersonic and subsonic channels of the tube (Mach numbers) and the thermal resistance of the separation wall. As it was shown earlier [8, 9], the reduction of thermal resistance due to the finning of the separation wall from the subsonic flow leads to an increase in the efficiency of the process: an increase in the coefficient of temperature efficiency and adiabatic efficiency. In Leontiev tubes, along with the development of the heat exchange surface of the separation wall, there is an additional opportunity to increase the efficiency of the energy separation process by reducing the length of the tube, and, therefore, hydraulic losses, primarily in the supersonic channel.

This paper presents the results of numerical simulation of energy separation in Leontiev tubes with a finned separation wall and different lengths of supersonic nozzle. As in [9], the longitudinal finning of the separation wall is considered only from the subsonic flow side, since supersonic flows are sensitive to obstacles on the streamlined surface.

2. Problem statement and solution method

Scheme of the tube, the geometry of the computational domain, boundary conditions and sample grid are presented in figure 1.

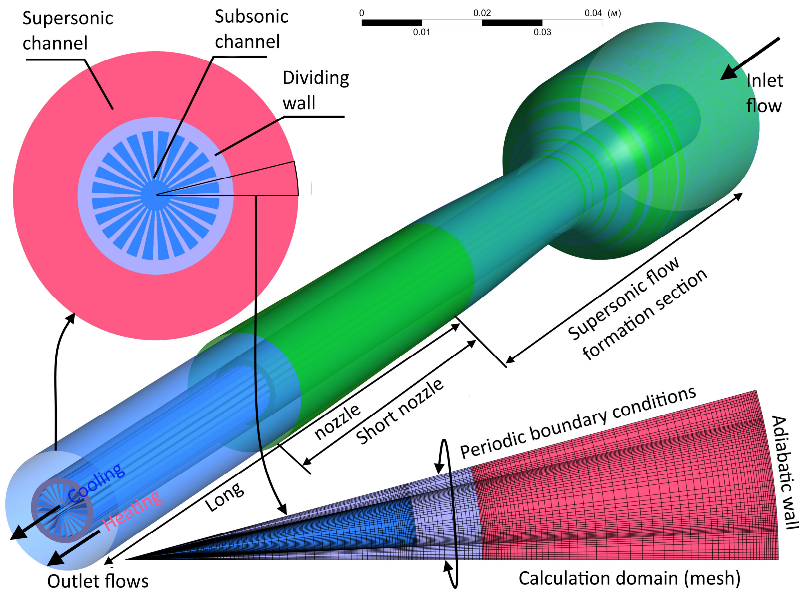


Figure 1. Energy separation tube with a finned separation wall and different nozzle lengths (flow diagram, geometry of the computational domain, boundary conditions and design grid).

Configuration of the supersonic nozzle and the geometry of the separation wall, with the exception of the finning and the length of the conical area of expanding part of the nozzle, fit the Leontiev tube nozzle from [5]: supersonic annular Laval nozzle with the length of 100 mm, inlet diameter of 30 mm and that in the critical section of 12.5 mm, and then a section with a length of 20 mm and an outlet diameter of 16 mm, expanding according to the law of a cubic parabola. The outer diameter of the separation wall is 10.4 mm. The short nozzle is 75 mm long and the long nozzle is 150 mm long. The maximum Mach number in the supersonic flow core for both configurations is 2.71 for the flow of a helium-xenon mixture ($\gamma = 1.68$). The expansion of the conical part allows compensating for the decrease in the hydraulic diameter, resulting from the growth of boundary layers, and keeping an almost constant Mach number in the flow core along the length. The inner channel is a tube with an inner diameter of 8.5 mm with 24 longitudinal ribs with the height of 3.25 mm (wall thickness δ =0.95 mm, thermal resistance $\delta/\lambda_s = 2.4\times10^{-6}$ m^{2}K/W, and efficiency of the ribs $\eta_2 = 7.4$). The designations of physical quantities correspond to the designations given in [8].

The total pressure and temperature at the inlet to the Leontiev tube were 7.5 atm and 295 K, respectively. The pressure at the outlet of the central subsonic channel decreased from 7.495 to 0.1 atm, thus providing a change in the gas flow rate in the channel. The pressure at the outlet from the supersonic channel was assumed to be equal to 1, 0.5 and 0.2 atm. The properties of the helium-xenon mixture corresponded to the work [9], and the Prandtl number was 0.22. The relation of pressure, temperature and density was set by the equation of state of the ideal gas.

Numerical simulation was performed using the ANSYS Fluent CFD package under the license of IT SB RAS. The strategy for obtaining a stationary solution with the necessary accuracy for calculating the integral mass and energy balances is described in detail in [9].

3. Results and discussion

Let us consider the results of modeling the total pressure loss in long and short Leontiev tubes for given conditions, shown in figure 2. It can be seen that in a supersonic annular nozzle, the gas expands to the specified static pressure at the outlet of 0.2 atm. The total pressure in the flow core for both configurations remains virtually unchanged up to the cross section at a distance of 175 mm from the tube inlet. For a short nozzle, this section coincides with the output section. For a long nozzle, the gas continues to expand for 75 mm more, but the total pressure in this section, as a result, decreases due to the growth of boundary layers on the nozzle walls and the pressure loss to overcome the friction force. It is obvious that for a short nozzle, the total pressure loss is less than for a long one, which can have a positive effect on the efficiency of energy separation. To do this, it is necessary that the heat exchange between supersonic and subsonic flows is realized more efficiently on the separation wall with a shortened length, which is determined by the wall finning.

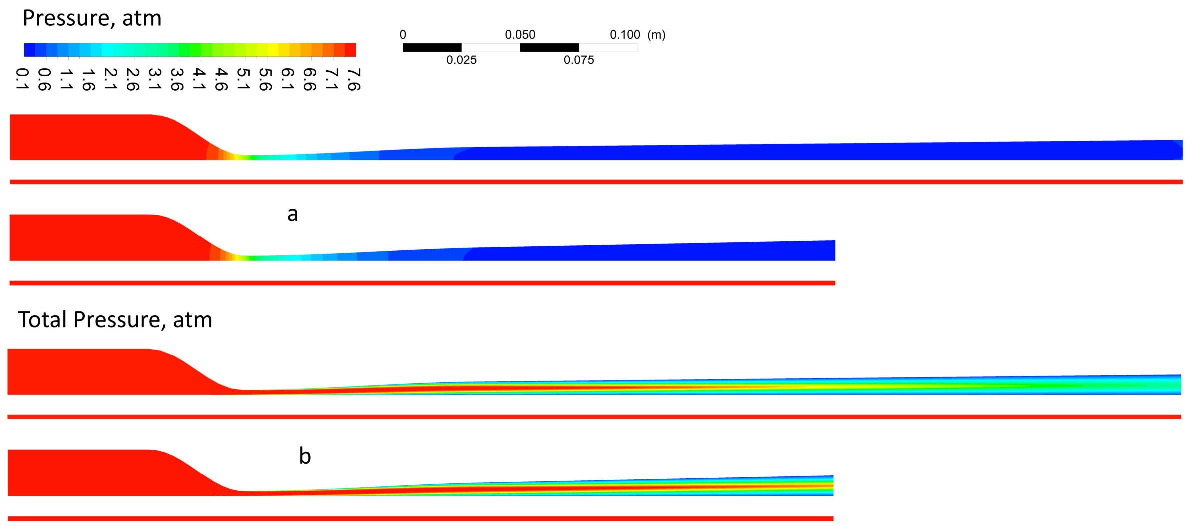


Figure 2. Static (a) and total pressure (b) fields in a longitudinal section of the considered Leontiev tube with finned wall at $\eta_2 = 7.4$, the pressure at the nozzle outlet of 0.2 atm and that at the outlet of the central channel of 7.495 atm; pressure fields are shown for long and short nozzles.

The total flow temperature fields are shown in figure 3. Apparently, in the case of a short nozzle, the temperature decrease of the separation wall along the tube length is more intense, and the gas in the inter-fin space takes the wall temperature and cools intensively. For a long nozzle, the gas cools slightly worse. It can be noted that in the case of a long nozzle, the gas in the central channel cools intensively at the initial section of the conical part of the nozzle. When approaching the outlet, the cooling intensity decreases, which indicates an inefficient heat exchange in this area, due to a decrease in the temperature difference between the wall and the gas. It may be stated that part of the heat exchange surface at the outlet of the nozzle is redundant. In fact, eliminating an inefficient surface and thereby reducing total pressure losses should lead to an increase in the efficiency of short Leontiev tubes compared to long ones.

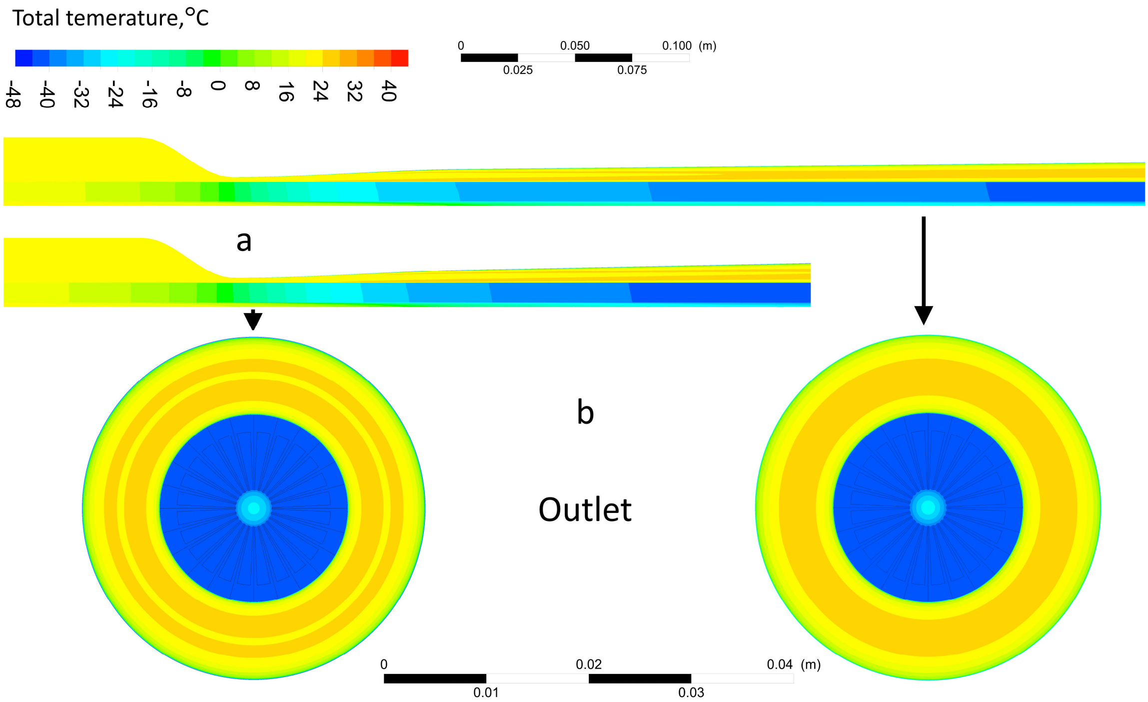


Figure 3. The total temperature field in the longitudinal section (a) and in the outlet section (b); the flow parameters correspond to those shown in Fig. 2; the data are presented for long and short nozzles.

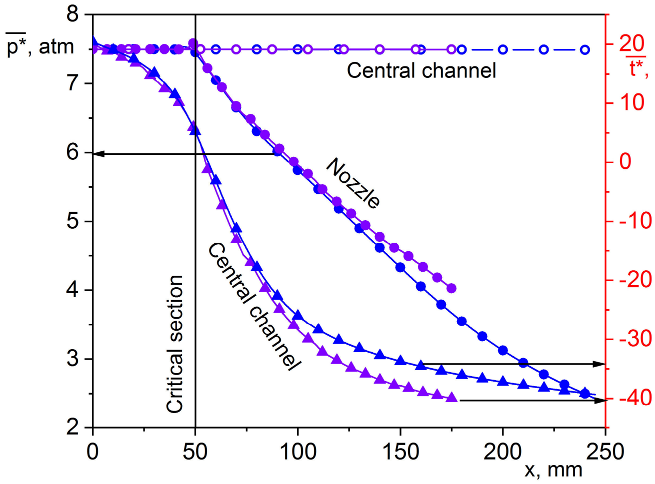
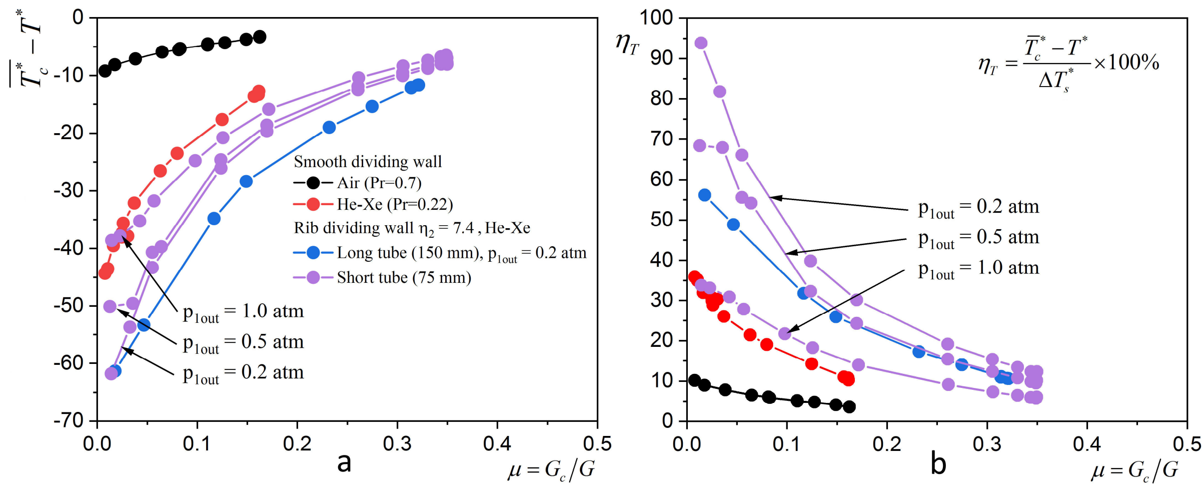


Figure 4. Average mass values of the total pressure in the nozzle (circles, scale on the left) and the total temperature in the central channel (triangles, scale on the right) along the long (blue) and short (purple) Leontiev tubes; hollow circles show the pressure in the central channel.

Figure 4 shows a comparison of the average mass values of total pressure and total temperature in different sections along long and short Leontiev tubes. It can be seen that starting from the critical section, the total pressure in the nozzle decreases almost linearly. Reducing the length of the nozzle at the same static pressure at the nozzle outlet leads to an increase in the total pressure at the outlet, which means that the flow remains operable and friction losses are reduced. It can be noted that the greatest degree of cooling the flow in the central channel $\overline{T_c^*} - T^* \approx -60$ degrees is achieved at the outlet of the tube, regardless of its length, but for a short tube, this is achieved on a smaller area of the heat exchange surface.

Figure 5 shows generalized data on the degree of cooling and the parameters of energy separation efficiency in long and short tubes with smooth ($\eta_2 = 1.0$) and finned walls ($\eta_2 = 7.4$) depending on the ratio of the flow rate in the central channel to the total gas flow rate through the tube.



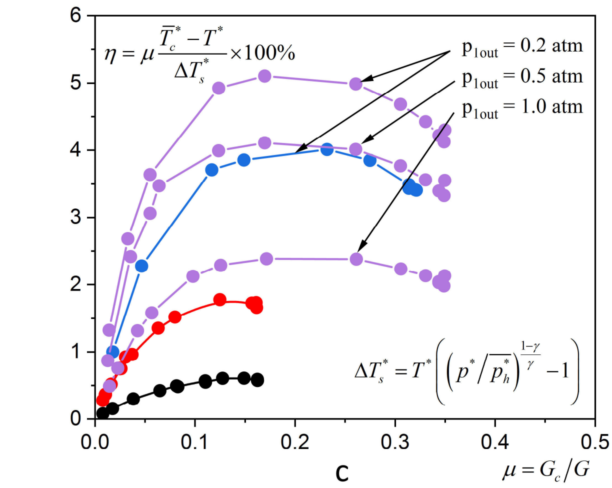


Figure 5. Degree of cooling (a), temperature efficiency factor (b) and adiabatic efficiency (c) for a long Leontiev tube with a smooth separation wall running on air (black dots), running on a helium-xenon mixture (red dots); for a long finned tube running on a helium-xenon mixture at $\eta_2 = 7.4$ (blue dots); for a short tube running on a helium-xenon mixture $\eta_2 = 7.4$ (purple).

From the presented data, it can be seen that the Leontiev tube with a finned separation wall is always more effective than tubes with smooth walls. The highest efficiency in both the degree of cooling and the efficiency factors (η_T, η) for a long tube is achieved at the maximum pressure drop in the supersonic channel of 7.5/0.2. In this case, there are no pseudo-shock-waves at the nozzle outlet [9], which reduces losses for flow braking. The thermal efficiency factor reaches 50% at maximum, and adiabatic efficiency is 4%. In a short tube operating at the same pressure drop, the degree of cooling approaches that in a long tube only at the lowest flow rate of the mixture through the subsonic channel.

When the flow rate in the subsonic channel increases, the degree of cooling slightly worsens, but the temperature efficiency and adiabatic efficiency increase significantly. So $\eta_T = 95\%$ in the maximum, and $\eta = 5.1\%$. It can be noted that for a short tube, the effect of the pressure drop in the supersonic channel has a significantly greater influence on the energy separation than for a long tube. For a long tube, when the pressure drop increases from 7.5/0.5 to 7.5/0.2, the coefficient of temperature efficiency and adiabatic efficiency practically do not change, while for a short tube, their significant growth is observed. Obviously, this is due to lower pressure losses for the short nozzle compared to the long nozzle, which leads to a greater change in the flow parameters in the nozzle (distribution of Mach number, temperature, and gas density). In general, the results of calculations have shown that reducing the length of the Leontiev tube has a positive effect on its efficiency at the developed heat exchange surface on the separation wall. The values of efficiency coefficients achieved in the calculations are the best at the moment, on temperature efficiency factor they exceed the values for the best samples of vortex tubes and approach them on the adiabatic efficiency.

Conclusions
On the basis of numerical simulation data, it is shown that the adiabatic efficiency of energy separation in a short Leontiev tube with a finned wall increases when the pressure at the outlet of the tube decreases, while the adiabatic efficiency does not change for smooth tubes. Adiabatic efficiency reaches a maximum of 5.1%. Reducing the length of the Leontiev tube has a positive effect on its temperature efficiency, provided that the heat exchange surface of the separation wall is developed. The achieved values of the temperature efficiency of 95% are almost two times higher than for long tubes and exceed the values of this parameter for the best samples of vortex tubes.

Acknowledgments
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References
[1] Burtsev S A, Leontiev A I 2014 *High Temperature* **52(2)** 297–307
[2] Leont’ev A I *High Temperature* 1997 **35(1)** 155–7
[3] Zditovets A G, Vinogradov Yu A, Strongin M M, Titov A A and Kiselyov N A Bezmashinnoe energorazdelenie gazovyh potokov 2016 (In Russian)
[4] Nakorjakov V E, Makarov M S, Petukhov Yu I, Vitovsky O V and Elistratov S L Heat transfer in a low-Prandtl gas mixtures flows 2015 (Novosibirsk: Akademizdat, In Russian)
[5] 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
[6] 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
[7] 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
[8] Makarov M S, Makarova S N, Naumkin V S 2018 *Journal of Physics: Conference Series* **1128** 012018
[9] Makarov M S, Makarova S N 2019 *Journal of Physics: Conference* **1359** 012022