Simulating gas-dynamic energy separation in laminar swirling flows

V S Naumkin and V I Terekhov
Kutateladze Institute of Thermophysics, Siberian Branch, Russian Academy of Sciences, 1 Lavrentyev Ave., Novosibirsk, 630090, Russia

e-mail: vsnaumkin@itp.nsc.ru

Abstract. Using numerical methods it is shown that the process of gas-dynamic energy separation can be observed in the laminar flow inside a vortex tube. The magnitude of the observed energy separation is less than the energy separation under turbulent conditions.

1. Introduction

The process of gas-dynamic energy separation in a Ranque-Hilsch vortex tube has been known for a long time and many works have dealt with its study [1, 2]. However, the mechanism of vortex energy separation has not yet been elucidated, and currently there are many hypotheses on this subject.

Effective energy separation is observed at high flow rates; therefore, the overwhelming number of theoretical and experimental studies is devoted to the turbulent flow regime. Most models trying to describe this phenomenon are based on the behavior of turbulence in swirling flows with a strong influence of centrifugal mass forces on turbulent transport processes. At the same time, there are theories of the Ranque-Hilsch effect based on the thermodynamic approach without taking into account the influence of the mass force fields on the structure of turbulence [3–6].

The study of temperature separation in a vortex tube in the laminar flow can bring some clarity to this process. In this case, there is no problem of adequate simulation of turbulence and the problem of the flow and heat transfer can be solved numerically without involving additional hypotheses about turbulence behavior.

The existing mathematical models that describe the mechanism of gas-dynamic energy separation inside a Ranque-Hilsch vortex tube are reviewed in [7]; the advantages and disadvantages of the models under consideration are described. The authors [7] proposed their own model for an unlimited stationary laminar compressible vortex flow, based on hypotheses about the flow symmetry, the constancy of dynamic viscosity coefficient and the fact that the radial velocity component is much smaller than the tangential component; the possible maximum and minimum temperatures achieved in the vortex flow are shown. Energy separation in a swirling flow in a laminar formulation was considered in [8] for a specific vortex tube geometry. It was shown that there is no need to attract additional hypotheses to describe the process of energy separation. The laminar flow inside a vortex tube was considered in [9] without taking into account dissipation, and it was said that some turbulence model should be used to take into account viscous heating and energy separation. However, the model obtained in this work can explain the temperature distribution inside the vortex tube. As it can be seen from the two above-mentioned works, in the literature there is no unequivocal answer about the necessity to use additional hypotheses describing the behavior of turbulent swirling flows.
Therefore, an urgent task is numerical simulation of the process of gas-dynamic energy separation in a Ranque-Hilsch vortex tube under laminar operating conditions.

Numerical simulation and experimental study of the effect of energy separation for a swirling flow of a viscous gas in a round tube was performed in [10]. It is shown for the first time that practically significant energy separation (with a difference of braking temperatures in the “cold” and “hot” zones of more than 10%) can exist in the laminar flow. The authors of this work formulated the most important conditions for effective energy separation in a vortex device: a) sufficiently high Mach number at the channel inlet, which ensures acceleration of gas in the potential vortex to transonic velocities; b) intense flow swirling, which ensures the predominance of circular motion over the flow rate and, accordingly, a significant increase in the Mach number at gas acceleration in a potential vortex; c) almost complete absence of convective heat transfer (and, consequently, mass transfer) between the vortex core and the free vortex region. According to [10], the presence of a recirculation zone is not the necessary condition for energy separation; on the contrary, expansion of this zone can lead to additional mixing of the flow and equalization of temperatures.

This work deals with numerical 3-D simulation of the energy separation effect in a non-stationary swirling laminar flow.

2. Problem statement

The problem was solved in a three-dimensional non-stationary formulation. The flow regime was assumed to be laminar. The geometric dimensions of the tube under study were taken from [10], but some sizes were changed. In particular, to increase the gas flow through the vortex tube (and, accordingly, the velocity), the diameter of six nozzles for the initial air supply was increased to 1 mm (Fig. 1). At a distance of 20 mm from the swirler, there were two outlets for exhaust air discharge. This is the main difference between the vortex tube under study and the Ranque-Hilsch classical vortex tube, in which the cooled gas outlet is located on the tube axis, and the heated gas outlet is at the periphery far from the swirler. In the vortex tube under consideration, the greatest cooling was observed near the swirler, and the maximum heating was observed at the tube ends.

We also considered the cases without a swirler, and air was tangentially supplied directly from the inlet nozzles into the vortex tube. In this case, the observed value of the temperature difference inside the vortex tube was less than in the case with a swirler.

![Figure 1](image1.png)

**Figure 1.** The scheme of the flow and dimensions of the studied vortex tube in millimeters.

Boundary conditions: at the inlet of the tangential nozzles a constant pressure and stagnation temperature of 300 K were set. At both outputs the pressure was constant. A boundary condition of the third kind was set on the vortex tube walls with heat transfer coefficient \( \alpha = 10 \) W/m\(^2\)K, the wall thickness was assumed to be 0.001 m, free stream temperature was 298 K (under adiabatic conditions, no energy separation was observed in this type of vortex tube). The working fluid was air; and density was calculated according to the ideal gas law.

The problem was solved in the Ansys Fluent 2020 R1 software package (academic license) according to an implicit scheme with discretization of equations by the first order upwind scheme.
3. Simulation results

The fields of full velocity and temperature for a vortex tube with a swirler and for the case when gas is tangentially supplied directly into the vortex tube are presented in Figs. 2-3. In both cases, the absolute pressure at the inlets was 12 bar, at the outlets, it was 3.95 bar. According to comparison of the velocity fields, in a vortex tube with a swirler, the velocity near the wall is higher (about 200 m/s) than in the tube without a swirler (about 100 m/s). In the axial region, in both cases, the maximum velocity is about 60 m/s. In the case with a swirler, due to a significant difference in velocities in the near-wall and axial regions, the zones with different thermodynamic temperatures are formed. While moving from the swirler to the tube ends, gas from the periphery exchanges heat with gas in the near-axis region by mixing both parts of the flow (Figure 4 above shows the presence of vortex structures between the near-axis and near-wall regions). There is “leveling” of the thermodynamic temperature while maintaining the velocity profile. After mixing, when the near-wall and axial parts of the flow slow down, the stagnation temperature changes: the high-velocity part is heated (316 K), the low-velocity (axial) part is cooled (287 K), which can be seen from the stagnation temperature field (Fig. 2 below). Thus, in the case under study, the difference in the total temperatures of the “heated” and “cooled” gas is 29 K.

In the second case, when gas is supplied directly into the vortex tube, the velocity difference in the axial and near-wall regions is small. The maximum achievable near-wall flow velocity does not allow efficient reduction in the thermodynamic temperature of gas in this area. As a result, the maximum difference in the stagnation temperature of the “heated” and “cooled” gas is ~ 4 K. It should be noted that in this case there is no intensive mixing of the near-wall and axial parts of the flow (Fig. 4 below), which leads to an extremely uneven distribution of the “heated” and “cooled” flow areas.

![Figure 2](image)

**Figure 2.** The fields of velocity and stagnation temperature in the vortex tube with a swirler. Pressure at the inlet – 12 bar, pressure at the outlet – 3.94 bar. ReD~3.5e5.
Figure 3. The fields of velocity and stagnation temperature in the vortex tube without a swirler. Conditions as in Fig. 2.

Figure 4. The vector velocity fields in the vortex tube with a swirler (at the top) and without a swirler (at the bottom). Conditions as in Fig. 2.

Figure 5. The field of stagnation temperature and vector field of velocity inside the vortex tube at the inlet pressure $P_0=7$ atm, $Re_D = 2000$. 
Despite the fact that in this work the effect of gas-dynamic energy separation inside a vortex tube was calculated without using any turbulence models, the Reynolds numbers, calculated by the inlet and vortex tube diameters, in this case correspond to the turbulent flow regime \( (Re_D \sim 10^5) \). The presence of secondary vortices (Fig. 4) also suggests that significant energy separation will be observed only in the turbulent flow regime. A decrease in absolute pressure at the inlet of this vortex tube to 7 atm allows obtaining the Reynolds number constructed by the tube diameter, corresponding to the laminar flow regime \( (Re_D=2000) \). At that, the observed effect of energy separation — the difference between the maximum and minimum temperature in the flow — is much smaller (about 18 K) (Fig. 5). It should be also noted that in this case, intensive mixing of the peripheral and axial flows is observed only at the vortex tube ends distant from the swirler. With a further decrease in the inlet pressure, the effect of energy separation decreases.

4. Origination of a vortex effect (hypothesis)

The main reason for the occurrence of gas-dynamic energy separation is a significant difference in the flow velocities at the periphery and on the channel axis, and equalizing of the thermodynamic temperature inside the vortex tube due to mixing of the axial and near-wall parts of the flow. Let us consider a simple example of a classic vortex tube. Let a gas flow equal to \( G_0 \) kg/s is fed to the tube inlet. Gas flow \( G_a = 0.1G_0 \) kg/s exits through the axial diaphragm, and gas flow \( G_p=0.9G_0 \) kg/s passes through the outlet far from the swirler.

![Figure 6](image)

The initial stagnation temperature is \( T^* \). The module of gas velocity at the periphery after the output from the swirler is \( U_p \) m/s, the module of gas velocity on the axis is \( U_a \).

Due to the velocity difference, the axial and peripheral regions have different thermodynamic temperatures, equal to \( T = T^* - \frac{U^2}{2cp} \) where \( cp \) is heat capacity of gas under a constant pressure. Inside the vortex tube, the peripheral gas is mixed with the gas in the axial region (convective heat transfer between the axial vortex filament and the near-wall vortex). As a result of mixing, the average thermodynamic temperature in the tube becomes equal to:

\[
T' = \frac{T_{cold} \cdot G_a + T_{hot} \cdot G_p}{G_0} = \frac{T_{cold} \cdot 0.1 \cdot G_0 + T_{hot} \cdot 0.9 \cdot G_0}{G_0} = T_{cold} \cdot 0.1 + T_{hot} \cdot 0.9
\]

The velocity module of the peripheral and axial flows in this case varies slightly, judging by the characteristic M-shaped velocity profile. After complete heat exchange, the braking temperature of both flows becomes equal to:

\[
T_{cold}^* = T' + \frac{U_p^2}{2cp}
\]

\[
T_{hot}^* = T' + \frac{U_a^2}{2cp}
\]

If we take the average gas velocity at the periphery equal to \( U_p=300 \) m/s, velocity on the tube axis \( U_a = 50 \) m/s, and the stagnation temperature at the swirler inlet \( T^* = 300 \) K, we obtain:

\[
T_p = 300 - \frac{300^2}{2 \cdot 1000} = 255K
\]

\[
T_a = 300 - \frac{50^2}{2 \cdot 1000} = 298.75K
\]
Thus, only due to the difference in the velocities of both flows, we can obtain the temperature difference at the hot and cold outlets of the vortex tube of about $\Delta T = 43K$. If the velocity at the periphery is equal to the velocity of sound (maximum achievable in this geometry), then the temperature difference will be $\Delta T \approx 60K$. According to the above formulas, the gas temperature at the cold outlet in this case will be $T_{cold} = 248K$ i.e. the gas is cooled by $52K$. Such a temperature of the cooled gas, as follows, for example, from [11], is practically achieved in many experiments.

The considered hypothesis of energy separation does not take into account such important factors that can significantly affect energy separation, as dissipative heating of gas in the near-wall region of the transonic part of the flow and a decrease in the gas temperature inside the swirler due to expansion of gas. The latter can significantly reduce the temperature at the cold outlet: for example, as the gas expands from pressure $P_1$ to pressure $P_2 = P_1/3$, the gas temperature can drop to $80K$.

Most likely, all of the above factors take place in a vortex tube and their combined effect will determine the observed effect of energy separation.

Conclusions
In this work, 3D simulation of the gas-dynamic energy separation process inside a vortex tube has been conducted without using any turbulence models. It is shown that the presence of a swirler in a vortex tube increases the gas velocity in the near-wall region as compared with a vortex tube without a swirler and direct gas input into the vortex tube. An increase in velocity occurs due to a decrease in the flow cross-section of the tube. Significant predominance of the gas velocity at the periphery of the vortex tube over the velocity on the tube axis leads to the vortex energy separation.

It is assumed that the main reason for the vortex effect is a significant difference in velocities in the near-wall and axial regions and mixing of these parts of the flow, which leads to equalization of thermodynamic temperature of the flows.

Acknowledgements
The work was financially supported by the Russian Science Foundation grant 18-19-00161.

References
[1] Kirmaci V, Kaya H 2018 Int. J. of Refrigeration 91 254
[2] Sharma T K, Rao G A P, Murthy K M 2016 Archives of Computational Methods in Engineering 24(2) 251
[3] Simoes-Moreira J R 2010 Int. J. of Refrigeration 33 765–73
[4] Saidi M H, Allaf M R 1999 Yazdi Energy 24 625–32
[5] Liew R, Zeegers J C H, Kuerten J G M and Michalek W R 20121 Physical Review Letters 109 054503
[6] Kolmes E J, Geyko V I, Fisch N J 2017 I. J. of Heat and Mass Transfer 107 771–7
[7] Katanoda H, Yusof M H, Morita H 2015 Int. J. of Refrigeration 59 115
[8] Tarunin E L and Alikina O N 2005 Int. J. Numer. Meth. Fluids 48 107–13
[9] Shtern V N and Borissov A A 2010 Physics of Fluids 22 083601
[10] Baranov V A, Smirnov E M, Vikultsev Yu A, Zaitsev D K 1996 Rus. J. Eng. Thermoph. 4(6) 291–306
[11] Eiamsa-ard S, Prompong P 2008 Renewable and Sustainable Energy Reviews 12 1822–42