Influence of the channel length of a vortex tube on the air temperature separation

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Abstract. A model of a counterflow vortex tube has been prepared to study the dependence of the influence of the tube length parameter on the cold and hot air production. Computational experiments were made using the OpenFOAM package. The prepared grid allowed us to carry out simulations for vortex tubes with lengths of the main channel varying from 20 to 70 cm. All calculations were performed with boundary conditions with constant inlet pressure and atmospheric pressure at the outlet. Results were obtained on temperatures and mass flow rates of the air in the cold and hot outlets of the vortex tube, depending on the length of the device. It is shown that an increase of the length of the vortex tube channel increases the production of cold air. An increase in the temperature of the produced hot air on vortex tube length increase was also noted.

1. Introduction

The vortex tube, a device, that generates cold without having any moving parts, is known since the 1930s [1, 2]. The simplicity of this device provides for ample opportunities: from conventional cooling mixture separation devices and power generation [3], cooling equipment in laboratories that operate on explosives [4]. It can also be used for air temperature control for divers and in submarines’ habitable stations; temperature control of hyperbaric chambers [5]; separation of particles and waste gas in industry [6]; cooling of nuclear magnetic resonance (NMR) spectrosopes [7] and nuclear reactors [4]; dehydration of gas [8]. Also, under certain conditions, the effect of temperature separation can be observed not only in gas, but also in liquid [9].

From this point of view, the vortex tubes arouse the great interest of many researchers. Up until now, a significant amount of work was published based on the results of experimental and theoretical studies of Rank–Hilsch effect (see reviews [10–12]). It should be noted that in these reviews it is emphasized that up to date there is no unified theory that would fully describe the said effect noted above. There is even no unified opinion on the underlying causes of the temperature separation. Therefore, a number of theoretical and experimental studies in this direction is being carried on.

In the majority of the studies, primarily experimental ones, only the different geometrical configurations of vortex tubes are considered [13]. The theoretical ones are more diverse. Most researchers consider effect of compressibility, shear stress and turbulent pulsations as the cause of the vortex tube effect, but at the same time, there is an alternative opinion that the causes
are acoustic effects arising happening in the tube [14]. Also, more subtle effects associated with, for example, analysis of the local entropy production [15] are recently being considered.

The absence of a universally accepted theory explaining the mechanism of the said phenomenon does not allow us to develop the most effective vortex tube configurations. It also determines the relevance of theoretical and experimental research on this topic. In the paper, we describe how the temperature separation depends on the hot outlet area, on the length and widening angle of the cold outlet, using computational modeling in OpenFOAM software.

2. The model and methods
  2.1. The simulated area
In the paper, a computational simulation of a counterflow vortex tube is carried out. This is such a configuration where cold and hot outlets are located at opposite ends of the tube. The circuit of the vortex tube under consideration is shown in figure 1. A geometry is set with only parameter related to the length of tube $L$ being changeable. These parameters consist of length and angle of widening of the cold outlet nozzle and the area of the hot outlet. All other dimensions (the length $\ell$ and angle of widening $\alpha$ of cold outlet nozzle, the diameter $D$, the cold outlet nozzle diameter $d$, inlet dimensions $p$, $q$ and $m$, the hot outlet size $h$) are fixed.

![Diagram of vortex tube](image)

**Figure 1.** The vortex tube scheme and geometry parameters ((a) from cold outlet side, (b) section through tube).

2.2. The mathematical model
Gas dynamics in the vortex tube channel is described on the basis of the standard system of equations (continuity, impulses and energy) closed by the equation of state of an ideal gas. In the momentum and energy equations, viscous terms are introduced for calculations using the $k - \varepsilon$ model of turbulence:

\[
\frac{\partial \rho}{\partial t} + \nabla (\rho \mathbf{U}) = 0,
\]
\[
\frac{\partial \rho \mathbf{U}}{\partial t} + \nabla (\rho \mathbf{U} \times \mathbf{U}) = -\nabla p + \nabla \tau,
\]
\[
\frac{\partial \rho E}{\partial t} + \nabla (\rho E \mathbf{U}) = -\nabla p \mathbf{U} + \nabla (\tau \times \mathbf{U}),
\]
\[
p = (\gamma - 1)\rho \varepsilon.
\]

Here we use the standard notation: $\mathbf{U}$ is the velocity vector, $\rho$ is the density, $p$ is the pressure, $E$ is the specific total energy, $\varepsilon$ is the specific internal energy, $\gamma$ is the adiabatic exponent, $\tau$ is
the viscous stress tensor, whose elements are calculated as

\[ \tau_{ij} = (\mu + \mu_t) \left[ \left( \frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} \right) - \frac{2}{3} \delta_{ij} \frac{\partial v_k}{\partial x_k} \right], \]

where \( \delta_{ij} \) is the Kronecker symbol, \( v_i \) is velocity vector components, \( \mu \) is the viscosity of the medium, \( \mu_t \) is the turbulent viscosity calculated from the \( k - \varepsilon \) turbulence model.

2.3. Algorithms and software

The calculations were performed in OpenFOAM software using sonicFoam solver. Much attention is paid to the preparation of a uniform orthogonalized finite-difference grid. This approach allows us to increase the time step without significant error increase.

A three-dimensional finite-difference grid was constructed. When preparing the grid, the features of the cylindrical configuration of the region and the possible influence of the grid on the results of calculations were taken into account, therefore the quality of the grid was specifically ensured [16].

3. Results and discussion

A simulation of a vortex tube having the following dimensions is performed (see figure 1): \( D = 4.7 \text{ cm}, \ d = 0.9 \text{ cm}, \ p = 1 \text{ cm}, \ q = 0.7 \text{ cm}, \ m = 1.8 \text{ cm}, \ h = 0.4 \text{ cm}, \ \ell = 2.5 \text{ cm}, \ \alpha = 3^\circ. \)

The parameter \( L \) assumed to be variable. The length of the vortex tube channel \( L \) varied from 20 cm to 70 cm.

In the numerical modeling, initial data simulating normal conditions were used: the pressure in the region is uniform and equal to the atmospheric pressure \( (10^5 \text{ Pa}) \); temperature throughout the area is equal to the room temperature \( (300 \text{ K}) \); gas (air) is stationary \( (U = 0 \text{ m/s}) \). In the calculations, the boundary conditions characteristic for the operating vortex tube are used. The inlet gas is supplied at the room temperature \( (300 \text{ K}) \) and at a high pressure \( (\sim 4 \cdot 10^5 \text{ Pa}) \). At the outlet, the atmospheric pressure \( (10^5 \text{ Pa}) \) is set, and for temperature and velocity the percolation condition is set. On the tube walls, the adhesion condition is set, the walls are thermally insulated.

Similar geometric parameters, initial and boundary conditions were used in [17, 18].

For all the investigated channel lengths of the vortex tube, the pressure, velocity, and temperature fields were calculated. We investigated the values of these quantities in the cross sections of the cold and hot outlets. To reduce the effect of turbulent pulsations on the result, we performed two actions on averaging the obtained values. The first step was averaging over the cross section. To do this, the corresponding section is divided into irregular subregions by the surfaceCut utility and the mean value of the physical quantity for the total area is calculated. In the second step, the area averages over several successive time steps are averaged over a period of time. The cross sections used for averaging are determined by the geometry of the computational domain. Time averaging for all calculations was carried out at the same moments at \( t = 0.07 \ldots 0.1 \text{ s} \).

Estimation of mass flow rate was made on the basis of the average velocity modulus in the corresponding cross section and the air density calculated by the state equation.

Figure 2 shows graphs describing the values of temperature and mass flow rate of air in the cross section of the outlet of the cold nozzle of the vortex tube. For these graphs, one can observe a converging monotonic increase in the values of \( T \) and \( Q \). However, it should be noted that the meaning of this growth is significantly different. So the rise in temperature of the cold outlet relative to the temperature of 300 K of the supplied air is only 0.2\% (see figure 2, (a)), while the increase in mass flow exceeds 7\% (see figure 2, (b)). Thus, within the considered values, the
increase in the length of the vortex tube channel leads to an increase in the production of cold air with a slight increase in its temperature.

Figure 3 shows graphs describing the values of temperature and mass flow rate of air in the annular section of the hot outlet of the vortex tube. Two competing processes should be noted on these graphs. Thus, the mass flow rate of air through the hot outlet of the vortex tube decreases significantly with increasing channel length. In the considered length range, there is a threefold drop in consumption from its initial value. This reduction in mass flow rate is accompanied by an increase in temperature.

In addition to a significant reduction in mass flow rate, we also draw attention to a significant

Figure 2. Dependencies of the average temperature $T$ (a) and the mass flow rate $Q$ (b) of air on the vortex tube channel length $L$ for the cold outlet cross section.

Figure 3. Dependencies of the average temperature $T$ (a) and the mass flow rate $Q$ (b) of air on the vortex tube channel length $L$ for the hot outlet cross section.
increase in air temperature. Thus, for a hot outlet, an increase in the length of the vortex tube channel is characterized by a significant reduction in the production of hot air with a simultaneous increase in its temperature.

4. Conclusion
The work shows the temperature and flow rates of hot and cold air leaving for vortex tubes, the configuration of which differs only in the length of the main channel of the tube. We have noted two pronounced dependencies on the length of the pipe. So, it is possible to observe the redistribution of the temperature of the exhaust air in favor of the hot component with increasing length of the pipe. However, on the other hand, an increase in the length of the pipe is accompanied by an increase in hydrodynamic resistance. Therefore, the mass flow rate is sharply reduced simultaneously with the increase in the hot air temperature.

On the contrary, for a cold outlet, an increase in the length of the vortex tube channel come as a reason for a significant increase in the production rate of the cold air with a slight increase in its temperature.

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