Vortex tube modelling: outlet parameter dependencies of cold air production

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Abstract. A model of a counterflow vortex tube has been prepared to study the dependence of the influence of the parameters of cold and hot outlets on the production of cold air. For a fixed geometry of the vortex tube, a simulation is performed with an independent change of the length of the cold outlet nozzle, the angle of the widening of the cold outlet nozzle, and the hot outlet area. In a series of experiments, the pressure of air supplied to the inlet varies in order to take into account the possible effects of computational and model errors. An anomalous increase in the temperature of the outgoing air was observed with a hot outlet area of ~30 cm². Conclusions were drawn about the range of reasonable values of the outlet parameters for the considered configuration of the vortex tube.

1. Introduction
The vortex tube as a device for generating cold that doesn’t have any moving parts has been known since the 1930s [1, 2]. The simplicity of this device provides ample opportunities for use: from conventional cooling devices to separation of mixtures and power generation [3], cooling equipment in laboratories operating on explosives [4]. It can also be used for air temperature control for divers and in submarine habitable stations; temperature of hyperbaric chambers [5]; separation of particles and waste gas in industry [6]; cooling nuclear magnetic resonance (NMR) spectrosopes [7] and nuclear reactors [4]; dehydration of gas [8]. Also under certain conditions, the effect of temperature separation is observed not only in the gas, but also in liquids [9].

From this point of view, the vortex tubes arouse the great interest of many researchers. To date, a significant amount of work has been 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 to date there is no unified theory that would fully describe the effect under consideration. There is not even a unified opinion on the root causes of 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 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 in the tube [14]. Also, more subtle effects associated with, for example, analysis of the local entropy production [15] began to be considered recently.

The absence of a universally accepted theory explaining the mechanism of the phenomenon under consideration 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 the dependence of the temperature separation on the hot outlet area, on the length and widening angle of the cold outlet, using computational modeling in OpenFOAM software.

2. The model
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 fig. 1. A geometry is set with only parameters related to the outlets 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 of the tube $L$; the diameter $D$; the cold outlet nozzle diameter $c$; inlet dimensions $p$ and $q$) are fixed.

![Figure 1. The vortex tube scheme and geometry parameters](image)

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:

$$\frac{\partial \rho}{\partial t} + \nabla (\rho \mathbf{U}) = 0;$$
$$\frac{\partial \rho \mathbf{U}}{\partial t} + \nabla (\rho \mathbf{U} \times \mathbf{U}) = -\nabla p + \nabla \tau;$$
$$\frac{\partial \rho E}{\partial t} + \nabla (\rho \mathbf{U} E) = -\nabla p \mathbf{U} + \nabla (\tau \times \mathbf{U});$$

where

$$p = (\gamma - 1) \rho \varepsilon.$$

Here we use the standard notation: $\mathbf{U}$ is the velocity vector; $\rho$ is the density; $p$ is the pressure; $E = \varepsilon + \frac{1}{2} |\mathbf{U}|^2$ 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

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

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.

A simulation of a vortex tube having the following dimensions is performed (see fig. 1): $L = 52$ cm; $D = 9.4$ cm; $p = 2$ cm; $q = 1$ cm; $c = 1.8$ cm. The parameters $h$, $\ell$ and $\alpha$ are assumed to be variable. The dimension $h$ is varied in such a way that the area associated with it ranged from 5 cm$^2$ to 50 cm$^2$. The length of the cold outlet nozzle $\ell$ varied from 1 cm to 20 cm. The angle of widening of the cold outlet nozzle $\alpha$ varies from 0 to 5 degrees.

For these parameters, 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 [16], therefore the quality of the grid was specifically ensured [17].

In the numerical modeling, initial data simulating normal conditions were used: the pressure in the region is uniform and equal to the atmospheric pressure ($10^5$ Pa); temperature throughout the area is equal to the room temperature (300 K); gas (air) is stationary ($U = 0$ 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 K) and at a high pressure ($\sim 4 \cdot 10^5$ Pa). At the outlet, the atmospheric pressure ($10^5$ 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. In a number of calculations, the inlet pressure was set to a value different from $4 \cdot 10^5$ Pa. Complete series of calculations were carried out for the cases $4.01 \cdot 10^5$ Pa and $3.99 \cdot 10^5$ Pa. Also, for additional analysis of the distribution of physical values for hot outlet areas of about 30 cm$^2$, simulations were carried out at an inlet pressure of $4.1 \cdot 10^5$ Pa and $3.9 \cdot 10^5$ Pa. Also, in some calculations, the volumetric flow rate of the supplied gas is set instead of the inlet pressure value.

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.

3. Simulation results

The computational simulation gives the following results.

When the length of the cold outlet nozzle is lesser than 6 cm, a small increase in the temperature of the outgoing air is observed, as demonstrated in fig. 2. With further increases in the length of the nozzle, the air temperature decreases, gradually reaching a constant value. If the nozzle has low widening angle (0.25°), then the temperature of the outgoing air reaches lower values. However, when the nozzle length is greater than 16 cm, the temperature of the outgoing air starts increasing. An similar increase, but at larger lengths, is expected for a cylindrical nozzle.

![Figure 2. The dependences of the cold outlet temperature on the cold outlet length](image)

With a change in the widening angle of the cold outlet nozzle at a fixed length (5 cm), one can observe a significant dependence of the temperature on the parameters of the gas supplied to the inlet (fig. 3). Thus, for a fixed volumetric flow rate, the air temperature decreases when angle increases, but at an angle greater than 3° it increases significantly. However, if the inlet pressure is set to a constant pressure, the outlet air temperature is inversely proportional to the logarithm of the widening angle of the cold outlet nozzle and decreases to a maximum calculated angle of 5°.
The dependence of the temperature of the cold air on the size of the hot outlet, as demonstrated on fig. 4, is much more interesting. With a fixed length and no widening of the cold outlet nozzle, one can observe a pronounced minimum of the temperature of the outgoing air. This minimum is observed with the area of the hot outlet approximate to 20 cm$^2$. However, in all calculations, the anomalous behaviour of air temperature in the hot outlet with an area ranging between 25-35 cm$^2$ was obtained. In this range, the temperature rises sharply, reaches a maximum for an area of 30 cm$^2$, after which it again decreases.

**Figure 3.** The dependences of the cold outlet temperature on the cold outlet widening angle

**Figure 4.** The dependences of the cold outlet temperature on the hot outlet area

### 4. Conclusion

The results show a significant influence of geometric parameters on the efficiency of the vortex tube. However, for significant conclusions additional studies are required both on a larger range of considered parameters and for different dimensions of the vortex tube and for various parameters of the air supplied to the inlet. It should be noted that the cold air production is significantly different for the constant pressure inlet boundary condition and for a given volumetric flow rate of inlet gas. This difference also requires additional research.
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