The effect of an additional air inlet in the hot outlet area on the overall effectiveness of a vortex tube

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Abstract. In this paper the modification of a vortex tube is shown. The feature of this vortex tube is that it has an additional air inlet in the hot outlet area along the tube axis designed to redistribute air consumption between cold and hot outlets. Computational experiments are done in openFOAM toolbox using sonicFoam solver. In order to increase computational speed the mesh is being decomposed into equal parts, which allows for the parallel run using MPI on a single computer. The results of the experiment show temperature values and air consumption on the corresponding outlets in relation to the change of the vortex tube length. A conclusion about the effective vortex tube length is made.

1. Introduction
The vortex tube is a device that separates a stream of compressed gas from vortex generators into two streams so that one of the streams is colder and the other one is hotter. This phenomenon is called Ranque–Hilsch effect and named after French engineer Georges–Joseph Ranque who discovered it in 1931 [1, 2].

This device is notably simple, has no moving parts and easy to manufacture. Due to this it is being used in numerous fields where colling or fractionation of gases or fluids is required. In this regard, research in the field of vortex generating devices is one of the focus areas, especially because the mechanism of temperature separation is not yet clear [3]. There are theoretical approaches to explain this phenomenon related to acoustics [4], and purely experimental [5]. The effects of changing the number of inlet nozzles (from 1 to 5), tube length and cold outlet diameter have been shown [6]. It is also demonstrated, that the inlet pressure is important and there is a small optimal conical angle of primary nozzle [7].

In general, described effect is of theoretical and practical interest and hence there are a lot of works dedicated to various aspects of study and use of vortex tubes [8–10]. This fact shows the persistent interest to this effect and the continuing relevance, that is noted in reviews [11–13].

Currently, studies of non-standard vortex tube configurations and their effect on it's characteristics are of particular interest. There are mentions of a double-circuit vortex tube [14], a tube with alternative shapes of the hot end [15] and even modified main cylinder [16].

In this paper the effect of an additional inlet along tube axis in the hot outlet area on overall vortex tube effectiveness is shown.
2. The model and the methods

2.1. The simulation domain

In this paper, a numerical modeling of a counterflow vortex tube with an additional inlet is made. For this case a vortex tube mesh was made according to schematics, that are presented in figure 1. Parameter $L$ of the vortex tube, which is the length of the tube, is the only one set to be changed during computational stage in order to examine the effect of the additional inlet. Other parameters (length $\ell$; tube diameter $D$; cold outlet nozzle diameter $d$ and widening angle $\alpha$; hot outlet ring width $h$; inlet dimenstions $p$, $q$ and $m$; additional inlet nozzle diameter $r$) stay fixed.

![Figure 1. The vortex tube schematics and dimensions (a — cold outlet side; b — sideview section)](image)

2.2. The mathematical model

Gas dynamics in the vortex tube canal is described on the basis of the standard system of equations (continuity, momentum 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:

- mass conservation (continuity) equation
  \[ \frac{\partial \rho}{\partial t} + \nabla (\rho \mathbf{U}) = 0 ; \]

- momentum conservation equation
  \[ \frac{\partial \rho \mathbf{U}}{\partial t} + \nabla (\rho \mathbf{U} \times \mathbf{U}) = -\nabla p + \nabla \tau ; \]

- energy conservation equation
  \[ \frac{\partial \rho E}{\partial t} + \nabla (\rho \mathbf{U} E) = -\nabla p \mathbf{U} + \nabla (\tau \times \mathbf{U}) ; \]

- state equation for an ideal gas
  \[ p = (\gamma - 1) \rho \varepsilon . \]

Here the standard notation is used: $\mathbf{U}$ is velocity vector; $\rho$ is density; $p$ is pressure; $E$ is specific total energy; $\varepsilon$ is specific internal energy; $\gamma$ is adiabatic exponent; $\tau$ is viscous stress tensor, which 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 Kronecker symbol; $v_i$ is velocity vector components; $\mu$ is substance viscosity; $\mu_t = \rho C_\mu \frac{k^2}{\varepsilon}$, is turbulent viscosity calculated using $k - \varepsilon$ turbulence model [17]:

- turbulent kinetic energy equation
  \[ \frac{\partial \rho k}{\partial t} = \nabla \left( \mu_t \nabla k \right) - \frac{2}{3} \rho \left( \nabla \cdot u \right) k - \rho \varepsilon, \]

- turbulence dissipation rate equation
  \[ \frac{\partial \rho \varepsilon}{\partial t} = \nabla \left( \mu_t \nabla \varepsilon \right) - \frac{2}{3} C_1 \rho \left( \nabla \cdot u \right) \varepsilon - C_2 \rho \varepsilon^2, \]

where $C_\mu = 0.09$, $C_1 = 1.44$, $C_2 = 1.92$, $\sigma_k = 1$ and $\sigma_\varepsilon = 1.3$.

### 2.3. Algorithms and software

The calculations were performed in OpenFOAM software using sonicFoam solver. Special attention was paid to uniformity of orthogonalized finite-difference mesh, since this approach allows to increase timestep without a significant rise in error [9]. In addition, with the increase of length of the vortex tube, cell count along the main axis of the tube is also increased to prevent cell stretching that could cause error.

The important thing before the computational stage is mesh decomposition, that separates mesh into several approximately equal parts that allows to make a parallel run and reduce computational time by the factor of 3.5 on 6 processes. By the means of openFOAM decomposition utility the mesh has been sliced into 6 submeshes using planes perpendicular to the main tube axis, minimizing the number of interacting cells between submeshes.

### 3. Results and discussion

A series of computational experiments was performed on multiple configurations of the vortex tube with following parameters: $D = 4.7$ cm; $r = d = 0.9$ cm; $h = 0.5$ cm; $p = 0.45$ cm; $q = 1$ cm; $m = 4$ cm; $l = 2.5$ cm. The parameter $L$ is variable and ranges between 20 and 80 cm.

As for initial state and boundary conditions for the vortex tube: the inside volume of the vortex tube there is air resting still at the temperature of 300 K and the pressure of $10^5$ Pa; on the inlets air with the temperature of 300K is being supplied at a constant volume flow rate (0.2 $m^3/s$ on the vortex generators and 0.02 $m^3/s$ on the additional inlet); It should be noted that on the outlets wave transmissive boundary condition is set. The tube walls are thermally insulated and have no friction.

Graphs of temperatures, velocity and mass rate are presented in figures 2 and 3 for hot and cold outlet respectively. Starting with minimal length behaviour of the tube is typical to a vortex tube: growth of the temperature on the hot outlet and drop on the cold outlet. This process goes on until it reaches the length of 50 cm. All simulations are ought to reach at least 150 ms of simulation time where last 50 ms are used to calculate average of the physical values. It’s assumed that up to 100 ms and further the flow is stable what can be observed as a set of similar values of averages on slices on the cold and hot side at discrete moments of time. For lengths over 50 cm simulation time has been risen up to 210 ms because the longer the tube, the longer it takes for the flow to stabilize. After simulation of all tubes with lengths between 20 and 80 cm with the step of 10 cm, the additional lengths 55, 65 and 75 cm were also taken due to their interesting behaviour.

It is evident that in all presented graphs the characteristics of the vortex tube are improving and are going to their supposed optimum at the length of 50 cm. Hot outlet shows notably smooth picture, nearly straight line in the temperature graph in figure 2 (a) and slightly jittery
Figure 2. Dependencies of the average temperature $T$ (a), the velocity $U$ (b) and the mass flow rate $Q$ (c) on the vortex tube channel length $L$ on the hot outlet cross section.

Figure 3. Dependencies of the average temperature $T$ (a), the velocity $U$ (b) and the mass flow rate $Q$ (c) on the vortex tube channel length $L$ on the cold outlet cross section.

In the end of graphs of mass rate and velocity in figures 2 (b) and 2 (c). However, for the cold outlet the graph line fluctuates a lot more. It reaches it's local minimum at 55 cm (see figure 3 (a)) where the temperature first slowly climbs up and then leaps up and down. The same happens for the velocity in figure 3 (b) and for the mass rate in figure 3 (c). Supposedly, the core physics of the flow for the lengths over 50 cm changes dramatically: while being faced against fast incident flow an additional inlet makes significant turbulent disturbance that either breaks smoothness of transition between outer and inner vortex flows or causes an oscillation. In any case, configurations with the lengths over 50 cm are yet to be carefully revised with possible recomputation with longer average interval.

In general, found dependencies demonstrate that such configuration of a vortex tube is able to reproduce Ranque–Hilsch effect which tells about a potential ability of using an additional inlet. Nevertheless, the lengths of the tube of 50 cm and more require special attention because the results on the cold outlet indicate particularly uneven transitions when in this exact range while being hidden behind instability the optimum could exist. Mainly, the points of the graph at 65 cm and over clearly appear as sporadic movement. Worth noting a hard to notice alignment around some average at the lengths between 70 and 80 cm that has occurred multiple times in different experiments.
4. Conclusion
Thus, the presented configuration of a vortex tube with an additional inlet in the hot outlet area demonstrates the Ranque–Hilsch effect as well as a classical configuration by gradually improving characteristics with the increase in length. However, after a certain point the core physics of the flow is undergoing a serious change that needs to be looked into more carefully at least because it’s hard to say anything unequivocal about what happens at the lengths over 50 cm. The assumption was made that the nature of such behaviour might be the turbulence itself, mostly due to collision of incident streams.

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