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Numerical research of the swirling supersonic gas flows in the self-vacuuming vortex tube

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Abstract. This article presents the results of simulation for a special type of vortex tubes – self-vacuuming vortex tube (SVVT), for which extreme values of temperature separation and vacuum are realized. The main results of this study are the flow structure in the SVVT and energy loss estimations on oblique shock waves, gas friction, instant expansion and organization of vortex bundles in SVVT.

Keywords: self-vacuuming vortex tube, supersonic swirling gas flows, oblique shock wave.

Nomenclature
$t$ – time, $x_i$ – Cartesian coordinates, $u_i$ – Reynolds-averaged components of instantaneous velocity vector in the Cartesian coordinate system, $u_i'$ – pulsation components of instantaneous velocity vector in the Cartesian coordinate system, $\rho$ – density, $p$ – pressure, $h_i$ – total enthalpy, $T$ – temperature, $\lambda$ – coefficient of thermal conductivity, $c_p$ – specific heat capacity at constant pressure, $\mu$ – dynamic viscosity, $\rho u_i' u_j'$ – components of turbulent stress tensor, $k$ – specific turbulent kinetic energy, $\omega$ – specific rate of dissipation of $k$, $P^s$ – total (stagnation) pressure, $T^s$ – total (stagnation) temperature.

1. Introduction
Vortex flows have been of significant interest since the mid-20th century because of their occurrence in industrial applications such as furnaces, gas turbines and collectors (Gupta et al. [1]). In addition, vortex (or high degree of swirling) can also produce a hot and cold stream separation via Ranque-Hilsch vortex tube [2, 3]. Nash [4] and Dobratz [5] provided extensive reviews of vortex tube utilizations and enhancements. Intense experimental and numerical studies of Ranque-Hilsch tubes have begun since 1931 and continue even nowadays [6, 7, 8]. The most famous scientific school studying the Ranque-Hilsch effect in Russia was led by Professor A.P. Merkulov [9, 10, 11]. In addition to traditional applications of vortex tubes, this school proposed a number of new utilizations in aviation, chemical industry, power industry, agriculture, etc. Special merit of this scientific school is the creation of vortex electro-discharged devices: CO₂-lasers and plasmatrons [12, 13]. A significant number of theories have been proposed to explain the vortex effect of «temperature separation» since its initial observations by Ranque [2]. Despite all proposed theories, none has been able to fully explain the one. This fact is partially compensated by the numerical models of flow in vortex tubes. Numerical studies of swirling gas flows in the vortex tube were presented by following researches [6,
7, 8]. Simulations were made using turbulent models ranging from simple RANS (as standard k-ω [6] to large eddy simulation (LES) [7]. At the same time the least developed type of vortex tubes in theoretical and experimental aspects is the self-vacuuming vortex tube (SVVT), where extreme values of temperature separation ($\Delta T_{cold}=152K$, gas - air [1]) and vacuum ($\pi^*=P^*/P_{axis}=40$, where $P^*$ - total gas pressure at the inlet of SVVT, $P_{axis}$ - gas pressure near the axis of SVVT) are realized. In contrast to classic vortex tubes [2, 3] SVVT have neither hot nor cold flow exits. Instead, SVVT is used for its internal body cooling. There are some engineering models for calculation of flows and thermodynamic performances of SVVT [13, 14]. Though they allowed creating a new class of electro-discharged devices (CO$_2$-lasers and plasmatrons [12]), still there are no theoretical studies of the flow behaviour in SVVT, based on modern computational fluid dynamics (CFD) simulation techniques. The present paper is devoted to the CFD study of strongly swirling gas flows in SVVT based on the RSM turbulence model.

2. Schematics of the problem geometry
Schematics of the problem geometry is shown in figure 1. The basic dimensions of SVVT are the following: tube’s radius and height are $R_t = 5$ mm, and $H_t = 11.5$ mm, respectively. Central body radius, fillet radius, diffusor radius and diffusor height are $R_{cb} = 0.5$ mm, $R_f = 1.5$ mm, $R_d = 25$ mm, $H_d = 1$ mm, respectively. The width of inlet is $a = 2.1$ mm, and its height is $b = 1.4$ mm.

![Figure 1. Schematics of the problem geometry (red dot marks reference frame origin)](image)

3. Mathematical model
The compressible turbulent flows in SVVT are governed by mass, momentum and energy conservation equations, together with equation of state. The Reynolds-averaged forms of these equations are:

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_k)}{\partial x_k} = 0,$$

$$\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial (\rho u_i u_k)}{\partial x_k} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_k} \left( \tau_{ki}^{eff} \right),$$

$$\frac{\partial (\rho h)}{\partial t} - \frac{\partial (\rho u_k h_k)}{\partial x_k} = \frac{\partial}{\partial x_k} \left[ \lambda \left( \frac{\partial T}{\partial x_k} \right) \right] + \frac{\partial}{\partial x_k} \left( \rho \tau_{ki}^{eff} \right),$$

where $h = h + \frac{1}{2} u_k u_k$ is the total enthalpy, $h = C_p T$ is the static enthalpy, $\tau_{ij}^{eff} = \tau_{ij} - \rho \frac{\partial u_i}{\partial x_j} \frac{\partial u_j}{\partial x_i}$ is the effective stress tensor, $\tau_{ij} = \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)$ is the viscous stress tensor, $W$ is the molar mass, and $R_\beta = 8.314472 m^2 \cdot kg/(s^2 \cdot K \cdot mol)$ is the universal gas constant.
In this study, the flow was considered fully turbulent. For the description of turbulence, Omega Reynolds Stress model was used [14]. It comprises six transport equations for turbulent stresses as well as an additional transport equation for $\omega$, which is similar to the equation of $k$-$\omega$ model.

4. Numerical model

For the numerical solution of governing equations, ANSYS CFX commercial CFD software was used. It utilizes a finite volume method. The simulation was carried out with the following boundary conditions: specified values of total (stagnation) pressure and total (stagnation) temperature at inlets, with flow direction at inlets normal to the boundaries; specified values of pressure and temperature at the exit. These values were interpreted as values of static parameters at those parts of boundary where the flow leaves the simulation domain and as values of total parameters at those parts of boundary where the flow enters the simulation domain in the case of the reversed flow. All the walls of SVVT were considered adiabatic. The inlet parameters varied: $P^*$ from 0.15 MPa to 0.7 MPa, and $T^*$ from 500K to 5000K. The gas was helium, with $W = 4.0 \text{ g/mol}$, $C_p = 5193.0 \text{ J/(kg\cdot K)}$. Transport properties $\lambda$ and $\mu$ were considered as functions of temperature according to [15].

The calculation was carried out in a pseudo-transient formulation with fixed pseudo-time step equal to $10^{-7}$ s. Convergence criteria, besides the standard ones based on average normalised residuals, were the global imbalances of mass and energy (the threshold value 0.1%) and constancy of mass flow rate.

The initial computational mesh featured $4.3 \cdot 10^6$ elements (1.5 $\cdot 10^6$ nodes) with the following adaptation, based on pressure gradient, up to $11.3 \cdot 10^6$ elements (3.0 $\cdot 10^6$ nodes).

5. Results and discussion

Simulations were carried out for different cases with different values of the inlet pressure and temperature. Figures 2-7 show the results for $T^*=500K$ and $P^*=0.3 \text{ MPa}$ (which was the main case).

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Figure 2. Comparison of viscous and inviscid simulation results (velocity coefficient in the inlet plane)
For the main case, a comparative analysis of viscous and inviscid (i.e. $\mu = 0$) flows was made (figures 2 and 3). Figure 2 shows that in the nozzle section of SVVT for both viscous and inviscid gas
the flow entering the main tube from the nozzle accelerates to supersonic and then decelerates to subsonic velocity. For the viscous flow, the deceleration occurs in a system of three oblique shocks, while for the inviscid flow it occurs in a single normal shock. This leads to a significant decrease of the total pressure losses in viscous flow comparing to inviscid one. However, the sum of losses in case of viscous flow is slightly larger: the resulting mass flow rate was about $1.5 \times 10^4$ kg/s for the viscous flow and about $1.6 \times 10^4$ kg/s for the inviscid. Figure 3 shows the difference in the general flow pattern. The “jets” produced by nozzles in the viscous flow case exhibit internal secondary swirl due to interaction, which is not observed for the inviscid flow. There is now a toroidal vortex at the inlet into the diffuser in case of viscous flow. In both cases, there are zones of reversed flow in the diffuser, but for the inviscid flow these zones are much more extensive.

Note that the flow in SVVT has a rather complex character: tangential inlets form the “jets” in which the gas first is accelerated to supersonic velocities and then decelerated in the system of oblique shocks. Besides, the interaction between the “jets” causes secondary swirling. In the end, the large peripheral vortex in the main part of SVVT consists of three (by the number of inlets) vortex cores. In spite of the fillet in the area of transition from the main part of tube to the diffuser, flow separation occurs, resulting in the toroidal vortex with double rotation. All these secondary vortex structures are significant sources of power losses, together with shocks. Unfortunately, these losses are difficult to assess explicitly.

Detailed study of simulated flow fields have showed some unexpected results: local increase of total pressure and total temperature (up to 5%) were observed. It may be considered as an error of the specific computational model. However, in [16] it has been suggested that these local disturbances can take place not due to errors of numerical simulation but because of the action of friction forces. The local increase of total thermodynamic parameters can be explained by interaction between swirled “jets” (vortex cores), because the observed increase of total parameters along the streamline belonging to one vortex core corresponds to the decrease of these parameters along the streamlines belonging to the other vortex cores. Note that in spite of somewhat questionable local variation, integrally all conservation laws are satisfied.

6. Conclusion
For the first time flow pattern in SVVT was studied with state-of-the-art CFD techniques. It has been found that this pattern is rather complex: it features both subsonic and supersonic regions, systems of oblique shocks, primary and secondary vortices with strong interaction. An attempt was made to estimate the sources of power losses. It has been found that only a small amount of losses could be attributed to friction and turbulence (from 2% to 10%, depending on inlet conditions, with losses due to turbulence making less than 1% for all cases). It is assumed that most of the losses occur due to shocks and secondary swirl generation.

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