Investigation of the cascade mechanism of energy exchange in swirling gas flows based on the effect of secondary swirling

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Abstract. The article presents the results of studies of the secondary swirling effect in supersonic rotating gas and plasma flows. It is shown that the secondary twist of the jets of gas flowing from the nozzle apparatus generates a cascade structure of vortices that separate energy in the field of azimuthal and radial pressure gradients. As shown by the calculations, the effect of energy separation is more significant the higher the level of secondary twisting of the nozzle jets, which, in turn, is determined by the level of energy dissipation. Experimental confirmations of the revealed cascade mechanism of energy separation in supersonic swirling gas flows are discussed. Keywords: secondary swirling effect, energy dissipation, energy separation, self-vacuuming vortex tube.

1. Introduction

This work is a continuation of the series of works by the authors [1-5] on the numerical study of the flow structure in supersonic swirling flows formed in the self-vacuuming vortex tubes (SVT). In these works, the influence of both the geometric characteristics of the SVT and approaches to numerical simulation was studied. The authors identified the effect of secondary swirling of the flow, which is manifested in the intensive twisting of the jets outflowing from the nozzle apparatus (vortex cords) around their axes. The vortex cords generate a cascade of macro-vortex structures in the chamber (figure 1), which implements the mechanism of energy separation in swirling gas and plasma flows.

![Figure 1. Cascade vortex flow structure in a vortex chamber.](image-url)
2. Numerical flow simulation in the SVT with a central body

The first object of research was a small-sized SVT (with a diameter of 1·10⁻² m) with a central body with helium as the working medium. The nozzle apparatus of this SVT consisted of straight tangential channels. The density of helium was considered to be temperature- and pressure-dependent following the equation of state of the ideal gas. The specific heat capacity at constant C_p pressure was considered constant and equal to 5197.5 J/(kg·K). The specific heat conductivity λ and the dynamic viscosity μ were considered temperature-dependent according to the correlations from [6].

At the inlets, the stagnation parameters were set \( p^* = 3 \cdot 10^5 \) Pa, \( T^* = 500 \) K, while at the outlet – static parameters \( p = 10^5 \) Pa, \( T = 300 \) K. The calculations were based on Reynolds equations, using the RSM-Omega turbulence model, and employing commercial software ANSYS CFX implementing the control volume method. The computational grid for flow modeling was an unstructured hybrid grid consisting of tetrahedral and prismatic elements. Prismatic elements were arranged in layers along the walls, 10 layers in total. The initial dimension of the grid was 4.3 million elements (1.5 million nodes) followed by adaptive grinding to 11.3 million elements (3.2 million nodes). In this case, the number of nodes is more significant, since ANSYS CFX builds the calculated control volumes around the nodes of the original grid.

The Reynolds stress transfer model used (RSM Omega) [7] is a modification of the Launder-Reece-Rodi model, to express the dissipation of turbulent stresses, which uses the specific rate of dissipation \( \omega \) instead of the rate of dissipation \( \varepsilon \), as in the original version. Numerical simulation of the flow in this SVT showed that after the nozzle section of the vortex chamber, where there is a system of oblique jumps of compaction, a supersonic flow mode is implemented in the entire chamber for the full flow rate. Figures 2 and 3 show examples of isosurfaces of the Mach number \( M = 1 \) for a different number of inputs.

The results of numerical simulation revealed the effect of secondary twisting of the jets (i.e., the twisting of the jet relative to its own axis) formed by separate inputs of the nozzle apparatus. It was found that the formation of a secondary swirling is associated with viscous (dissipative) effects since modeling of an inviscid gas flow based on Euler equations showed that in this case, the gas jets formed in the nozzle apparatus do not twist relative to their own axis. At the same time, the effect of energy separation in the SVT is absent.

The influence of the geometric characteristics of the nozzle apparatus on the formation of a secondary twist and the effect of energy separation was studied. First, the influence of the number of inlets was considered. When changing the number of inlets, the ratio of the total inlet area to the outlet area remained constant and equal to 1:20. This ensured the constancy of the primary spin in the SVT. The separate inlet also remains constant – a rectangle with an aspect ratio of 3:2 (long side is oriented along the radius of the tube, short side – along the axis of the tube). Also, for the case of three inlets, the design of the nozzle apparatus with circular cross-sections of the inlet nozzle was considered.

Table 1 shows the results of the study of the influence of the number of inlets on the performance characteristics of the pipe – the degree of pressure reduction, as well as a decrease in the static and full flow temperature in the pipe. As is seen from the Table, the best indicators are achieved when the number of inlets is equal to three. Table 2 shows the results of a study of the influence of the inlet shape for the case of three inlets. This Table shows that the rectangular shape of the inlet provides the best characteristics of the SVT. An attempt was also made to estimate the number of secondary and tertiary vortex structures formed in the SVT at a different number of nozzle inlets. These results are shown in Table 3.
Figure 2. Isosurface $M = 1$ for the SVT with one inlet.

Figure 3. Isosurface $M = 1$ for the SVT with three inlets.

Table 1. Influence of the number of nozzle inlets on the performance of the SVT.

| Numbers of inlets | $\pi_{\text{min}} = p_{\text{min}} / p^*$ | Maximal decrease in static temperature flow $\Delta T$, K | Maximal decrease in the total temperature, $\Delta T^*$, K |
|-------------------|---------------------------------|---------------------------------|---------------------------------|
| 1                 | 0.089                           | 168                             | 48                              |
| 2                 | 0.062                           | 197                             | 49                              |
| 3                 | 0.043                           | 252                             | 88                              |
| 4                 | 0.086                           | 201                             | 60                              |
| 6                 | 0.112                           | 166                             | 59                              |

Table 2. Influence of the inlet shape (for the case of three inlets) of the nozzle unit on the performance of the SVT.

| Inlet cross-section shape | $\pi_{\text{min}} = p_{\text{min}} / p^*$ | Maximal decrease in the static temperature $\Delta T$, K | Maximal decrease in the total temperature $\Delta T^*$, K | Maximal azimuthal velocity of the vortex cords near own axis |
|--------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| Rectangular.             | 0.043                           | 252                             | 88                              | M=0,95                           |
| Circle                   | 0.066                           | 236                             | 61                              | M=0,84                           |

Table 3. Estimation of the number of secondary and tertiary vortex structures in the main part of the SVT.

| Number of inlets | The approximate number of secondary and tertiary vortex structures |
|------------------|---------------------------------------------------------------|
| 1                | ~3…4                                                          |
| 2                | ~5…7                                                          |
| 3                | ~6…8                                                          |
| 3 (circle)       | ~4…5                                                          |
| 4                | ~5…7                                                          |
| 6                | ~5…7                                                          |
3. Numerical flow simulation in the SVT without a central body

For comparison with the results of the planned experiments, a simulation of the flow in the SVT without a central body was also performed. In this larger-scale SVT (3·10⁻² m in diameter), the working body was air. The nozzle apparatus in this SVT was formed by profiled blades. In this case, two configurations of the nozzle device were considered – with a step and without a step. The ratio of the total area of the inlets formed by the nozzle blades to the exit area was equal to 1: 20. In addition to the influence of the nozzle configuration, the influence of the SVT configuration was studied – asymmetric with one diffuser and symmetrical with two diffusers.

The density of air was considered to depend on temperature and pressure following the equation of state of an ideal gas. The specific heat capacity at constant pressure $C_p$, the specific heat conductivity $\lambda$, and the dynamic viscosity $\mu$ were considered temperature-dependent according to the correlations from [6]. At the inlet, the braking parameters were set $p^* = 4\cdot10^5$ Pa, $T^* = 293K$, at the outlet – static parameters $p = 10^5$ Pa, $T^* = 293K$.

Similarly to the small-sized SVT with helium, it was also found that the flow at the periphery of the SVT was supersonic. Table 4 shows the results of the study of the influence of the nozzle design on the SVT characteristics. As is seen from the Table, the greatest rarefaction and the greatest decrease in total temperature are predicted when using a nozzle device without a step. It can be assumed that this is because the step in the nozzle apparatus prevents the interaction of the jets, leading to the formation of a secondary swirling. In this case, a symmetrical configuration with two diffusers is preferred.

| Nozzle apparatus | Number of diffusers | $\pi_{\text{min}} = p_{\text{min}}/p^*$ | Max. decrease in a static temperature $\Delta T$, K | Max. decrease in a total temperature $\Delta T^*$, K |
|------------------|---------------------|--------------------------------------|-----------------------------------------------|-----------------------------------------------|
| With a step      | 1                   | 0,020                                | 180                                           | 82                                            |
| Without a step   | 2                   | 0,017                                | 188                                           | 81                                            |
| With a step      | 2                   | 0,022                                | 185                                           | 103                                           |
| Without a step   | 1                   | 0,017                                | 183                                           | 127                                           |

For the optimal configuration of the pipe (symmetrical, with a nozzle without a step), the influence of the flow pattern (laminar or turbulent) and the scale effect was also studied. Simply disabling the turbulence model, i.e. switching from the Reynolds equations to the unmodified Navier-Stokes equations, did not allow obtaining convergence of the numerical solution. Therefore, the Reynolds number for the flow in the pipe was lowered by a factor of 1000. This was done due to two factors: reducing the geometric dimensions of the SVT by 10 times and increasing the dynamic viscosity of the working fluid by 100 times. Since the dynamic viscosity and thermal conductivity of real gases are related, the thermal conductivity was also increased by 100 times. The viscosity and thermal conductivity were still considered as temperature-dependent but following the molecular kinetic theory [8]. The coordinated change in the viscosity and thermal conductivity allowed maintaining similarity in the Prandtl number. A comparison of results for turbulent and laminar flows is shown in Table 5. As is seen from the Table, with a small Reynolds number (laminar flow), the characteristics of the SVT significantly deteriorate, although the effects of vacuuming and energy separation are still observed. We can assume that this is because, in the case of laminar flow, even the increased value of the dynamic viscosity for reducing the Reynolds number is about 10 times less than the maximum value of the turbulent dynamic viscosity in the case of a turbulent flow.

| Flow pattern | $\pi_{\text{min}} = p_{\text{min}}/p^*$ | Maximal decrease in static temperature $\Delta T$, K | Maximal decrease in total temperature $\Delta T^*$, K |
|--------------|--------------------------------------|-----------------------------------------------|-----------------------------------------------|
| Laminar      | 0,522                                | 6                                             | 6                                             |
| Turbulent    | 0,017                                | 183                                           | 127                                           |
4. Results of comparison of experimental and calculated characteristics of the self-vacuuming vortex tube

The results of an experimental study of a vortex glow discharge conducted at the Institute of Chemical Physics of the Russian Academy of Sciences in the late ‘80s can serve indirect confirmation of the secondary swirling effect [9, 10]. During the study, the high-speed shooting of multiple breakdowns with a resolution time of $10^{-6}$ s was performed. As follows from figure 4, in a smoldering vortex discharge, the breakdown takes place at the relative radius of the chamber $r=0.25-0.3$. The result was paradoxical since, in a stationary mode, the minimum pressure is realized on the axis of the vortex chamber. This experimental fact can be explained by the effect of secondary twist, where on the time scale ($10^{-7}$-$10^{-6}$ s) the minimum pressure is realized on the axis of the vortex cord.

Numerous experimental studies of vortex tubes [9, 10] have shown that the maximum efficiency is achieved with a three-node tangential inlet. However, this fact has not been explained until recently. The numerical simulation of the swirling flow in the SVT based on the RANS and SRS models of turbulence allowed explaining this phenomenon – the number of macro-vortices in the cascade structure is maximum for three-node inlet, which explains the more perfect energy separation process in the vortex chamber. The secondary swirling effect and direct calculations allow explaining the experimental fact that a nozzle with a rectangular cross-section is optimal compared to the round one with the same area since the perimeter of the rectangular nozzle is larger. Following this, the jet flowing out of the nozzle with a rectangular cross-section has an additional twisting moment that increases its circumferential velocity of the vortex cords, which, in turn, leads to an intensification of energy exchange in the vortex chamber (Table 2). Figure 5 shows a comparison of calculated and experimental values of the temperature distribution in the SVT. As follows from this illustration, the agreement is satisfactory. There are other experimental confirmations of the influence of the secondary swirling effect on the energy separation process in the vortex chamber [11].

![Figure 4. Multiple breakdowns in a vortex glow discharge.](image)

![Figure 5. Radial temperature distribution in the SVT vortex chamber: + - experiment, ● - calculation](image)
Conclusions
This article presents the results of a study of the cascade vortex structure in the supersonic swirling gas flows. The cascade system of macro-vortices in the vortex chamber is formed due to the azimuthal pressure gradient caused by secondary vortices, which are jets outflowing from the nozzle into the chamber. In this case, the velocity of rotation of the jets relative to its axis reaches sound values, which, in turn, due to the main twisting of the flow (global twisting), leads to a supersonic flow mode in the entire volume of the vortex chamber. The absence of seal jumps after the nozzle is explained by the fact that the circumferential component of the velocity does not contribute to the seal surges. The formed cascade of vortex structures in the field of radial pressure gradient implements the mechanism of energy separation in the swirling gas flow. Simulation of the gas flow in a vortex chamber has shown that an increase in the circumferential component of the velocity of the secondary vortex leads to an increase in the separation effect in the vortex chamber. The rotation velocity of the secondary vortices depends on the viscosity of the gas (laminar or turbulent flow) and the design of the nozzle apparatus. The above simulation allows answering the question about the optimal number and shape of nozzles – with a three-way nozzle inlet, the number of vortex structures is maximum, and the effect of energy separation is maximum. An important sign of the realization of the cascade mechanism of energy separation in the vortex chamber with the effect of secondary twist is the growth effect of temperature separation in the vortex chamber when the number of formed vortex macrostructures is increasing. This fact is confirmed by the experiment [9, 10].

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