Effect of different inlet pressures on the temperature field, velocity field and pressure field of a vortex tube

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Abstract. In view of the wide application of vortex tube (VOTU) in the market, and in order to enhance the capability of VOTU in the higher inlet pressure, three-dimensional numerical simulations were performed with existing experimental data and models to analyse the flow fields of VOTUs at different pressures. With the increase of pressure, the maximum temperature of the VOTU rises rapidly and the minimum temperature decreases smoothly. Meanwhile, when the VOTU works under high pressure, the wall thickness and sealing degree of the VOTU design should be increased accordingly, while the inner wall of the VOTU should be made of wear-resistant material to avoid the wear of the VOTU caused by the long-term scouring of the high-speed airflow.

1. Introduction

The VOTU (VOTU) is a portable device that employs compressive gas for cooling and heating. It mainly consists of nozzle inlet, vortex chamber, cold gas outlet pipe, hot end tube, and flow control valve [1, 2]. The compressed gas enters from the VOTU inlet and forms a high-speed cyclonic fluid inside the vortex chamber, which will form a three-dimensional compressible turbulent flow at the hot end tube, the VOTU generates a cold airflow at one end and a hot airflow at the other end [3]. And it is an expansion and depressurization device with a lightweight construction and without moving parts, making it easy to maintain. This is beneficial to the environment by eliminating the use of refrigerants [4, 5].

Although the internal design of VOTU is simple, the flow state of the fluid inside the tube and the energy separation process require thorough investigations. Researchers investigated the working mechanism of energy separation by analysis, simulation and experiment, but there is no one universal rational explanation [6]. In fact, many factors that affect the effectiveness of the cyclone can be divided into two categories, one is the cyclone structure parameters, which are the number of cyclone inlet nozzles, nozzle material, shape, hot and cold tube shape, diameter, and so on. The second is the thermal nature of the compressed gas parameters, which are the working fluid, the gas inlet pressure, the inlet temperature [7-9].

The magnitude of the inlet pressure will affect the flow state of the internal temperature and cyclonic fields [10]. Attalla experimentally investigated the effect of structural parameters of the
VOTU on the temperature separation, due to the experimental conditions, the maximum inlet pressure can only be 0.6 MPa, but the experimental results found that the inlet pressure is greater than the effect of the number of nozzle runners on the VOTU, when the pressure is greater than 0.6 MPa, what kind of energy separation law the VOTU will be requires further study. This paper uses the experimental data of Attalla to conduct more systematic and in-depth simulations by numerical simulation of computational fluid science, which provides a new way to study the complex flow and energy separation effect inside the VOTU [11].

2. Simulation

2.1. Physical dimensions of the VOTU

Figure 1 shows the dimensions of the numerical simulation of VOTU, and the simplified model of VOTU was created by 3D data modeling software SolidWorks 2016, the length of the hot end pipe and the cold end pipe are 112.5 mm and 5 mm respectively, and the diameter is 7 mm and 5 mm respectively.

![Figure 1. Diagram of the numerical simulation dimensions of VOTU.](image)

2.2. Governing equations

For the numerical simulation of VOTUs, the choice of computational model is crucial. By reviewing the literature, it was found that Bazgir et al. [12, 13] applied the RNG k-ε turbulence model in the numerical simulation of the VOTU, numerical simulation data show that the model can more accurately reflect the real flow state, the distribution of the internal temperature field and flow field, so the RNG k-ε turbulence model was used in this study. RNG k-ε turbulence model for numerical simulations.

The controlling equations are respectively:

\[
\frac{\partial}{\partial x_j} (\rho u_i u_j) = - \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_i} \left[ \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} \eta_\gamma \frac{\partial u_k}{\partial x_k} \right] \\
+ \frac{\partial}{\partial x_j} \left( \frac{\mu_t}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} \rho k \frac{\partial u_k}{\partial x_k} \eta_\gamma \\
\frac{\partial}{\partial x_i} \left[ \rho (h + \frac{1}{2} u_j u_j) \right] = \left( \frac{\partial}{\partial x_j} \right) \left[ k_{eff} \frac{\partial T}{\partial x_j} + u_i (\tau_{ij})_{eff} \right] k_{eff} \\
= K + \frac{c_p \mu_t}{\rho_t} T \\
\frac{\partial}{\partial x_i} (pk u_i) = \nabla \cdot \left[ \alpha_k k_{eff} \nabla k \right] + 2 \mu_t E_{ij} E_{ij} - \rho \varepsilon - Y_m \\
\frac{\partial}{\partial x_i} (p \varepsilon u_i) = \nabla \cdot \left[ \alpha_k \varepsilon \eta_{eff} \nabla \varepsilon \right] + C_v \frac{\varepsilon}{k} 2 \mu_t E_{ij} E_{ij} - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} 
\]

2.3. Boundary condition
To ensure the accuracy of the simulation data, boundary conditions are one of the important settings. The standard wall function method is used in the near-wall area, and the effect of viscosity on the VOTU is not considered. The inlet is a pressure inlet with an initial temperature of 277 K and the outlet is a pressure outlet.

2.4. Grid independence study
The number of meshes affects the results of numerical simulations, the mesh of the VOTU is analyzed independently in this part. As shown in Table 1, the VOTU was divided into four different mesh numbers, 360377, 415651, 498330, and 624494, in Mesh 19.0. Numerical simulations were performed in Fluent 19.0, and the following numerical simulation results were obtained for the VOTU cold end temperature differences of 16.0 K, 16.6 K, 18.4 K, and 17.5 K, respectively. The results are consistent with the experimental results $\Delta T = 19.0$ K, the analysis reveals that the VOTU will have a large error when the number of grids is not enough, and when the number of grids is more, not only the accuracy is not high, but also a lot of calculation time will be consumed, therefore, the number of grids used in this simulation is 498330.

| Cells    | 360377 | 415651 | 498330 | 624494 |
|----------|--------|--------|--------|--------|
| $\Delta T$(K) | 16.0   | 16.6   | 18.4   | 17.5   |

3. Results and discussion

3.1. Validation
Attalla studied the influence of inlet pressure on the cold outlet temperature. Figure 2 shows the CFD simulation data of the VOTU compared to the experimental data of the cold outlet temperature. The inlet pressures are 0.2 MPa-0.6 MPa, and the experimental temperature differences are 17.0 K, 18.0 K, 19.0 K, 19.5 K, and 21.0 K. The results obtained from the numerical simulations are, respectively, 17.0 K, 18.1 K, 18.4 K, 20.0 K, and 21.0 K. Numerical simulations using the RNG $k$-$\varepsilon$ model were chosen to be accurate and reliable, it can truly reflect the fluid flow state inside the VOTU.

![Figure 2. Comparison of CFD data of VOTU with experimental data.](image)

3.2. Effect of different inlet pressures on the axial temperature distribution of VOTU
The dark area in the core part of the VOTU in Figure 3 represents the cryogenic airflow inside the VOTU. The area of the cryogenic airflow increases slowly with the gradual increase in pressure. After the high-speed airflow enters from the inlet of the VOTU, higher temperature airflow is formed
outside the vortex chamber, while a lower temperature gas flow will be formed in the center region inside. The same conclusion was reached by Aghagoli [10], where the warmer airflow was distributed in the outer part and the cooler airflow in the central part [14]. The increase in pressure leads to an increase in the flow of low-temperature gas and a decrease in temperature.

Figure 4 shows that the temperature inside the vortex chamber is almost symmetrically distributed, and the higher temperature gas flow is distributed on the outside of the vortex chamber and increases more with the increasing pressure, compared to the more stability in the increase of the low temperature gas flow.

![Figure 3. Radial temperature distribution diagram of VOTU.](image)

![Figure 4. Radial temperature distribution at different inlet pressures.](image)

3.3. Influence of inlet pressure on VOTU radial velocity
The VOTU inlet pressure variation also affects the radial velocity distribution. As shown in Figure 5 the contour chart of the radial velocity distribution of the vortex chamber. As shown in Figure 5 the color of the outer area of the vortex chamber gradually deepens, but the low velocity fluid in the central area has little effect on the change of pressure. The numerical simulation results are similar to Adib's data, where there is a minimum tangential velocity in the central region, an increase in the outer velocity, and a decrease in the velocity near the wall due to friction [15]. As can be seen in Figure 6, with the increasing pressure, the low velocity fluid inside the VOTU is always in the range of 20 m/s-40 m/s. When the inlet pressure is 1 MPa, the maximum inlet velocity of the VOTU is 258 m/s, and when the inlet pressure increases to 2 MPa, the maximum velocity surges to 367 m/s.

The inlet pressure has a significant effect on the maximum radial velocity of the VOTU, and the maximum radial velocity rises sharply with the increase of pressure, and the high-speed airflow is
distributed on the outer side of the vortex chamber. Therefore, when the VOTU works at high pressure, the wall thickness and sealing degree of the VOTU design should be increased accordingly, and the inner wall of the VOTU should be made of wear-resistant material to avoid the wear of the VOTU caused by the long-term scouring of the high-speed airflow.

![Figure 5. The influence of inlet pressure on VOTU radial velocity.](image1)

![Figure 6. Radial velocity distribution at different inlet pressures.](image2)

3.4. Effect of different inlet pressure on the radial pressure distribution of VOTU
The inlet pressure is the dominant factor impacting the capability of the VOTU. Due to the process of expansion and decompression of the high pressure gas into the VOTU, the inner core flow has a low static pressure caused by the expansion process [10, 15]. Figure 7 exhibits a contour graph of the internal section of the vortex chamber, and it is obvious that the radial region to the center of the external section of the vortex chamber also shows a remarkable pressure gradient, and the pressure gradient increases with the gradual increase of the inlet pressure. It is the unique pressure gradient inside the VOTU that leads to a certain regular three-dimensional vortex flow inside the VOTU.

Figure 8 shows the VOTU radial pressure distribution at different inlet pressures, the same as the temperature distribution and velocity distribution, the radial pressure is symmetrically distributed inside the vortex chamber, and the lowest pressure distribution in the central region is basically the same, once again, the greater the pressure will lead to an increase in the pressure gradient inside the vortex chamber, increasing the temperature separation of the VOTU.
4. Conclusion
In this paper, three-dimensional numerical simulations were performed using available data to investigate the effects of different pressures on the internal temperature and flow field, as well as the energy separation of the VOTU at higher than 0.6 MPa. Analysis of the axial temperature distribution of the vortex chamber can be concluded that the temperature at the cold end drops slower and the hot airflow increase faster as the pressure enhances. The analysis of radial velocity shows that when the VOTU works under high pressure, the wall thickness and sealing degree of the VOTU design should be increased accordingly, and the inner wall of the VOTU should be made of wear-resistant material to avoid the wear of the VOTU caused by the long-term scouring of the high-speed airflow.

Author Contributions
Qijun Xu: Conceptualization, Formal analysis, Data curation, Writing - original draft, Review and Editing. Jing Xie: Conceptualization, Funding acquisition, Supervision, Writing - original draft, Review and Editing. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest
The authors declare no conflict of interest

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