Effect of different inlet pressures of vortex tube on internal flow field

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Abstract. Numerical simulations were used to investigate the distribution of the internal pressure, velocity, and temperature fields in the vortex tube (VOTU) at inlet pressures of 1-4 MPa to reveal the causes of temperature separation. A three-dimensional model with a nozzle flow channel number of 5 was drawn, and the simulation was performed in Fluent 19.0 with CO₂ as the working fluid. The simulation results show that when the inlet pressure of the VOTU is greater than 2 MPa, the temperature separation between the hot and cold air streams of the VOTU gradually increases with the increase of the inlet pressure. The maximum temperature is 285 K and the minimum temperature is 257 K at an inlet pressure of 1.0 MPa, and the maximum temperature is 319 K and the minimum temperature is 243 K at an inlet pressure of 4.0 MPa. As the inlet pressure increases, the temperature difference inside the VOTU will also increase. In the high-pressure condition, the wall thickness and sealing degree of the VOTU design should be increased accordingly, while the inner wall side of the VOTU needs to use wear-resistant materials to delay the long-term scouring of the VOTU caused by high-speed airflow. The results of the study have certain guiding significance for the design and manufacture of VOTUs.

1. Introduction
The most prominent advantage of vortex tubes (VOTUs) compared to other refrigeration devices is that they have no moving parts, light weight, simple structure, easy production, low cost, and long maintenance intervals [1, 2]. However, VOTUs also exist weaknesses such as low refrigeration efficiency and small cooling capacity, which limit its expansion in the industrial field. The VOTU mainly consists of nozzle inlet, vortex chamber, vortex generator, hot end tube, hot end control valve, hot end outlet, cold end control valve and cold end outlet. The pressurized gas enters the vortex generator through the nozzle inlet in the tangential direction and then rotates at high speed in the vortex chamber, where the gas is divided into hot and cold streams due to energy separation [3, 4]. In fact the energy separation in the VOTU is caused by various factors, such as the number of inlet nozzles, the shape of the outlet at the cold and hot ends of the VOTU, the length and diameter of the VOTU at the hot end of the tube, and the working fluid [5].
The inlet pressure is the source of power for the VOTU to produce temperature separation, and different inlet pressures generate positive effects on the internal temperature field and the flow of the cyclonic flow field. Hitesh [6] built a VOTU experimental device to study the effect of compressed air from 0.2 MPa to 0.5 MPa on the cold mass fraction (the ratio of mass flow rate at the cold end of the VOTU to the inlet mass flow rate) of the VOTU. With the experimental data of Han [4], Aghagol [7] studied the flow field of a VOTU at three inlet pressure states of 0.55 MPa, 0.85 MPa, and 1.3 MPa using three-dimensional numerical simulations and performed a thermodynamic analysis, concluding that the higher the pressure the more pronounced the temperature separation phenomenon is, but it is not known whether the pressure is still greater at pressures greater than 1.3 MPa temperature separation phenomenon.

In experimental studies of CO2 VOTUs, the compressed gas is supplied to the VOTUs through CO2 cylinders, and higher pressures of CO2 need to be pressurized through CO2 compressors. Few researchers at home and abroad have studied the performance of VOTUs utilizing CO2 at a pressure of 2 MPa or higher. Therefore, in this paper, a VOTU model is established to numerically simulate the flow analysis of the internal flow field of the VOTU at inlet pressures of 1 MPa, 2 MPa, 3 MPa, and 4 MPa using CO2 as the working fluid. This paper reveals the flow law of the internal flow field of the VOTU, and lays the foundation for the design and practical application of the VOTU in the future.

2. Numerical simulation of VOTU

2.1. 3D geometry model of VOTU

The number of inlet nozzles of the VOTU was designed to be 5, and the lengths of the hot-end and cold-end tubes were 120 mm and 30 mm, respectively. The energy separation process inside the VOTU is extremely complex. In order to obtain a more realistic flow state, reasonable assumptions are needed for the VOTU model during the numerical simulation calculation[8].

(1) Adiabatic isentropic flow inside the VOTU, with constant internal gas viscosity and constant pressure specific heat capacity.

(2) No internal heat source inside the VOTU, and no heat exchange between the tube wall and the external environment.

(3) Neglecting the effect of gravity on the flow state.

(4) The flow inside the VOTU is steady state flow.

2.2. Meshing of VOTU

The VOTU model is meshed using the software Mesh 19.0. Since the 3D VOTU model is complex, a non-structural mesh is chosen for the delineation, as shown in Figure 2. The boundary layer mesh is divided at the inlet nozzle of the VOTU, and local mesh encryption is performed. The mesh number and quality also affect the accuracy of the simulation results. The mesh quality can be checked by the mesh orthogonal quality in Mesh 19.0. The mesh number of 489320, 655192, 896873, 1101509, 1272830 is selected for the calculation. The result of the mesh independence check shows that the difference of...
temperature difference values at the cold end is less than 1%, so the VOTU with mesh quantity of 896873 is selected for the simulation calculation in Fluent 19.0.

![Figure 2 Nonstructural grid of VOTU](image)

2.3. VOTU boundary conditions and control equations

VOTU three-dimensional coordinates schematic diagram shown in Figure 2, the center of the hot end of the tube as the origin, the cold end of the tube exit, nozzle inlet for the Z axis and Y axis positive direction, respectively, the nozzle inlet for the Y axis positive direction, nozzle inlet are tangential into the VOTU.

VOTU boundary conditions for the pressure inlet, the total inlet pressure of 1 MPa ~ 4 MPa, the temperature of 285 K, cold end and hot end outlet are pressure outlet, the tube wall to choose the wall adiabatic no-slip boundary conditions. The outlet pressure at the cold and hot ends was fixed, and the internal flow state of the VOTU was studied by varying the total inlet pressure [9].

The standard k-ε model [10] was chosen, which can simulate the flow state inside the VOTU more accurately and reduce the time used for the simulation. For the three-dimensional compressible flow inside the VOTU the mass, momentum and energy equations are:

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \quad (1)
\]

\[
\frac{\partial (\rho u_i)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[ \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} -\frac{2}{3} \delta_{ij} \frac{\partial u_k}{\partial x_k} \right) \right] + \frac{\partial}{\partial x_j} (-\rho u_i u_j) \quad (2)
\]

\[
\frac{\partial (\rho k)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \tau_{ij} \right]_{\text{eff}} + \frac{\partial \rho q}{\partial x_j} \quad (3)
\]

\[
\frac{\partial (\rho \varepsilon)}{\partial x_j} - \frac{\partial}{\partial x_j} \left[ (\mu + \mu_t/\sigma_\varepsilon) \frac{\partial \varepsilon}{\partial x_j} \right] = C_1 \varepsilon \left( \frac{\varepsilon}{k} \right) G_k - C_2 \varepsilon^2 \left( \frac{\varepsilon}{k} \right) S_k - C_3 \varepsilon \left( \frac{\varepsilon}{k} \right) + C_4 \varepsilon \left( \frac{\varepsilon}{k} \right)^{3/2} - S_{\varepsilon} = 0 \quad (4)
\]

In the equation:

- \( G_k \): the generating term of turbulent energy k due to the mean velocity gradient.
- \( G_b \): the generating term of turbulent energy k due to buoyancy.
- \( \sigma_k \): the Prandtl (Prandtl number) corresponding to the turbulent energy k.
- \( \sigma_\varepsilon \): the Prandtl (Prandtl number) corresponding to the dissipation rate \( \varepsilon \).
3. Results and discussion

3.1. Effect of different inlet pressures on the pressure distribution inside the VOTU
Figure 3 shows the radial pressure contour diagram of the VOTU at different inlet pressures. The high-pressure CO₂ enters the vortex chamber tangentially from the inlet of the VOTU nozzle, and the pressure gradually decreases to form a high-speed cyclonic flow with gradually increasing velocity, as shown in Figure 3, most of the pressure drop in the VOTU occurs inside the vortex chamber, and the maximum pressure drop is 0.5 MPa when the inlet pressure is 1 MPa, and 2.3 MPa when the inlet pressure is increased to 4 MPa. The pressure gradient inside the vortex chamber is a critical factor in generating high speed cyclonic flow.

Inside the nozzle, high-pressure gas does not occur large pressure loss, so it can be concluded that the length of the nozzle does not affect the pressure distribution of the VOTU. When the gas enters the vortex chamber from the nozzle after the tangential direction of the inner wall is sprayed, the pressure gradually decreases, but on the other side of the non-tangential direction and the vortex chamber connection part of the pressure buildup phenomenon, the VOTU to avoid pressure buildup, slow down the high-speed airflow on the vortex chamber wear and tear, shorten the life of the VOTU.

3.2. Effect of different inlet pressures on the radial velocity distribution of VOTU
The variation of the VOTU inlet pressure also affects the radial velocity distribution, as shown in Figure 4. The high velocity airflow enters the nozzle and reaches its highest velocity at the connection between the nozzle and the vortex chamber [11]. Inside the vortex chamber, the higher velocity airflow is distributed on the outer side, and the velocity is lower in the center. With the increasing inlet pressure, the initial velocity of the VOTU inlet also increases, and it can be observed from the radial velocity cloud figure 4 that the higher the pressure, the greater the separation between the high velocity airflow and the low velocity airflow, and it can also be seen from figure 5 that the minimum radial velocity at the seven pressure states is distributed in the range of 25 m/s ~ 75 m/s, and the maximum radial velocity is 220 m/s at an inlet pressure of 1 MPa When the inlet pressure is 1 MPa, the maximum radial velocity is 220 m/s, and when the inlet pressure is 4 MPa, the maximum radial velocity is 482 m/s. It can be seen that the inlet pressure has a greater influence 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 in the outer side of the vortex chamber. Therefore, when the inlet pressure of the VOTU is greater than 2 MPa, the wall thickness and sealing degree of the VOTU design should be increased accordingly, while the inner wall side of the use of abrasion-resistant materials to avoid the long-term scouring of high-speed airflow caused by wear and tear on the tube wall.

![Figure 3 Radial pressure contour of VOTU at different pressure](image-url)
3.3. Effect of different inlet pressures on VOTU diameter to temperature

Figure 8 illustrates the contour plot of the radial velocity distribution of the VOTU at different inlet pressures. After the high-pressure airflow enters the VOTU, the airflow temperature is higher near the outer side of the vortex chamber and lower at the axial position. As the pressure continues to rise, the separation of hot and cold airflow becomes more obvious.

The inlet pressure affects the inlet velocity of the airflow and thus the separation of the hot and cold airflow in the VOTU [12]. As can be seen in Figure 9, the temperature inside the vortex chamber is symmetrically distributed, with the highest and lowest temperatures of 285 K and 257 K for an inlet pressure of 1.0 MPa and 319 K and 243 K for an inlet pressure of 4.0 MPa, respectively.

As the inlet pressure increases, the temperature difference inside the VOTU also increases. The axially lower temperature region is always in the X-direction, within a circular region of 2 mm radius, and does not change with increasing pressure, and it can be found by analysis that the size of the axially circular region is related to the diameter and shape of the cold outlet of the VOTU, and that the temperature fluctuation is smaller at the same pressure state inside this region [13-15].
4. CONCLUSION
The analysis of the pressure distribution inside the VOTU yields that the wall thickness and sealing degree of the VOTU tube design should be increased accordingly in the high-pressure state, while the inner wall side of the VOTU uses wear-resistant materials to avoid the long-term scouring of the VOTU by the high-speed airflow.

The temperature inside the vortex chamber is symmetrically distributed, and the maximum and minimum temperatures are 285 K and 257 K when the inlet pressure is 1.0 MPa, and 319 K and 243 K when the inlet pressure is 4.0 MPa. When the inlet policy increases, the temperature difference inside the VOTU will also increase.

The length of the hot end of the VOTU in this simulation is 120 mm. In the design of the VOTU, if the working pressure of the VOTU is greater than 2 MPa, the temperature turning point can be moved to the cold end by extending the length of the hot end of the VOTU to increase the temperature separation of the VOTU.

**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.
Acknowledgments
This research was supported by Science and Technology Innovation Action Plan of Shanghai Science and Technology Commission (19DZ1207503), Public Service Platform Project of Shanghai Science and Technology Commission (20DZ2292200).

Conflicts of Interest
The authors declare no conflict of interest.

References
[1] A M A, C H A B, D M S A. An experimental study of nozzle number on Ranque Hilsch counter-flow vortex tube - ScienceDirect[J]. Experimental Thermal and Fluid Science, 2017,82:381-389.
[2] Dutta T, Sinhamahapatra K P, Bandyopadhyay S S. Experimental and numerical investigation of energy separation in counterflow and uniflow vortex tubes[J]. International Journal of Refrigeration, 2020,123:9-22.
[3] GUO Xiangji, ZHANG Bo, LIU Bo, et al. A critical review on the flow structure studies of Ranque-Hilsch vortex tubes[J]. International Journal of Refrigeration, 2019,104:51-64.
[4] Han X, Li N, Wu K, et al. The influence of working gas characteristics on energy separation of vortex tube[J]. Applied Thermal Engineering, 2013,61(2):171-177.
[5] Jee Kanu N, Ashok Patil S, Sutar V, et al. Design and CFD analyses of aluminium alloy-based vortex tubes with multiple inlet nozzles for their optimum performances in sustainable applications[J]. Materials Today: Proceedings, 2021,4(7):25-36.
[6] Thakare H R, Parekh A D. Experimental investigation & CFD analysis of Ranque–Hilsch vortex tube[J]. Energy, 2017,133:284-298.
[7] Aghagoli A, Sorin M. Thermodynamic performance of a CO2 vortex tube based on 3D CFD flow analysis[J]. International Journal of Refrigeration, 2019,108:124-137.
[8] Zangana L , Barvari R . The effect of convergent-divergent tube on the cooling capacity of vortex tube: An experimental and numerical study[J]. AEJ - Alexandria Engineering Journal, 2020,59(1):239-246.
[9] Pinar A M, Uluer O, Kirmaci V. Optimization of counter flow Ranque–Hilsch vortex tube performance using Taguchi method[J]. International Journal of Refrigeration, 2009,32(6):1487-1494.
[10] Rafiee S E, Sadeghiazad M M. Experimental and 3D CFD analysis on optimization of geometrical parameters of parallel vortex tube cyclone separator[J]. Aerospace Science and Technology, 2017,63:110-122.
[11] Bazgir A, Nabhani N, Bazooyar B, et al. Computational Fluid Dynamic Prediction and Physical Mechanisms Consideration of Thermal Separation and Heat Transfer Processes Inside Divergent, Straight, and Convergent Ranque-Hilsch Vortex Tubes[J]. Journal of Heat Transfer, 2019,141(10):101701.
[12] Parker M J, Straatman A G. Experimental study on the impact of pressure ratio on temperature drop in a Ranque-Hilsch vortex tube[J]. Applied Thermal Engineering, 2021,189(7):116653.
[13] LI Long, LI Yan, HE Wangyun. Three-dimensional numerical simulation of the effect of vortex chamber structural parameters on the cooling performance of small-diameter vortex control [J]. Journal of Applied Basic and Engineering Sciences, 2016,24(3):528-539.
[14] Hu Z, Li R, Yang X, et al. Energy Separation for Ranque-Hilsch Vortex Tube: A short review[J]. Thermal Science and Engineering Progress, 2020,19:100559.
[15] Zangana L M K, Barvari R R I. The effect of convergent-divergent tube on the cooling capacity of vortex tube: An experimental and numerical study[J]. Alexandria Engineering Journal, 2020,59(1):239-246.