

Article

Numerical Simulation of the Effect of Different Numbers of Inlet Nozzles on Vortex Tubes

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Abstract: In order to broaden the application of vortex tubes (VOTU) in industry and to improve the efficiency of cooling and heating, numerical simulations of vortex tubes were carried out. In this study, the temperature, velocity, and pressure fields of three VOTUs with inlet nozzles of 2, 3, and 6 were investigated at different inlet pressures based on previous experimental data and by three-dimensional numerical simulation. It was found that the increase of inlet pressure leads to the increase of energy separation between the hot and cold ends of the three VOTUs. As the number of inlets increases, the pressure difference between the tube wall and the core region gradually strengthens. In contrast, the pressure in the tube center is not affected by the inlet pressure. The number of nozzles affects the inlet and outlet temperatures of the VOTU. When the number of nozzles is 3, and the inlet pressure is 0.6 MPa, the VOTU shows the maximum hot and cold outlet temperature difference of 66 K. The maximum velocity of VOTU appears at the connection of the inlet and vortex chamber, so the inlet is tangential to VOTU, which is beneficial to reduce the loss of gas energy. The wall thickness of the inlet increases gradually to avoid the high-speed gas flow on the erosion of the wall surface. This study has profound guidance for the one-dimensional design of VOTUs.

Keywords: CFD; vortex tube; temperature separation; inlet pressure; number of nozzles



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1. Introduction

The vortex tube (VOTU) is a particularly mechanical refrigeration unit, where temperature separation is a unique phenomenon in the production of hot and cold air streams [1]. The compressed gas enters the vortex chamber through one or more nozzles, the gas rotates at high speed and, due to the energy separation effect, the hot gas flow flows out from the hot end control valve, the cold gas flow flows in the opposite direction of the hot gas flow through the cold end tube and the cold end control valve [2]. The VOTU itself is simple in structure, without any moving parts, not easily damaged, light in mass. VOTU is inexpensive to produce, but its lower heating and cooling capacity and efficiency limit its application in the industry [3]. There is still no accepted precise theory that can explain the energy separation mechanism of VOTU essentially [4]. A large number of researchers have carried out a lot of work on the heating and cooling performance of VOTU and their energy separation efficiency using experimental or numerical simulation methods [5,6].

In order to reduce the energy loss formed in the vortex chamber, nozzles are designed to enter along the tangential direction of the VOTU; nozzles are critical fixed components of the VOTU, the number of which directly affects the performance of the VOTU [5]. Dincer [7] simulated and predicted the effects of VOTU aspect ratio, inlet pressure, and the number of inlet nozzles on VOTU performance using an artificial neural network approach,

and found that 4 nozzles improved the VOTU performance most significantly, finally, the model was validated by experimental data, and the results were consistent. In addition, Mohammadi [8] conducted an experimental study using a VOTU made of brass in order to obtain the optimal number of nozzles and nozzle diameters for the VOTU, concluding that the temperature drop of the VOTU increased with the increasing number of nozzles and the performance of the VOTU improved with the optimal number of nozzles of 2. However, with the increasing amount of inlet air, the hot and cold air streams were mixed, leading to decreased performance. However, during the experimental study of the number of nozzles of the VOTU by Kaya et al. [9], it was found that the maximum temperature difference of 58.6 K could be achieved when the length-to-diameter ratio of the VOTU was 14, the cold mass fraction ratio was 0.36, the inlet pressure was 0.55 MPa, and the number of inlet nozzles was 6. In addition, it was found that the number of inlet nozzles could significantly change the temperature at the outlet of the hot end of the VOTU and the internal velocity [9]. Mete [10] investigated the effect of the VOTU aspect ratio and the number of inlet nozzles on the outlet temperature at both the hot and cold ends of the VOTU. In the experiments, dry air was used as the working fluid, and it was found that the larger the inlet nozzle aspect ratio, the larger the temperature difference between the hot and cold ends of the VOTU; it was also found that single nozzle outperformed multiple nozzles, because the more nozzles, the greater the resistance to flow in the VOTU, and increased the degree of turbulence. However, the reason for the increase in flow resistance of multiple nozzles was not explained in detail.

Using computational fluid dynamics (CFD), Kanu [11] investigated the performance of single-nozzle VOTU and multi-nozzle (1, 2, and 4) VOTU made of aluminum alloy. With the increasing number of nozzles, the temperature difference at the hot end of the VOTU gradually decreases, while the temperature difference at the cold end of the VOTU is increasing. The cold end temperature of the single nozzle VOTU is 257 K, and the cold end temperature of 4 nozzles VOTU can reach 208.9 K [11]. However, Bhote simulated numerically and validated experimentally the effect of VOTU with the number of nozzles of 2, 4, 6 on their performance coefficients as well as the temperature difference at the cold end and came to a different conclusion that the performance coefficient kept increasing with the increase of the inlet pressure of the VOTU, but it decreased with the increase of the number of nozzles, and the maximum performance coefficient was 0.14 for the number of nozzles of 2 [12]. Shamsoddini [13] studied the effect of the number of nozzles 2, 4, 6, 8 on the cooling power of the VOTU as well as the temperature and flow fields at the cold outlet using only numerical simulations, and the results showed that the cooling power increased as the number of nozzles grew, the cooling power of the VOTU with 8 nozzles increased by 8.7% compared to 2 nozzles. However, the study was not experimentally validated and the accuracy of the data is yet to be verified.

Pinar [14,15] investigated the effects of inlet pressure, the number of nozzles, and cold mass fraction on the cold and hot temperature differences in VOTU using the Taguchi method, and found by variance and regressive analysis that both the cold end temperature difference and the hot end temperature difference would gradually increase with increasing inlet pressure, and the cold mass fraction would decrease with an increasing number of inlet nozzles at constant pressure. It is concluded that the optimal inlet pressure is 0.65 MPa and the optimal number of nozzles is 2 [15]. Similarly, Gökçe [16] used the Taguchi method to investigate the effect of various factors, inlet pressure, number of nozzle inlets, nozzle material, etc., on the outlet temperature difference between the hot and cold ends of the VOTU. Ultimately, it was found that pressure was always the most prominent factor affecting the temperature separation between the hot and cold ends of the VOTU, followed by the number of inlet nozzles of the VOTU. It was noted in the study that the optimal temperature difference was derived for a VOTU nozzle number of 6, but no detailed analysis or discussion of the reasons was carried out. Rafiee [6] proposed a new approach to study VOTU by changing the angle of the inlet nozzle to make it a converging nozzle with a convergence ratio ranging from 1 to 2.85. Numerical simulations and experimental

studies have shown that changing the convergence angle of the inlet nozzle does improve the performance of the VOTU, and the VOTU has a maximum cold end temperature difference when the convergence ratio is 1.9.

In summary, numerous research results show that the number of inlet nozzles of the VOTU has a large effect on the temperature of the hot and cold ends of the VOTU as well as the internal flow field, but only through experimental studies cannot present the distribution of the internal flow field and temperature field of the VOTU, and cannot exhaustively analyze the effect of the number of inlet nozzles on its temperature separation. In order to investigate the effect of the different numbers of nozzle runners on the internal flow field, temperature field, and outlet temperature of the hot and cold ends of the VOTU, this study selected the experimental data of Attalla [3] to investigate the effect of the number of nozzles on the energy separation of the VOTU by means of numerical simulation, and made a reasonable analysis through the available experimental and simulation data to lay the foundation for the design of the VOTU.

2. Simulation

2.1. Geometric Parameters of the VOTU

Based on the physical VOTU experimentally studied by Attalla [3], a simplified model of the VOTU was built in this study using the 3-dimensional data modeling software SolidWorks 2016, as shown in Figure 1. The VOTU simplified model mainly consists of cold outlet, hot outlet, cold end tube, hot end tube, and inlet. Figure 1 shows the VOTU model with the nozzle runner number of 2, the hot end tube length is 112.5 mm, the diameter is 7 mm, the cold end tube length is 5 mm, and the diameter is also 5 mm. The nozzle is rectangular with a side length of 1 mm. Figures 2 and 3 show the axial cross-sectional view and radial cross-sectional view of the three-dimensional model of the VOTU, respectively.

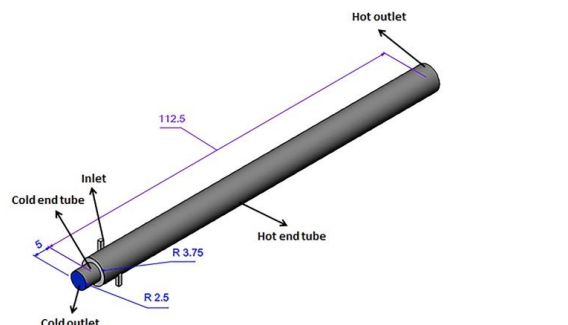


Figure 1. Dimensional model drawing of the VOTU.

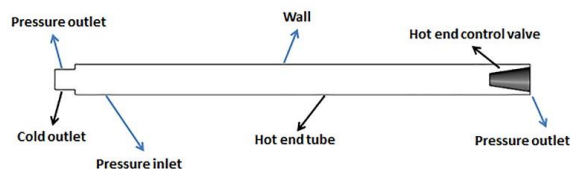


Figure 2. Axial section of the VOTU.

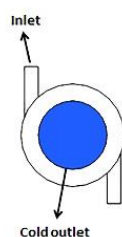


Figure 3. Radial section of the VOTU.

2.2. Governing Equations

The internal flow of a VOTU in three-dimensional space is complex, and the choice of a numerical simulation model is crucial in order to simulate its internal flow more realistically. No single model can be applied to all computational problems; it is necessary to consider the accuracy of the computational results, the capability of the computer, and the computational time. It is shown in the literature that the RNG k - ε turbulence model can accurately reflect the distribution of temperature and flow fields inside the VOTU. Bazgir [17,18] used the RNG k - ε turbulence model in numerical simulations and the results showed that the energy separation mechanism of the VOTU could be clearly predicted, and the outlet temperature at the hot and cold ends has a small difference compared with the experimental value. In this study, the RNG k - ε turbulence model is used for numerical simulation, and swirl Dominated Flow and Curvature Correction are to be selected in the viscous model. Assume that the flowing mass is an ideal gas with constant physical properties and the flow in the tube is an adiabatic isentropic process. The tube wall is well insulated and free of internal heat sources. Since the centripetal force generated by the high-speed flow of fluid inside the tube is much larger than the gravity, the effect of gravity on the flow can be ignored [19,20]. For the three-dimensional compressible flow, the controlling equations are respectively [6]:

$$\frac{\partial}{\partial x_i}(\rho u_i) = 0 \quad (1)$$

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

$$\begin{aligned} \frac{\partial}{\partial x_i} \left[u_i \left(\rho \left(h + \frac{1}{2} u_j u_j \right) \right) \right] = & \frac{\partial}{\partial x_j} \left[k_{eff} \frac{\partial T}{\partial x_j} + u_i (\tau_{ij})_{eff} \right] k_{eff} \\ = & K + \frac{c_p \mu_t}{Pr_t} \end{aligned} \quad (3)$$

The RNG k - ε turbulence model was applied to describe the flow and temperature patterns in the VOTU. k is the kinetic energy and ε is the dissipation rate, with the following governing equations [19]:

$$\frac{\partial}{\partial x_i}(\rho k u_i) = \nabla \cdot [\alpha_k \mu_{eff} \nabla k] + 2\mu_t E_{ij} E_{ij} - \rho \varepsilon - Y_M \quad (4)$$

$$\frac{\partial}{\partial x_i}(\rho \varepsilon u_i) = \nabla \cdot [\alpha_\varepsilon \mu_{eff} \nabla \varepsilon] + C_{1\varepsilon}^* \frac{\varepsilon}{k} 2\mu_t E_{ij} E_{ij} - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} \quad (5)$$

2.3. Boundary Condition

In this study, the experimental data of Attalla [3] are simulated and the boundary conditions of the VOTU calculation model are consistent with the experimental conditions. Study the changes of temperature and flow fields inside the VOTU for different initial inlet pressure states when the number of nozzle runners is 2, 3, and 6. The boundary conditions are set at the inlet for the pressure inlet and at the outlet for the pressure outlet, the inlet pressure is set to 0.2 MPa, 0.3 MPa, 0.4 MPa, 0.5 MPa, and 0.6 MPa, the VOTU outlet is in direct contact with the atmosphere, set the pressure outlet to 0 MPa. Compressed air is set as the working fluid, and the initial temperature is set to 277 K, the swirl pipe wall is set to a no-slip boundary condition and assumed to be adiabatic.

2.4. Grid Independence Study

The 3D model of the VOTU was meshed in Mesh 19.0 and the simulation was performed by Fluent 19.0. The mesh division is shown in Figure 4. The peculiarity and quantity of meshes affect the results of numerical simulation of VOTU. Therefore, the analysis of grid independence ensures the authenticity and accuracy of numerical simulation results [6]. In order to select the number of meshes for numerical simulations with three

different nozzle runner numbers, the VOTU with nozzle runner number 2 was divided into meshes of 252,036, 309,764, 392,155, and 520,322, and the numerical simulation results are shown in Table 1. The numerical calculation results of the VOTU with an inlet temperature of 277 K, an inlet pressure of 0.4 MPa, and a nozzle number of 2 were compared with the experimental data $\Delta T = 21.7$ K by numerical simulation. It was found that when the number of grids was 252,036 and 309,764, the temperature difference at the cold end of the VOTU was 16.5 K and 16.0 K, respectively. The smaller number of grids leads to lower calculation accuracy, which cannot reflect the temperature change inside the VOTU, and the difference between the simulation results and the real experimental values is large. When the number of grids is 392,155 and 520,322, the temperature difference between the cold end of the VOTU is 21.1 K and 20.0 K, respectively.

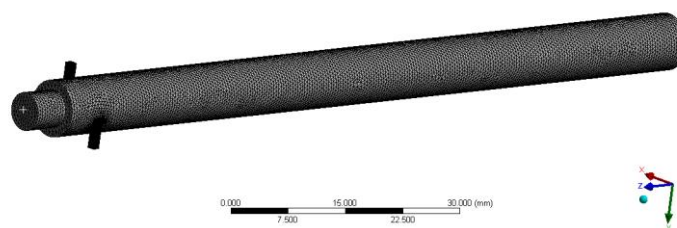


Figure 4. Meshing of the 3D numerical model of the VOTU.

Table 1. Numerical simulation results of a VOTU with nozzle number 2 for different grid numbers. (Inlet temperature = 277 K, inlet pressure = 0.4 MPa, $\Delta T = T_{in} - T_{cold}$, Experimental data $\Delta T = 21.7$ K).

Cells	252,036	309,764	392,155	520,322
$\Delta T(K)$	16.5	16.0	21.1	20.0

It can be seen that when the number of grids reaches a certain number, the numerical calculation value is close to the experimental value, but considering that an excessive number of grids will consume a lot of time for simulation and affect the calculation efficiency. Therefore, through comparative analysis, it is found that when the number of nozzle runners of the VOTU inlet is 2, the most suitable number of grids for simulation calculation is 392,155. Similarly, the initial inlet conditions are constant, the number of nozzles is 3, and the temperature difference of the experimental value is 23.2 K. At this time, the error of the grid numbering of 422,405 is the smallest, as shown in Table 2. Table 3 illustrates that when the number of VOTU nozzles is 6, the experimental temperature difference at this time is 19.0 K, and the optimal grid number is obtained as 498,330. Table 4 shows the calculated data of orthogonal quality, aspect ratio, and skewness for three different VOTU meshes. Compared to the optimal values, the meshes are able to realistically simulate the temperature, velocity, and pressure fields inside the VOTU.

Table 2. Numerical simulation results of a VOTU with nozzle number 3 for different grid numbers. (Inlet temperature = 277 K, inlet pressure = 0.4 MPa, $\Delta T = T_{in} - T_{cold}$, Experimental data $\Delta T = 23.2$ K).

Cells	282,783	339,920	422,405	655,581
$\Delta T(K)$	20.7	21.4	23.4	22

Table 3. Numerical simulation results of a VOTU with nozzle number 6 for different grid numbers. (Inlet temperature = 277 K, inlet pressure = 0.4 MPa, $\Delta T = T_{in} - T_{cold}$, Experimental data $\Delta T = 19.0$ K).

Cells	360,377	415,651	498,330	624,494
$\Delta T(K)$	16.0	16.6	18.4	17.5

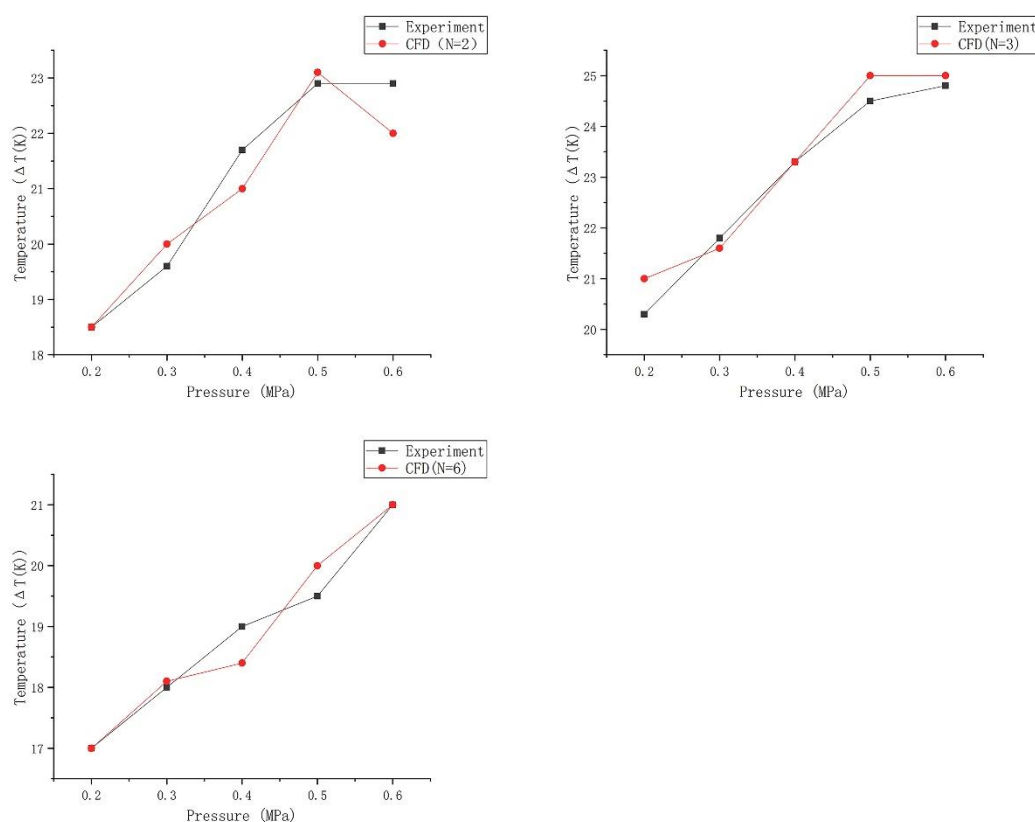
Table 4. Mesh quality evaluation of three different types of VOTUs.

Cells	392,155 (N = 2)	422,405 (N = 3)	498,330 (N = 6)	Optimum value
Orthogonal Quality	0.8	0.8	0.8	1.0
Aspect Ratio	1.8	1.8	1.8	1.0
Skewness	0.2	0.2	0.2	0

3. Results and Discussion

3.1. Validation

Attalla experimentally investigated the effect of different inlet pressures and the number of inlet nozzles on the cold exit temperature of the VOTU. By comparing the experimental data with the simulated data, it was found that the cold end exit error of the numerical simulation was within 1 K. In Figure 5, the number of nozzles is 2 and the pressure is 0.6 MPa, the difference between numerical simulation and experimental data is 0.9 K. This indicates that the cold end temperature error of the VOTU with 2 nozzles is slowly increasing with the increase of pressure, within the acceptable range. It can be concluded that the numerical simulation data obtained from the 3D numerical model established in this paper based on the actual dimensions of the experimental VOTU are accurate and close to the experimental data, indicating that the RNG $k-\varepsilon$ model established in the numerical simulation can accurately simulate the flow state of the experimental VOTU and also produce correct simulation data results.

**Figure 5.** Comparison of experimental data and CFD simulation results for VOTU with nozzles 2, 3, 6.

3.2. Comparison of Hot and Cold End Outlet Temperature

Figure 6 indicates the effect of different inlet pressures on the outlet temperatures of the hot and cold ends of the VOTU for three different numbers of nozzles. With the increasing pressure, the temperature at the hot end of the VOTU outlet increases, the maximum value appears at the pressure of 0.6 MPa, the maximum temperature is 341.2 K, 342.6 K, 335.1 K, corresponding to the number of inlet nozzles 2, 3, 6, respectively. The temperature at the cold end of the VOTU outlet decreases less, the lowest temperature is 255 K, 252 K, 256 K, respectively.

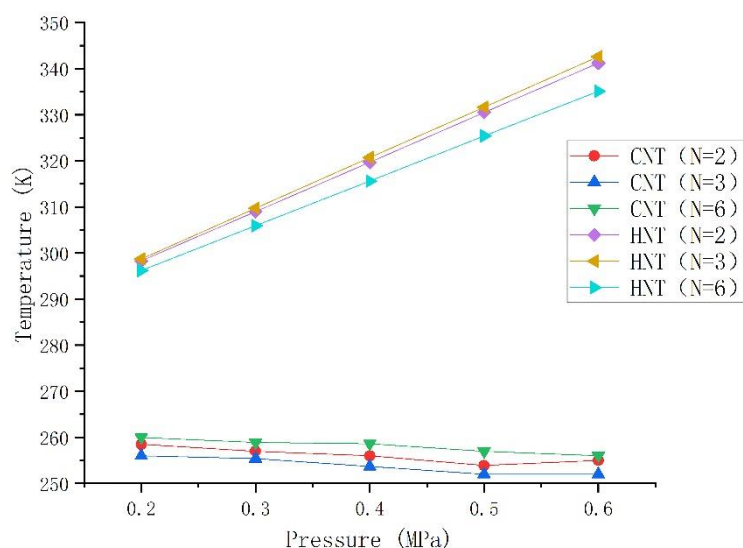


Figure 6. Effect of different numbers of nozzles and different pressures on the outlet temperature of the hot and cold end of the VOTU, CNT = cold end temperature, HNT = hot end temperature.

The heightening in the separation of the hot and cold end exit temperature of the VOTU is that the increase in the inlet pressure could enable the inlet fluid kinetic energy to reinforce, causing the internal cyclonic velocity to spread. The temperature at the hot end of the VOTU outlet has an upward tendency; with the heightening in pressure, the cold end of the outlet temperature also decreases, but the reduction becomes slower. It can be concluded that increasing pressure can reduce the cold outlet temperature and reach a certain limit value. Comparing 2, 3, 6 different nozzle numbers of VOTU, it can also be observed that the number of different nozzle runners on the VOTU of the hot and cold end temperature separation has a certain effect, in the current geometry; when $N = 3$, the VOTU sustains the excellent hot and cold end temperature separation effect. Attalla [3] also reached the corresponding conclusion in their experiments.

3.3. Radial Pressure Distribution with Different Numbers of Nozzles

The experimental results were evaluated and the improvement of the vortex tube performance was mainly due to the increase of the inlet pressure [21,22]. Figure 7 exhibits the contour diagram of the pressure distribution with the number of different nozzles at the same inlet pressure. The radial pressure contour plot in Figure 7 is similar to the numerical simulation results of Adib [23]. The compressed gas entering the inlet nozzle is the single source of power for the VOTU, economizing the use of refrigerant compared to other refrigeration units. Pressure drops quickly from the inlet nozzle to the vortex chamber in the process. From the figure, it can be seen that there is a clear pressure gradient in the vortex chamber, the pressure potential energy changes to kinetic energy, increasing the cyclonic velocity of the gas. In Figure 7, only the contour plot of the distribution for an inlet pressure of 0.2 MPa is placed, due to the fact that the distribution is basically the same in other pressure states. As seen in Figure 7, the number of inlets of the VOTU has a small

effect on the pressure distribution, and the high-pressure airflow is distributed around the tube wall, and the pressure gradually decreases toward the center of the tube.

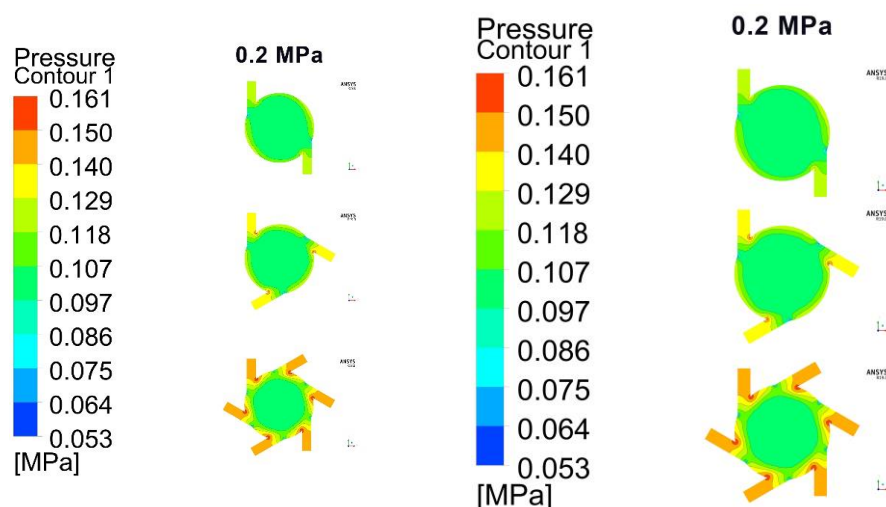


Figure 7. Contour diagram of radial pressure distribution with the different numbers of nozzles for an inlet pressure of 0.2 MPa.

However, the number of inlets affects the magnitude of the pressure reduction. As shown in Figure 8, when the number of inlets is 2, 3, 6, the influence of different inlet pressures on the pressure distribution of the VOTU diameter, with the increasing number of inlets, the pressure difference between the tube wall and the core region gradually increases, the pressure in the center of the tube is not affected by the inlet pressure.

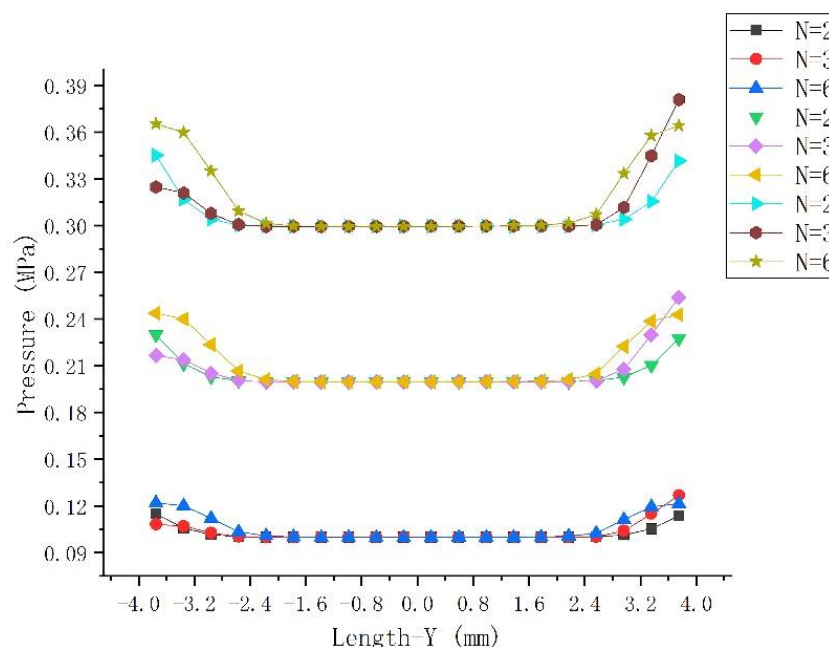


Figure 8. Pressure distribution curves for different inlet pressures for VOTU with nozzles 2, 3, 6 in the radial direction.

3.4. Temperature Distribution of VOTU with Different Numbers of Nozzles

Figure 9 illustrates the radial temperature contours of the three inlet nozzles at different inlet pressure states. The radial temperature distribution reflects the energy exchange process between the hot and cold airflow of the VOTU. It is obvious from Figure 9 that

there is obvious temperature stratification after the high-pressure airflow entering the vortex chamber. As the pressure continues to rise, the peripheral high-temperature airflow rises dramatically, while the cold airflow only decreases slightly. When the inlet pressure is 0.2 MPa, the minimum temperature of inlet nozzle numbers 2, 3, 6 are 258.5 K, 256.0 K, 260.6 K, and the maximum temperature is 289.9 K, 289.7 K, 279.7 K, respectively, as shown in Figure 10. Similarly, the minimum temperature is 256.0 K, 253.8 K, 259.1 K, and the maximum temperature is 303.9 K, 302.1 K, 286.7 K, respectively, for an inlet pressure of 0.4 MPa. In addition, the minimum temperature is 255.0 K, 252.0 K, 256.0 K, and the maximum temperature is 314.0 K, 318.0 K, 293.2 K, respectively, for an inlet pressure of 0.6 MPa. At the same pressure, the number of nozzles affects the inlet and outlet temperature of the VOTU; when the number of nozzles is 3, the maximum temperature difference between the hot and cold outlet of the VOTU, the number of inlets is 6 and reduces the energy separation of the VOTU.

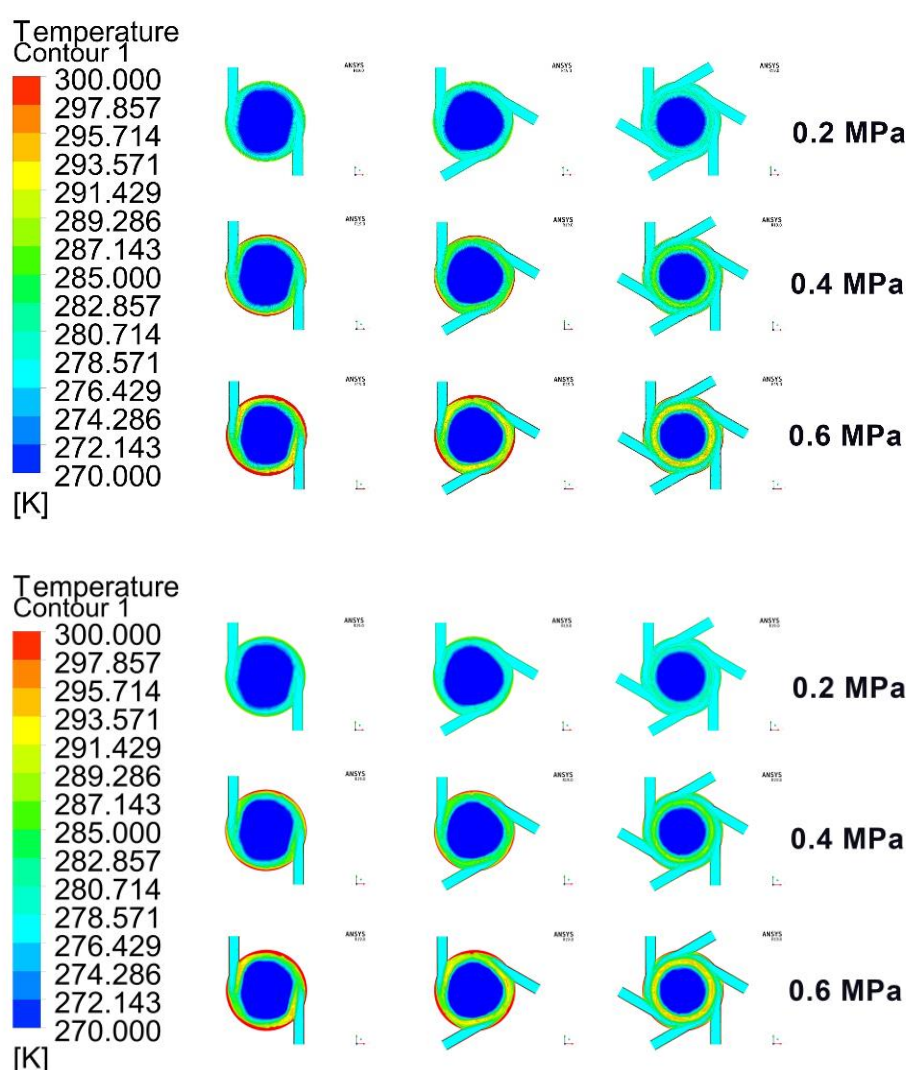


Figure 9. Contour diagram of radial temperature distribution in the VOTU radial direction for different inlet pressures for the number of nozzles 2, 3, 6.

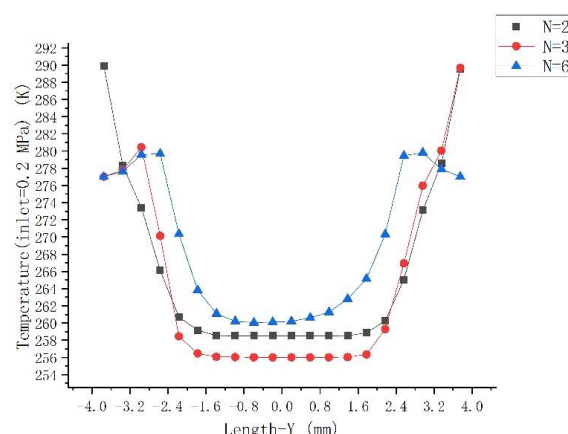


Figure 10. The graphs of radial temperature distribution for different numbers of nozzles at an inlet pressure of 0.2 MPa.

Figure 11 demonstrates the contour plot of the axial temperature distribution of the VOTU for three different numbers of inlets at a pressure of 0.2 MPa. In the figure, it is obvious that there is also a significant temperature gradient in the axial direction of the VOTU, and this temperature gradient is mainly concentrated in the direction of the vortex chamber, there is no significant energy separation in the region near the hot end valve [24]. Moreover, when the number of nozzles is 3, the area of cold airflow is significantly larger than those of the other two types of VOTU. Too many nozzles affect the energy separation of the VOTU, so that the temperature separation between the hot and cold ends is reduced. The fluid flows tangentially into the vortex chamber along the outer edge of the tube for tangential vortex flow. When the fluid passes through the hot end tube to reach near the hot end valve, the influence of the hot end valve pressure causes a reverse vortex flow of fluid in the center of the VOTU. Energy is transferred between the hot fluid on the outside of the tube walls and the cold fluid on the inside. The outer fluid warms up while the inner fluid cools down. The high-temperature fluid flows out of the hot end outlet and the low temperature fluid flows out of the cold end outlet. The number of nozzles is too much, which leads to an increase in gas friction inside the vortex chamber, and an increase in the energy loss of the VOTU.

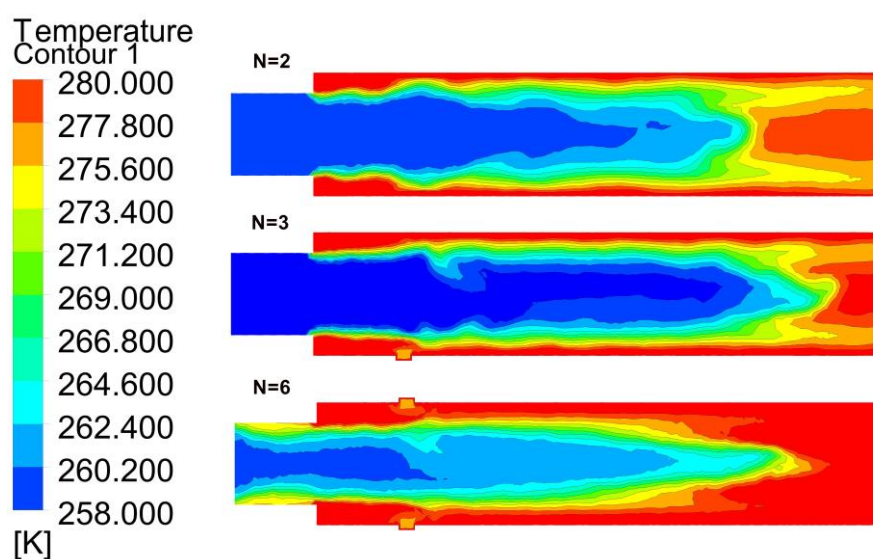


Figure 11. Contour diagram of axial temperature distribution of VOTU with different numbers of nozzles at the inlet pressure of 0.2 MPa.

3.5. Radial Velocity Distribution of Different Numbers of Nozzles

High-pressure gas in the vortex chamber forms a high-speed vortex flow, resulting in a large pressure gradient at the wall of the VOTU to the core, so the radial velocity is a direct factor to produce energy separation, which is advantageous to explore its temperature separation mechanism [20]. The effect of different pressures on the radial velocity of three different VOTU is shown in Figure 12. At the same pressure, with the increasing number of VOTU inlets, the distribution of radial velocity has a small change, when the number of inlet nozzles is 6, there is a significant decrease in the area of low-velocity airflow.

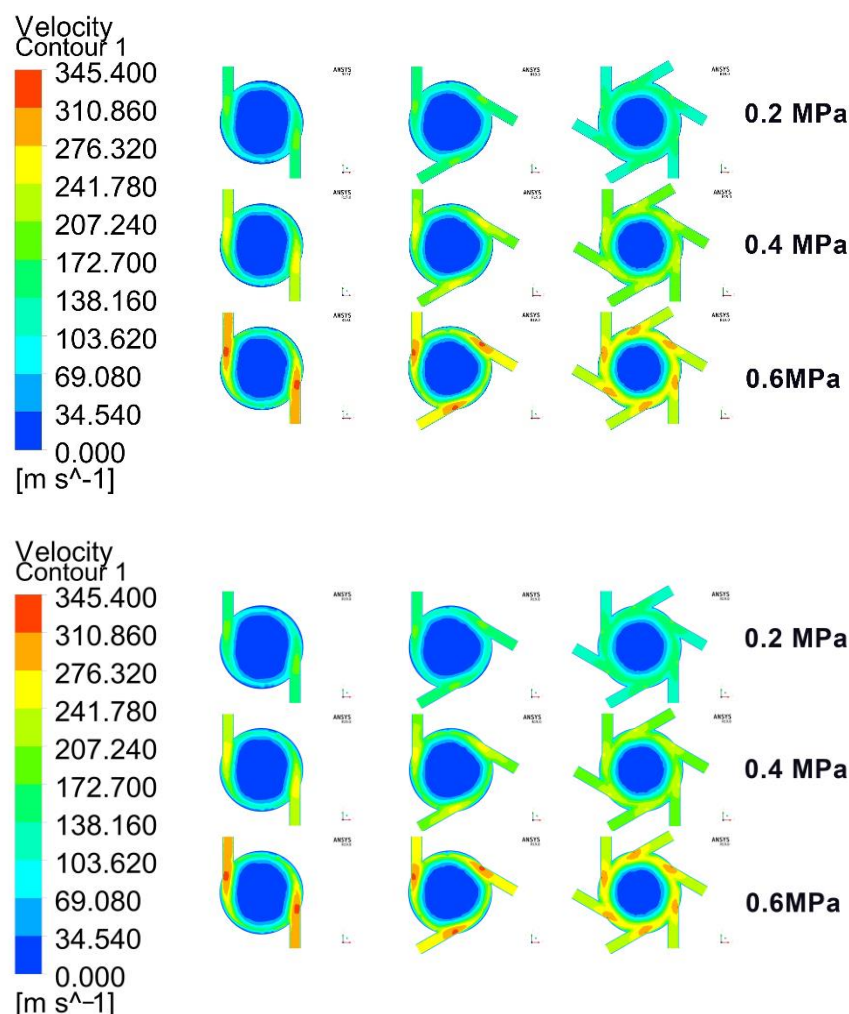


Figure 12. Contour diagram of radial velocity distribution of VOTU with different numbers of nozzles at inlet pressure of 0.2 MPa, 0.4 MPa, and 0.6 MPa.

With the increasing pressure, the tangential cyclonic velocity of the vortex chamber is also increasing, because the fluid is tangential into the vortex chamber, so the fluid flows tangentially along the outer edge, the outer edge pressure is higher than the pressure in the central region, and the pressure is symmetrically distributed, as shown in Figure 13. When the number of inlet nozzles is 3, the highest radial velocity inside the vortex chamber is greater than those of the other two types of VOTU. As can be seen from the contour, the maximum velocity in the VOTU appears at the connection between the inlet nozzle and the vortex chamber, so the inlet nozzle tangential into the VOTU is conducive to reducing the loss of gas energy. In order to avoid erosion of the wall by high-speed airflow, the wall thickness at the inlet nozzle needs to increase.

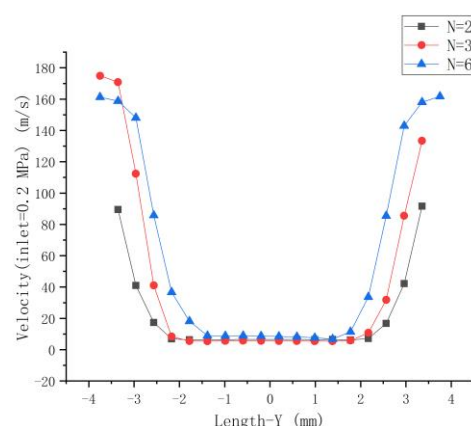


Figure 13. The graphs of radial velocity distribution for different numbers of nozzles at an inlet pressure of 0.2 MPa.

4. Conclusions

In this study, the accuracy of the numerical simulation of the three-dimensional model in this paper was verified based on previous experimental conditions and data, and the effects of different inlet pressures on three different inlet nozzle numbers of the VOTU were analyzed based on the data from the numerical simulation, and the distribution of the temperature, velocity, and pressure fields inside the VOTU were explored. The following conclusions were that the increase in inlet pressure leads to an enhancement of the energy separation between the hot and cold ends of the three VOTUs. As the number of inlets increases, the pressure difference between the tube wall and the core region gradually strengthens, while the pressure in the center of the tube is not affected by the inlet pressure. The number of nozzles affects the inlet and outlet temperatures of the VOTU. When the number of nozzles is 3 and the inlet pressure is 0.6 MPa, the VOTU shows the maximum hot and cold outlet temperature difference of 66 K. The maximum velocity of VOTU appears at the connection between the inlet and the vortex chamber, so the inlet is tangential to VOTU, which is conducive to reducing the loss of gas energy, and the wall thickness of the inlet increases one by one to avoid the erosion of the wall by the high-speed airflow. The above conclusions provide valuable guidance for the use of VOTUs in industry and in one-dimensional design.

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