Research on the Feasibility Verification Based on Continuous Vortex Ring Generator and the Matching Degree of Device Parameters

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Abstract. This paper proposes a new type of continuous vortex ring generator, which can significantly increase vortex ring generators' ventilation by studying the matching degree of device parameters. This paper uses the model proposed by Gharib analysis, and the dimensionless circulation of the vortex ring measured by the vortex profile method to explore the properties of the vortex ring. In this paper, by studying the generation principle of a vortex ring in which a dynamic fluid flows through mechanical drainage and alternately ejected from a tapered spout and an annular spout, explore the best conditions for the continuous vortex ring. The research results show that a section of static fluid with a radial restriction is driven by the same dynamic fluid with a certain speed, and the fluid-carrying capacity of the vortex ring increases as the length to diameter ratio increases, after reaching a certain length no more noticeable change. An annular spout is equipped with a guide cylinder, and its clearance coefficient is within a specific reasonable range. When the annular spout ejects an airflow whose length-to-diameter ratio is in a specific functional relationship with the clearance coefficient, a high-quality vortex ring can be produced.

1. Introduction

In the air supply field, the commonly used air supply method is to blow out gas to form ordinary wind continuously. Still, the propagation distance of typical wind is short, and the wind speed is often unevenly distributed, resulting in poor results at a distance.

The vortex ring is a concentrated type of vortex [1]. A push plate vortex ring mostly produces the traditional vortex ring, and a motor drives a stationary fluid to move the push plate, and a shear force is generated through the tapered spout to form a vortex ring [2]. This method has been widely used in Song Minho [3], Maxworthy [4], Didden [5], and Dabiri [6]. Under the same wind speed, the vortex ring travels farther than ordinary wind. Utilizing the characteristics of low wind speed and long-distance propagation of the vortex ring, air can be sent to a longer distance with less energy. The wind speed is distributed uniformly without increasing energy consumption, ensuring the device's air supply effect at a distance. However, the propagation speed of the vortex ring produced by this method is relatively low. According to Shuuser [7], when the vortex ring is clamped, the vortex ring's axial propagation speed is about 1/2 of the average wind propagation speed. The vortex ring generation time
interval is large, and the ventilation volume is small, which cannot meet the ventilation volume requirements in the air supply field. Domestic and foreign research involved in influencing vortex ring orifice size of vortex rings, Dabiri [8] studies have shown that, as the diameter of the spout outlet, the spout outlet will have a higher energy vortex ring structure; Wang Xuedong [9], who studied the effects of different jet apertures and different distances from the orifice to the wall of the composite jet exciter on the vortex ring force generated when the composite jet vortex ring hits the wall. Gharib [10] summarizes the dimensionless circulation by the circulation profile method and the expression of growth time. However, the optimization and improvement of the vortex ring generation method are rarely involved. Steinfurth Ben [11] used experimental methods to study the vortex ring generated by pulse emission of high-pressure air through a rectangular length-diameter ratio outlet into a static environment. The article pointed out that the gas carrying capacity can be significantly improved by changing the vortex ring generation method, which leads this article to improve the vortex ring's comprehensive properties by enhancing the generation structure and overcoming the disadvantages of the vortex ring. This paper designs and improves the mechanism of the device, improves the gas flow path, and improves the stability of the vortex ring; guides the dynamic gas to be sprayed alternately from different outlets to form a continuous vortex ring, which solves the problem of gas blockage while achieving the purpose of cutting off the gas. And it can effectively increase the vortex ring's speed and air amount.

2. Introduction to the principle of continuous vortex ring generation

Within a specific range, the Reynolds number has a weaker influence on physical parameters such as the vortex ring radius, annulus volume, and propagation velocity, but is strongly affected by the airflow length-diameter ratio L/D (L is the airflow length, D is the airflow diameter). In 2013, Xiang Yang [12]’s research conclusion showed that when the Reynolds number is constant, a vortex ring of better quality can be produced when the L/D is about 4. At this time, the vortex ring volume reaches its maximum, which can carry more gas. By a mechanical structure, the guide fast dynamic airflow discharged alternately from different orifices by controlling the gas discharge alternating time adjustment length-diameter ratio L / D and producing better quality vortex ring, the device structure shown in Figure 1.

![Figure 1. The continuous vortex ring generator](image)

The following is the specific process of producing a continuous vortex ring: First, the upper air inlet starts to operate, feeds dynamic gas, the shutter mechanism gradually opens, and the 2- chamber gas slowly accelerates from the middle and curls after the sheer force of the retrieval spout Form a vortex ring. When the optimal vortex ring generation time is reached, the shutter mechanism is gradually closed to cut off the gas in the 2-chamber. Simultaneously, the five small holes on the shutter mechanism have not been opened due to a certain overlap angle of the baffle, resulting in a very short gas interruption. The shutter mechanism continues to close, and the gas enters the annular flow channel in the lower part of the 3-chamber and is ejected from the annular spout to form a vortex ring. Such reciprocation creates a continuous vortex circulation, as shown in Figure 2.
3. Study on the principle of the swirl ring produced by the annular spout

3.1. The principle of the vortex ring generated by the tapered spout

In the continuous vortex ring's actual application, the device's length is a physical quantity that needs to be considered. The longer the distance, the larger the space occupied. The larger part of the device length is the tapered spout vent pipe. Its size is related to the quality of the vortex ring produced by the tapered spout. To explore this connection, this paper proposes two hypothetical theories. Push plate airflow hypothesis theory means that during the device's operation, the airflow in 1-chamber is always flowing and has a certain speed. The air in 2-chamber and 3-chamber are alternately at rest when the shutter blades are cut off. When the shutter blades are opened (relative to Room 2), the dynamic airflow enters 2-chamber from 1-chamber and has a certain initial velocity. The resulting phenomenon is that the active gas pushes the inert gas and forms a vortex ring under the shear force of the tapered spout. This phenomenon is similar to the generation principle of the push plate type vortex ring, the dynamic gas is the push plate, and the active gas is pushed forward to produce the vortex ring. Under the assumption, the active gas at the rear can only be used as a push plate and cannot generate a vortex ring. According to the conclusion of Gharib [10], the length of the 2-chamber tube needs to be four times the diameter of the 2-chamber tube to have a better-quality vortex ring, which undoubtedly dramatically increases the size of the device. Direct injection gas flow hypothesis theory means that when the shutter blade opens the 2-chamber and enters one room, the gas with a certain initial velocity can directly form a vortex ring under the action of the shear force of the tapered spout, without pushing a static fluid. Under the assumption, it is no longer necessary for 2-chambers to achieve a 4:1 length-diameter ratio, and the length of the device can be significantly reduced.

3.2. The principle of the vortex ring produced by the annular spout

The application of annular spouts in generating vortex rings has been less studied before. The basic idea of forming a high-quality vortex ring is to design the annular columnar gas to simulate the traditional columnar gas vortex ring's generation process. Therefore, the guided annular spout are proposed in this paper. To solve the problem of the gas collapsing, this paper designs a guide cylinder inside the annular gas to simulate the vortex process of the columnar gas so that the central airflow cannot curl inward and can only Forward propagation, forming a columnar airflow in front of the spout, thereby creating a stable vortex ring to propagate forward.

4. Research methods

4.1. Mathematical model

4.1.1. Tapered spout geometry model

To explore the continuous vortex ring's generation principle, determine the best two-chamber tube length, obtain the vortex ring propagation speed and other parameters, and use ANSYS FLUENT for numerical simulation analysis. When modeling and simulating actual problems, the model is often simplified. Therefore, the device is set to be axisymmetric. Set baffle length 50mm, width 4mm, air
inlet radius 67.5mm, 2-chamber air inlet radius 40mm, 3-chamber air inlet diameter 30mm, 2-chamber tube length L setting series value 40, 80, 120, 160, 200, 240, 280, 320, unit mm, tapered spout outlet diameter 90mm, vortex ring generator 25mm high. The $\kappa - \omega$ model based on Reynolds stress time average (RANS) is used to solve the problem.

Using the I-CEM meshing, with hybrid meshing method, since the baffle is set as a moving part, the mesh needs to offer higher quality requirements. The vortex ring generator section is encrypted; the calculation accuracy can be improved simultaneously and reduce computing time, as shown in Figure 3.

![Figure 3. Two-dimensional model of the vortex ring generator](image)

### 4.1.2. Annular spout geometry model

Solving the $\kappa - \omega$ model based on Reynolds stress time average (RANS) and setting a rotationally symmetric model can significantly reduce the calculation amount and improve the calculation accuracy. Setting model import length 30mm, through a section of size 220mm, width 100mm rectangular flow channels (analog this area 3 chamber cavity volume), the long sides 40mm, the short side 20mm, length 30mm tapered discharge spout. For internal testing, there is a diversion wall 75mm long for forced curling of gas, and a rectangular observation area with a length of 1500mm and a width of 600mm is set at the rear, as shown in Figure 4. Use Mesh to pre-process the model; the maximum mesh size does not exceed 2.5mm; set the boundary conditions and mesh properties to generate the mesh. There are 148070 grids in the computational domain, and the time step is 0.05s. Besides, this paper also uses 90,000 grids and 0.1s time step to correct the above grid and time step. The difference between the results is less than 2%, which has high accuracy.

![Figure 4. Two-dimensional axisymmetric model and grid diagram](image)

### 4.1.3. The setting of FLUENT boundary conditions

| Table 1. Boundary conditions of the tapered spout model. |
|---------------------------------------------|
| Speed inlet       | Pressure outlet | Baffle up and down movement cycle | Wall surface roughness |
| 1m/s              | 1.013*10^5 Pa   | 0.32s                          | 0.001mm                |

| Table 2. Boundary conditions of the tapered spout model. |
|---------------------------------------------|
| Speed inlet | Pressure outlet | Intake time | Wall surface roughness |
| 1m/s        | 1.013*10^5 Pa   | 0.32s      | 0.001mm                |
4.2. Experiment system
The continuous vortex ring generator consists of an axial fan, a shutter cutting mechanism, and a control system. The axial flow fan drives the air, and the shutter cut-off mechanism is under the controller's control. By controlling the clockwise rotation and counterclockwise rotation of the gear ring, realize the control of passing airflow and disconnecting airflow. The following is the device structure diagram and the test system consists of a continuous vortex ring generator, a black screen, and a camera, as shown in Figure 5.

![Device structure diagram](image1)

**Figure 5.** The continuous vortex ring generator and experimental apparatus schematic

4.3. Vortex ring analysis
Herein by Xiang Yang's [12] dimensionless loop of the formula is applied to an annular spout ring vortex. Annular spout type dimensionless annular volume $\Gamma^*$

$$\Gamma^* = \frac{U_g \times T}{D_F}$$

(1)

In the formula, $U_g$ as the average velocity gas outlet, $D_F$ as a boundary vortex ring diameter, $T$ is the jet time. The growth time of the vortex ring $T^*$

$$T^* = \frac{U_g \times T}{D_S}$$

(2)

In the formula, $D_S$ is the annular spout clearance. Gharib [10] found that its circulation does not increase further after the vortex ring grows for a certain period. When its dimensionless growth time reaches 4, the circulation reaches the maximum. The vortex ring propagates forward, and the circulation remains stable. This paper draws on the vortex ring contour method of Gharib [10] and Maxwothy [4] to determine the vortex ring boundary, as shown in Figure 6.

![Image of dimensionless circulation and growth time and vortex profile method](image2)

**Figure 6.** Image of dimensionless circulation and growth time and vortex profile method

Since the primary generating is gas curling, this paper uses Xiang Yang's [12] formula to further study the annular spout vortex ring. Because the annular spout involves the influence of the inner and outer diameter of the spout, this paper considers the influence factors by setting the clearance factor $\delta$. 

| $U_g$ | $D_S$ | $T$ | $\delta$ |
|------|------|-----|-------|
| 4m/s | 1.013*10^5 Pa | 0.4s | 0.001mm |
Clearance factor $\delta$

$$\delta = \frac{D_1 - D_2}{D_1}$$  \hspace{1cm} (3)

In the formula, $D_1$ is the large diameter of the annular spout and $D_2$ is the small-diameter of the annular spout. By exploring separately when the clearance factor $\delta$ and the growth time $T^*$ are unchanged, the optimal local value is found by setting a series of parameters. To determine the best clearance factor $\delta$ and the best growth time $T^*$ of the vortex ring produced by the annular spout.

5. Results and analysis

5.1. Simulation results

5.1.1. Tapered spout
Measure the vortex ring's circulation by the vortex ring profile method and observe the effect of the tube length of the 2-chamber on the circulation under the same ventilation condition, as shown in Figure 7.

![Figure 7. Vortex ring contour method to determine the vortex ring boundary](image)

When the 2-chamber tube's length is short, the gas is blown out in a trapezoid shape, and the airflow is more disordered. When the static airflow in the 2-chamber tube is pushed out, the turbulent airflow at the rear begins to be sheared by the tapered spout to produce a vortex ring. The shape of the vortex ring is irregular. The stability is low; when the 2-chamber tube's length is long, the gas has a specific turbulent flow effect in the box. After the front static gas is blown out, the rear gas is also relatively stable, producing a better-quality vortex ring.

5.1.2. Annular spout
To better observe the airflow pattern, this paper uses velocity contour to present the observation results at different times, as shown in Figure 8. When $t=0.5s$, the gas is blocked by the guide wall and curled outward passively, initially forming a vortex ring. When $t=1.0s$, the vortex ring is clamped, and the gas ejection is interrupted at this time to form a complete vortex ring. When $t=5.0s$, the vortex ring propagates forward, the vortex airflow velocity is faster, and the vortex ring shape is stable.

It can be seen that the gas has obvious curling, and the guided annular spout can form a vortex ring that spreads stably, which has application value. Because its generation mechanism is quite different from the usual vortex ring generation method, further exploring the relationship between its generation properties and parameters is necessary.
5.1.3. Experimental test results
In the experiment using the vortex ring profile method to measure the circulation, the vortex ring structure is not apparent at the beginning and cannot be directly observed; after a certain distance of propagation, the structural characteristics gradually appear, and the measurement of circulation can be infinite at this time, as shown in Figure 9.

5.2. Data analysis

5.2.1. Tapered spout
The study found that when the tube length is short, the vortex ring's quality will increase significantly as the tube length gradually increases. However, after a certain length, the vortex ring does not increase significantly. It can be seen from the results that the theory of push plate airflow generation applies to this vortex ring generation method. When the length-diameter ratio is about 2.5, the loop volume reaches about 90% of the optimal loop volume, which has a good profit., as shown in Figure 10. To further reduce the length of the 2-chamber, honeycomb panels can be added to the pipe to stabilize the airflow.
5.2.2. Annular spout

(1) Propagation velocity
To further understand the nature of the vortex ring produced by the annular spout, this paper measures the vortex ring's speed made by the annular spout at different positions and obtains the speed curve. As can be seen from the figure, until the vortex ring stabilizes, the maximum speed of 1 m/s or so, the propagation distance of 2.5 m or so, as shown in Figure 11. The speed of the annular spout vortex ring is mainly determined by the fan speed, can significantly increase the speed and propagation distance of the vortex ring, and has good application value in the field of air supply.

![Image of annular orifices generating a vortex ring propagation speed mode and distance image](image)

**Figure 11.** Annular orifices generating a vortex ring propagation speed mode and distance image

(2) Optimum growth time $T^*$
According to the experimental results, when the annular airflow is ejected, the air velocity in the middle is zero, the airflow will collapse toward the center. Finally, a columnar airflow will be formed. The formed columnar airflow curls outward to create a vortex ring. Therefore, the vortex ring produced by the annular spout is the same as the traditional vortex ring. The theory of Gharib [10] can be applied to determine its optimal growth time. when

$$T^* = \frac{U_g T}{D_S} = \frac{4}{\sqrt{2g - 6}}$$

The circulation formed does not increase anymore, and the vortex ring reaches the optimal generation time. It is found in the experiment that the optimal growth time $T^*$ can be applied to the clearance factor in a particular range. When the clearance factor is close to 1, the clearance is equal to the large diameter, which is the traditional tapered spout. The above formula can be applied well, but when the clearance factor is close to 0, the clearance is very small relative to the large diameter. When the gas collapses to the middle, there will be a massive speed loss. The amount of gas within a unit distance is not enough to maintain the vortex ring's radius, resulting in a low quality of the vortex ring. Therefore, this article explores the optimal range of the clearance factor when the growth time is optimal. This paper takes the clearance factor of 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1 series of values for exploration. According to different clearance factors, the annular spout vortex ring's optimal growth time can be derived. The influence of the clearance factor on the vortex ring's quality can be explored under the optimal growth time. As the clearance factor is reduced, increasing the optimum growth time. The experimental data shows that when the clearance factor is more significant than 0.4, the vortex ring circulation's deviation from the optimal circulation is less than 10%, within the acceptable range. When the clearance factor is less than 0.4, the vortex ring circulation is severely reduced, resulting in a low-quality vortex ring, as shown in Figure 12.
6. Conclusions

After simulation and physical verification, the following conclusions are drawn:

(1) Push plate airflow hypothesis theory is applicable to the way of generating vortex rings by cutting off the airflow by the shutter mechanism. When the central tube's length to diameter ratio is 2.5, the vortex ring has better quality.

(2) The annular spout can produce a high-quality vortex ring when the clearance factor is $\delta$ greater than 0.4, and the airflow length-diameter ratio is $4/\sqrt{2\delta - \delta^2}$.

(3) The continuous vortex ring generation method is composed of a central spout and an annular spout, which can produce a constant vortex ring, which overcomes the shortcomings of the traditional vortex ring and the truncated vortex ring, changes the half-period to a full-period, and increases the ventilation by one, about times. It provides greater possibilities for the application of the vortex ring in the field of air supply.

Acknowledgments

The authors would like to express their sincere appreciation to Hubei Key Laboratory of Advanced Technology for Automotive Components for continuous support. The authors also acknowledge the support of the Hubei Collaborative Innovation Centre for Automotive Components Technology. This work is financially funded by the National Natural Science Foundation of China (NSFC) (Grant No. 51675391). This contribution is also supported by the 111 Project (Grant No. B17034).

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