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Numerical Simulation Study on Optimization Design of High Efficiency and Low Noise Centrifugal Fan

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Abstract: Considering centrifugal fan as a key component of pneumatic conveying system, the research on the key technology of high-efficiency and low-noise design of centrifugal fan has gradually become the bottleneck of environmental sanitation equipment development. The generation mechanism and research methods of aerodynamic noise of centrifugal fan are summarized. Compared with experimental result of the noise frequency spectrum, the feasibility of the numerical simulation method based on detached eddy turbulence model is validated. Furthermore, based on the numerical simulation technology, the effects of inlet design, adding short blades, double outlet design, inclined volute tongue on the aerodynamic performance and aerodynamic noise of centrifugal fan are explored. The research results are observed in the following: (1) The inlet air flow distortion significantly affects the vortex generation and vorticity distribution inside and at the outlet of the fan, and the straight tube or arc tube inlet can significantly reduce the vorticity generation and reduce the aerodynamic noise. (2) Adding short blades is an effective measure to reduce the aerodynamic noise. Compared to the original design, the outlet aerodynamic noise for the optimization design can be reduced by 5.26 dB at most. However, the improvement of aerodynamic performance is relatively limited. (3) The aerodynamic performance of the double outlet design is obviously improved, while the noise reduction effect can be achieved by reducing rotation rate after meeting basic requirement of the aerodynamic performance. (4) The inclined volute tongue has slightly effect on reducing aerodynamic noise and improving aerodynamic performance. The research results in this paper will offer new insights into the design of high-efficiency and low-noise centrifugal fan, and provide the method support for the innovative design of pneumatic conveying system in environmental sanitation equipment industry.

1. Introduction

With the development of urbanization in China, the environmental sanitation equipment represented by cleaning vehicles is playing an increasingly important role in beautifying the city appearance and environment [1]. At present, the environmental sanitation mechanization rate of the main and secondary trunk roads in cities and towns in China is 70~80%, and that of large and medium-sized cities can reach more than 90%. In contrast, the environmental governance of the growing number of urban "capillaries" (such as back streets and alleys, sidewalks, auxiliary roads, etc.) has many obvious shortcomings, such as hiding dirt in every corner, insufficient regional space, low efficiency and safety of traditional manual operations, and low coverage of sanitation machinery. The challenges brought by emerging operation scenarios, as well as the development trend and demand for new energy and miniaturization of environmental sanitation operation equipment, have increasingly stringent requirements on efficient energy saving and low-noise operation of products. Centrifugal fan is the core working part of the pneumatic conveying system of environmental sanitation equipment. Its working efficiency and operating noise are of great practical significance for the efficient, energy-saving and low-noise operation of environmental sanitation equipment. The key technology of efficient and low-noise centrifugal fan design is increasingly becoming the bottle neck of industry development.

As for the design of high efficiency and low noise centrifugal fan, there are two main types of research carried out by domestic and foreign scholars. One is the structural optimization research based on active noise control technology, and the other is the optimization measures research based on passive noise reduction design. In terms of active noise reduction design, predecessors have made corresponding research achievements in rotor blade design [2-10], volute tongue structure design [11-13], collector design [14-19], anti-vortex ring design [20-22], etc. In terms of passive noise reduction design, predecessors mainly put forward asbestos sound lining volute [23], muffler [24-25] and other measures. However, most of the current research on the design of high-efficiency and low-noise centrifugal fans is only from the perspective of noise reduction technology or methods. For the pneumatic conveying system of environmental sanitation equipment with energy batteries as the main power source, noise reduction design is only one of the important research directions. At the same time, it is also necessary to comprehensively consider the energy conservation and efficiency of the aerodynamic performance of fans, The basic design principle is to reduce the aerodynamic noise of the pneumatic conveying system on the premise of meeting the requirements of aerodynamic performance. The ideal design goal is to significantly reduce the energy consumption during operation and the aerodynamic noise.

Therefore, from the perspective of low noise and high efficiency and energy saving, this paper reviews the generation mechanism of aerodynamic noise of centrifugal fans, focuses on the research in the fields that are less studied at present, such as inlet distortion, adding short blades, double outlet design, inclined volute tongue, etc., and analyzes the influence of these factors on the aerodynamic noise and aerodynamic performance of centrifugal fans, It provides a theoretical reference for the design and research of high-efficiency and low-noise centrifugal fans for environmental sanitation equipment.

2. Basic Principles and Research Methods of Aerodynamic Noise of Centrifugal Fans

2.1. Basic Principle of Aerodynamic Noise of Centrifugal Fan

The aerodynamic noise of centrifugal fan can be divided into two categories according to the action mechanism: one is discrete noise, namely rotary noise, the other is vortex noise, namely broadband noise. The aerodynamic noise of centrifugal fan is the result of the superposition of the two. The main sound source of discrete noise is the volute tongue area, while the main sound source of eddy noise includes four areas, namely, the air inlet area, the axial clearance between the impeller and the housing, the air passage between the blades and the wake area at the edge of the impeller wing. The classification of aerodynamic noise sources of centrifugal fan is shown in Figure 1.

Discrete noise is also called rotary noise or blade passing frequency noise. When the gap between the volute tongue and the blade outlet edge is small, the rotating blade passage sweeps over the volute tongue surface, and periodic pressure and velocity pulsations will be formed. The noise generated by this pulsation is called discrete noise or rotary noise.

Vortex noise is also known as vortex noise. It is the broadband noise radiated by the interaction and coupling between impeller blade and air flow during impeller rotation, mainly including incoming turbulence noise, turbulent boundary layer noise, trailing edge vortex shedding noise and tip noise. The main reasons are the separation of boundary layer near the blade outlet, the separation of airflow in the volute, the separation of flow at the blade inlet and the deterioration of flow when deviating from the optimal design conditions. The frequency of vortex noise depends on the relative velocity of blade and air flow. The vortex noise shows an obvious continuous spectrum, that is, it has a very wide frequency.

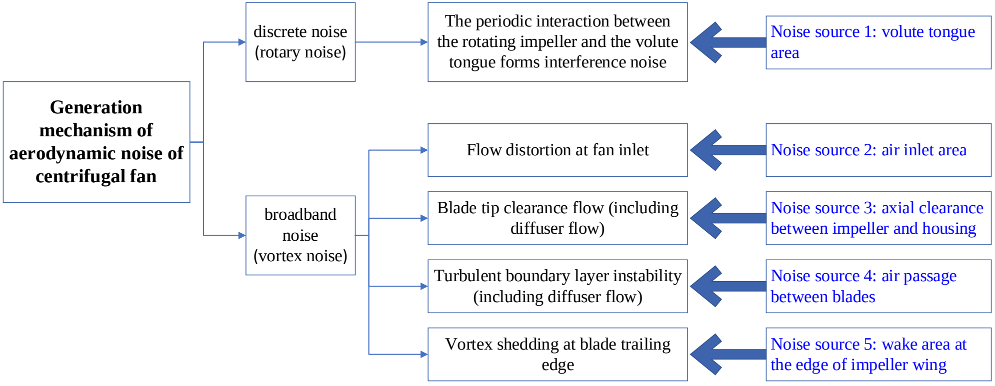


Figure 1: Classification of aerodynamic noise sources of centrifugal fan

2.2. Research Methods of Aerodynamic Noise of Centrifugal Fan

There are mainly two kinds of methods for numerical simulation of aerodynamic noise (CCA), one is hybrid method [26], that is, CFD method is used to calculate the flow field first, and then the sound propagation; The other is the Direct Numerical Computation (DNC) [27], which mainly refers to the calculation method based on Lattice Boltzmann Method (LBM) technology.

At present, the hybrid method is widely used in engineering to calculate aeroacoustics: CFD (Computational Fluid Dynamics) + Kirchhoff method; CFD + Lighthill sound analogy theory. Among them, Lighthill sound analogy theory is widely used. The idea of Lighthill's sound analogy theory is that the propagation of small flow disturbance is controlled by wave equation at a place far away from the strong flow; The sound source is modeled from the area with strong flow. The noise generation process is mathematically simplified to study the sound propagation in a static sound medium, and the flow effect is replaced by the sound source. Firstly, the turbulence information of the flow field is calculated by CFD method; Then, as the input of aerodynamic noise calculation, the equivalent sound source is defined, and the acoustic information in the flow field is solved by the method of acoustic analogy; Finally, it is generally necessary to further calculate the far-field noise.

The direct method (DNC) is mainly based on the lattice Boltzmann technique. Unlike the traditional CFD method, which is based on the assumption of continuous fluid medium, using N-S equation to describe the motion of fluid, LBM method uses discrete Boltzmann equation to simulate fluid on a more basic dynamic level. Compared with traditional CFD tools, another perspective is to study fluids from the micro perspective. However, if we want to completely reproduce all the dynamic behaviors of microscopic particles, the amount of calculation is very huge, and it is basically impossible to carry out engineering applications at the current computer level. The method of describing macro motion by solving the velocity distribution function of particle clusters in space has better practicability. LBM is such a mesoscopic scale method between macro and micro. At present, the mainstream engineering application software of aerodynamic noise calculation and analysis based on LBM technology includes XFlow software [28-34] and PowerFLOW software [35-38], which are commercial software developed from the theory of fluid statistical mechanics. Compared with XFlow software, PowerFLOW software has more obvious advantages in aerodynamic noise calculation, which can capture vorticity generation more accurately, and the calculation accuracy of noise spectrum results is better. However, the analysis of aerodynamic noise by PowerFLOW software requires very high computing resources and engineers' professional knowledge background, which cannot be widely used in engineering practice.

In this paper, the CFD + Lighthill acoustic analogy theory method in the mixed method is selected for numerical simulation of aerodynamic noise. The detached Eddy Simulation (DES) turbulence model [39-40] is used for CFD calculation of aerodynamic flow field. The basic idea of DES turbulence model is to use Reynolds Average Navier Stokes (RANS) in the flow attachment area with dissipation as the main feature, and use Large Eddy Simulation (LES) in the separation area with large eddy transport as the main feature to calculate the flow field turbulence. DES model method gives full play to the advantages of RANS in simulating wall shear flow and LES in predicting separated flow, which can not only achieve the accuracy of LES in simulating complex flow field, but also greatly reduce the calculation time by reducing the number of grids [41].

3. Feasibility Verification of Numerical Simulation Technology

3.1 Verification and Analysis of Grid Independence

In order to verify the influence of grids on the calculation results, this paper selects four kinds of grids: 2.45 million, 3.99 million, 5.87 million and 7.22 million for comparative analysis. Without losing generality, the original structural scheme working condition with fan speed of 2970 rpm is selected as the benchmark working condition. The increase in the number of grids is mainly due to the local densification of the rotor area, the volute tongue area, and the inner wall of the volute. The results show that when the grid size is more than 3.99 million, the computational results of aerodynamic performance are close to the same, and the basic change is small; When the grid is densified to more than 587W, the computational results of aerodynamic noise are close to the same and tend to be stable. See Table 1 for specific verification results.

Table 1: Mesh grid independence verification results of original scheme

Number of mesh grids	Outlet mass flow(kg/s)	Total pressure(Pa)	Torque(N·m)	Total sound pressure level(dB)
2,450,000	1.707	1497.34	18.07	100.07
3,990,000	1.715	1421.52	18.29	101.13
5,870,000	1.723	1553.27	18.41	102.31
7,220,000	1.719	1552.01	18.38	102.75

3.2. Comparison between Simulation Analysis and Experimental Test Results

Similarly, the fan speed of 2970 rpm (corresponding motor speed of 1800 rpm, mechanical transmission ratio of 1: 1.65) is selected as the benchmark working condition in the original structural scheme. The HUYI instrument intelligent wind speed, wind pressure and air volume meter (model ZC1000-1F) is used to obtain the measurement results of the flow velocity and total pressure at two points at the air inlet (measuring points # 1 and # 2) and two points at the air outlet (measuring points # 3 and # 4), and compare them with the simulation calculation results. The results show that the relative deviation of the flow velocity results is within 16%, and the relative deviation of the total pressure results at the air outlet measuring points is within 15%, The relative deviation of the total pressure results at the air inlet is relatively large. See Table 2 for specific comparison results.

The Siemens LMS sound and vibration dynamic testing system (model: SCR05) is used to obtain the total sound pressure level and spectrum of the noise at three points with horizontal distances of 1.0m, 3.5m and 7.5m from the air outlet and equal to the central point of the outlet, and compare them with the simulation results. See Table 3 for comparison of total sound pressure level results and Figure 2 for comparison of spectrum results. It should be noted that since 0.0001s is used as the time step in the calculation, the spectrum range of the extracted sound pressure level is 0-5000Hz, while the spectrum acquisition range in the experimental measurement is 0-25600Hz.

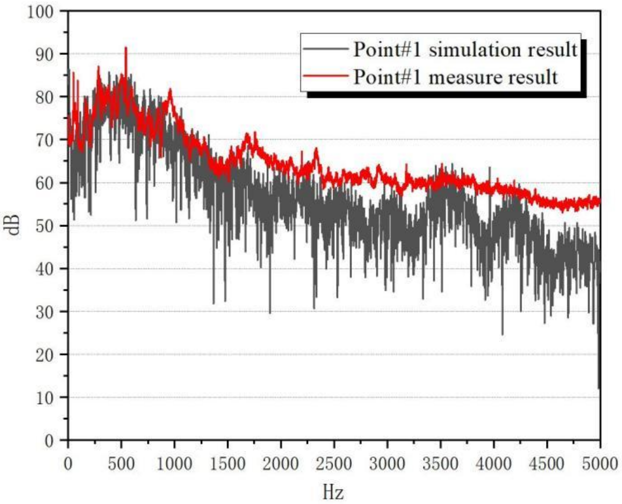
Table 2: Comparison between simulation and experimental results of flow rate and total pressure under benchmarking conditions

Measuring points No.	Flow velocity(m/s)			Total pressure(Pa)		
	Simulation result	Measure result	Relative error(%)	Simulation result	Measure result	Relative error(%)
#1	37.39	33.2	12.62	-89.64	-130.7	31.42
#2	37.47	32.5	15.29	-91.10	-121.2	24.83
#3	46.70	42.5	9.88	1510.31	1390.0	8.66
#4	46.61	41.2	13.13	1507.42	1315.6	14.58

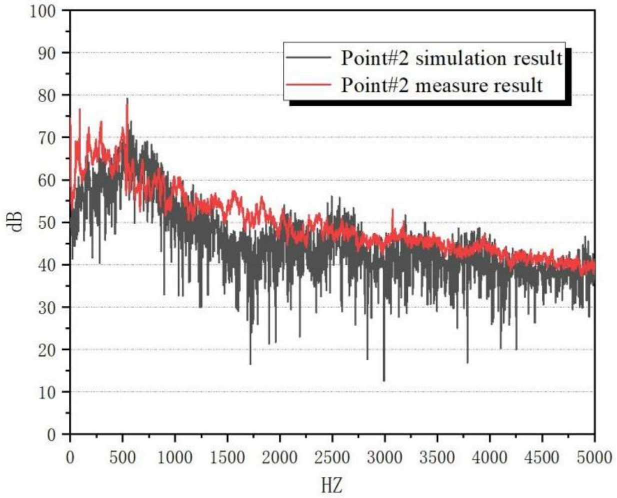
Table 3: Comparison between total sound pressure level simulation calculation results and experimental measure results

Measuring points No.	Total sound pressure level(dB)		
	Simulation result	Measure result	Relative error(%)
#1	104.47	107.20	2.55
#2	91.61	93.43	1.95
#3	86.74	88.55	2.04

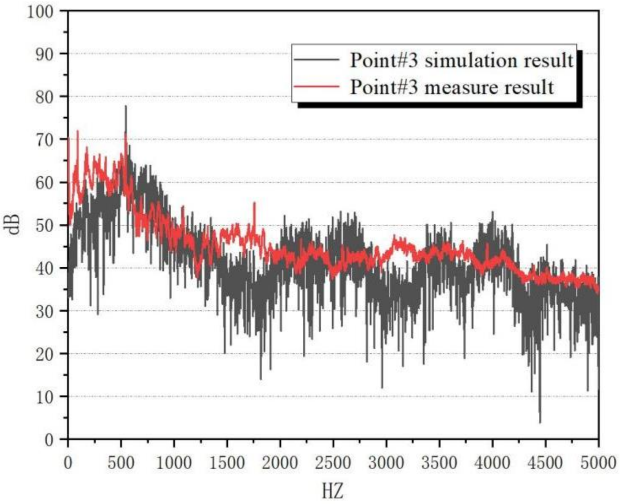
It can be seen from Figure 2 that the simulation calculation results show that the discrete noise basic frequency (544.5Hz) of the four measuring points can be well captured, and the calculated value of the corresponding sound pressure level of this Hz is also close to the experimental measurement results. From the comparison of aerodynamic noise spectrum results, it can be seen that the numerical calculation spectrum and experimental measurement spectrum of the three measuring points generally have a high degree of coincidence, and the difference in total sound pressure level is small, especially for measuring point # 2 and measuring point # 3. However, the total sound pressure level calculated by measuring point # 1 is slightly lower than the experimental measurement value, which is mainly reflected in the calculation results of 1700Hz-5000Hz medium frequency band are generally slightly lower than the experimental measurement value. Therefore, from the perspective of engineering practice, the above comparative verification results prove the feasibility of engineering application of the hybrid method based on detached eddyturbulence model in this paper.



(a) Comparison of measuring point # 3 results



(b) Comparison of measuring point # 2 results



(c) Comparison of measuring point # 3 results

Figure 2: Comparison of noise spectrum simulation calculation and experimental test results: (a) measuring point # 1, (b) measuring point # 2, (c) measuring point # 3

4. Result and Discussion

4.1 Effect of Inlet Structure on Aerodynamic Noise and Aerodynamic Performance

With the development of electrification and miniaturization of environmental sanitation equipment, the installation space of fans and other components is relatively limited. In addition, the position of trash can outlet is generally high, so it is easy to have sudden change of direction connection or lack of necessary guiding device in the design of fan inlet pipeline, which leads to distortion of air flow at the fan inlet, thus affecting the aerodynamic noise and aerodynamic performance of the fan. Figure 3 shows the geometric model of the fan assembly in the original scheme, in which the air inlet is connected in a sudden change direction. This section focuses on the analysis of the influence of air inlet structure on aerodynamic noise and aerodynamic performance.

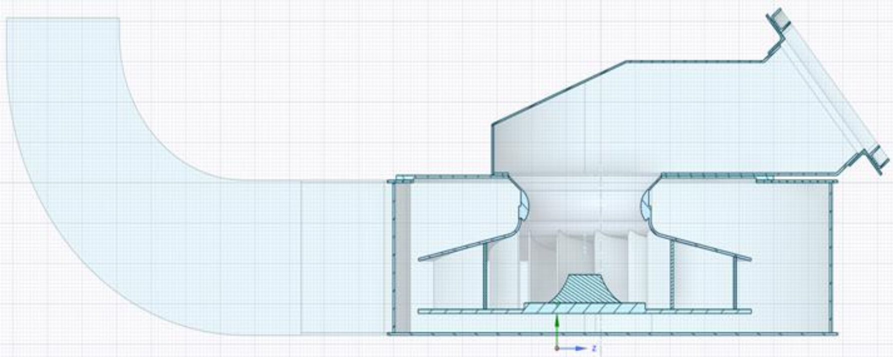


Figure 3: Central section of original fan assembly

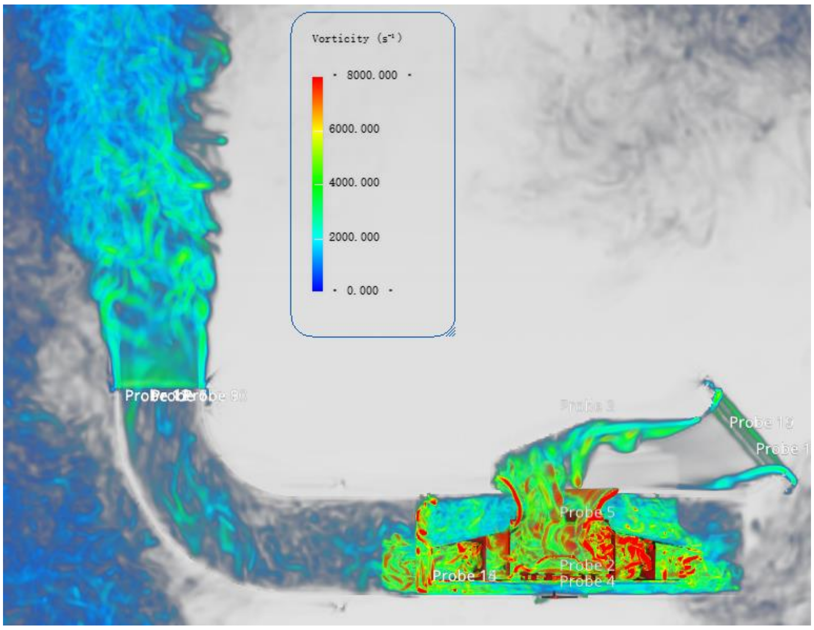


Figure 4: Vorticity distribution of original fan assembly

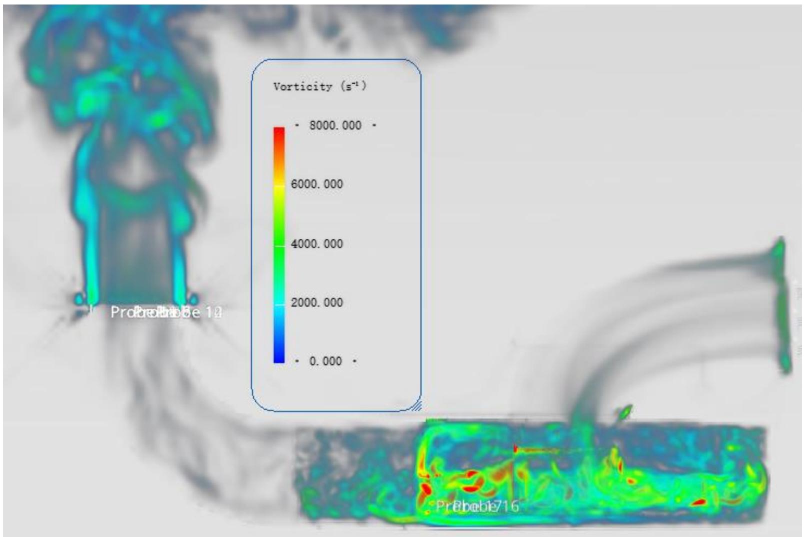


Figure 5: Vorticity distribution of optimization fan assembly of arc round pipe type air inlet

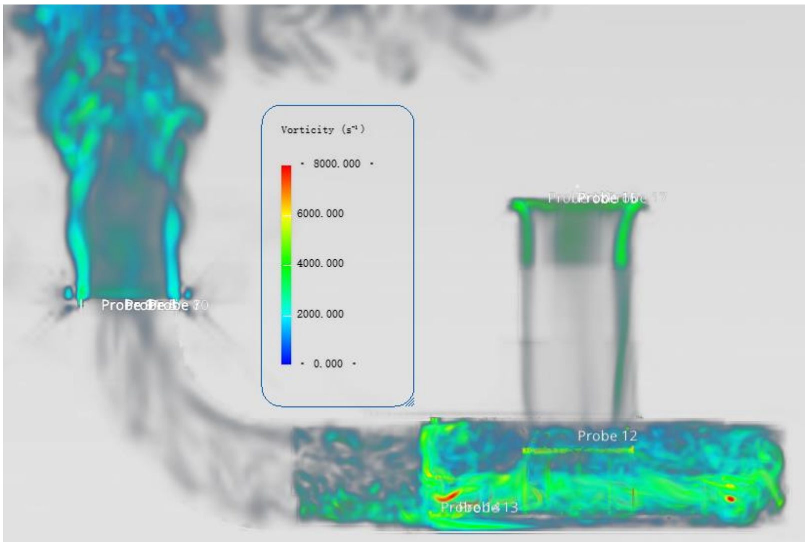
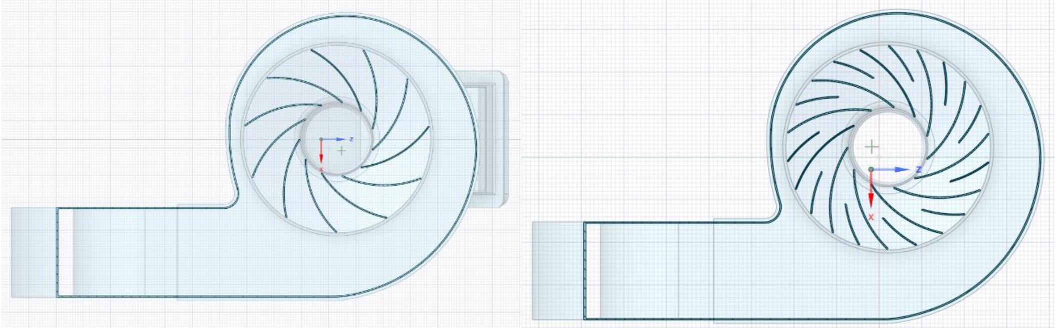


Figure 6: Vorticity distribution of optimization fan assembly of straight pipe type air inlet

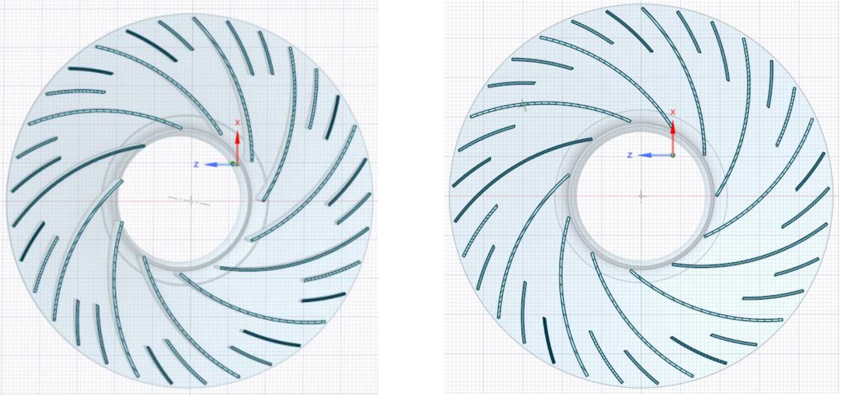
Figure 4 - Figure 6 compares the vorticity distribution maps of the three inlet structures, and it can be seen that the original scheme has obvious inlet airflow distortion, resulting in a large number of vortices, which radiate outward through the fan outlet. There is no airflow distortion at the inlet at the arc and straight pipe inlets, and the overall vorticity is small. By comparing the total sound pressure level of the noise at the outlet horizontal distance of 1.0m (measuring point # 2 in Table 3 in Section 2.2) under these three working conditions, the total sound pressure level of the original scheme is 104.47dB, the total sound pressure level of the arc round pipe type air inlet is 100.15dB, and the total sound pressure level of the straight round pipe type air inlet is 99.71dB. The ranking results of the total sound pressure levels of the three schemes from large to small are consistent with the results of the eddy current distribution law. In terms of aerodynamic performance, compared with the original structure scheme, the flow of the optimized scheme of the arc round pipe inlet and the straight round pipe inlet is increased by 16.3% and 18.2% respectively, and the total pressure is increased by 14.3% and 15.1% respectively, but the torque is increased by 4.7% and 4.4% respectively.

4.2 Effect of Adding Short Blades on Aerodynamic Noise and Aerodynamic Performance

Adding short blades is a structural optimization measure that can increase the aerodynamic performance of fans and reduce aerodynamic noise. Three optimization schemes for adding short blades are proposed in this section: the optimization scheme (1) is to add 1/2 times of the original blade arc length to the center line of adjacent fan rotor blades, as shown in Figure 7 (a); The optimization scheme (II) is to add two short blades at equal distance between adjacent fan rotor blades. The arc length of short blades adjacent to the compressed air surface is 1/3 times of the original blade arc length, and the arc length of short blades adjacent to the leeward surface is 1/4 times of the original blade arc length, as shown in Figure 7 (b); The optimization scheme (III) is to add two short blades at equal distance between adjacent fan rotor blades. The arc length of short blades adjacent to the compressed air surface is 1/4 times the original blade arc length, and the arc length of short blades adjacent to the leeward surface is 1/3 times the original blade arc length, as shown in Figure 7 (c).



(a) Blade of original scheme (b) Blade of optimization scheme (I)



(c) Blade of optimization scheme (II) (d) Blade of optimization scheme (III)

Figure 7: Geometric model of rotor blade in original scheme and optimization schemes

Table 4: Comparison of aerodynamic performance and aerodynamic noise results

Test conditions	Outlet mass flow(kg/s)	Total pressure(Pa)	torque(N·m)	Total sound pressure level(dB)
Original scheme	2.21	1853.4	20.33	99.71
Optimization scheme (I)	2.27	1979.2	19.12	97.15
Optimization scheme (II)	2.23	2011.7	18.70	95.34
Optimization scheme (III)	2.24	2044.9	18.81	94.45

From the aerodynamic performance results, compared with the original scheme, the optimization schemes (I), (II) and (III) have improved in terms of increasing the total pressure of the fan and reducing the torque, among which the optimization scheme (III) has the most obvious improvement in aerodynamic performance, while the outlet flow of the three optimization schemes has only slightly increased. From the aerodynamic noise results, similarly, the aerodynamic noise reduction of the optimized scheme (III) is the most prominent, and the total sound pressure level of the outlet noise is the smallest, which is 5.26 dB lower than the original scheme. See Table 4 for specific comparison results. It should be noted that, in order to meet the requirements of single factor control variable analysis, the original scheme analyzed in this section is the structural scheme of straight pipe type air inlet fan assembly in Section 3.1, and the other three optimization schemes are also straight pipe type air inlet structures.

4.3 Effect of Double Outlet Design on Aerodynamic Noise and Aerodynamic Performance

The double outlet design is an optimization scheme to improve the aerodynamic performance. Four optimization schemes are proposed in this section: the optimization scheme (1) is to design double outlets based on the original scheme; The optimization scheme (II) is to design double outlets based on the optimization scheme (I) in Section 3.2; The optimization scheme (III) is to design double outlets based on the optimization scheme (II) in Section 3.2; The optimization scheme (IV) is the double outlet design based on the optimization scheme (III) in Section 3.2. The original scheme and the optimized scheme analyzed in this section are both straight tube type air inlet structures. The double outlet design scheme is shown in Figure 8.

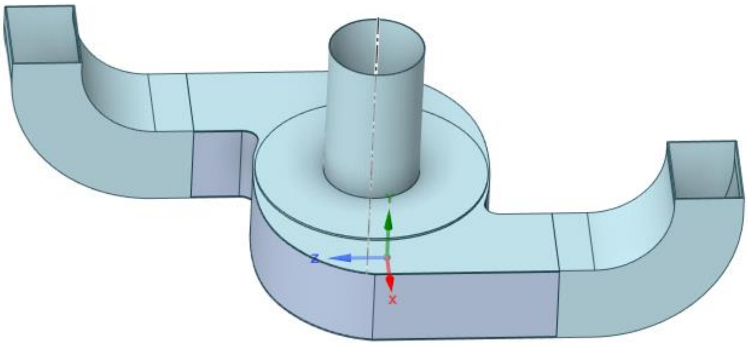


Figure 8: Geometric model of double outlet design

Table 5: Comparison of aerodynamic performance and aerodynamic noise results

Test conditions	Outlet mass flow(kg/s)	Total pressure(Pa)	torque(N ·m)	Total sound pressure level(dB)
Original scheme	2.21	1853.4	20.33	99.71
Optimization scheme (I)	2.54	2091.4	22.07	102.32
Optimization scheme (II)	2.57	2171.4	21.11	100.49
Optimization scheme (III)	2.67	2134.9	21.79	101.07
Optimization scheme (IV)	2.69	2203.4	21.53	100.76

It can be seen from Table 5 that the aerodynamic performance of the double outlet design has been improved significantly, and the outlet flow can be increased by about 20% in general; With the increase of flow rate and total pressure, the aerodynamic noise at the outlet of the four optimization schemes has increased, the maximum increase is about 2.61 dB, and the minimum increase is about 1.05 dB. Therefore, the double outlet design scheme can reduce the noise by reducing the low fan speed under the condition of meeting the aerodynamic performance.

4.4 Effect of Inclined Volute Tongue Design on Aerodynamic Noise and Aerodynamic Performance

The volute tongue area of the fan is a structure that mainly affects the discrete noise in the aerodynamic noise. In previous studies [11], it was found that the rational design of the inclined volute tongue can reduce the aerodynamic noise, but no previous studies have been conducted on the influence of the volute tongue structure design on the aerodynamic performance. In this section, three optimal design conditions of inclined volute tongue, i.e. 15 °, 20 ° and 28 °, are selected for analysis and compared with the original scheme.

Table 6: Comparison of aerodynamic performance and aerodynamic noise results

Test conditions	Outlet mass flow(kg/s)	Total pressure(Pa)	torque(N ·m)	Total sound pressure level(dB)
Original scheme	2.21	1853.4	20.33	99.71
Optimization scheme (I)	2.24	1889.1	20.47	98.43
Optimization scheme (II)	2.19	1794.3	19.69	98.32
Optimization scheme (III)	2.16	1769.5	19.71	99.61

It can be seen from the comparison results in Table 6 that the total sound pressure level of the three optimization schemes decreases less, and the inclined volute tongue has less effect on reducing aerodynamic noise. This is not quite consistent with the conclusions of previous studies. The main reasons may be two aspects. One is that the fan size studied in this paper is larger than that of previous studies, which has certain size effects. The other is that the research method in this paper is based on the calculation method of detached eddy model, which has differences in research methods. In addition, from the comparison of aerodynamic performance parameters such as outlet flow, total pressure and torque in Table 6, it can be seen that the design of inclined volute tongue plays no significant role in improving fan efficiency and reducing energy consumption.

5. Conclusions

New requirements such as new energy, miniaturization and emerging operation scenarios put forward new requirements for the design of environmental sanitation operation equipment. The pneumatic conveying system not only needs to improve the operation efficiency, reduce the operation energy consumption, but also reduce the operation aerodynamic noise. In this paper, the centrifugal fan, the core component of the pneumatic conveying system, is taken as the research object. Through the noise spectrum experiment, the feasibility of the numerical simulation research method based on the detached eddy turbulence model is verified, and four factors, namely, the air inlet, the addition of short blades, the double outlet design, and the inclined volute tongue, are explored to improve the aerodynamic performance of the centrifugal fan and reduce the aerodynamic noise at the outlet. The following research conclusions are obtained:

(1) In the original structure scheme, the air flow at the air inlet was obviously distorted, resulting

in a large number of vortices in the fan interior and outlet. The straight or arc round pipe type optimization scheme can significantly reduce the vortices in the fan interior and reduce aerodynamic noise; The optimization scheme of straight tube has the best noise reduction effect, reducing the total sound pressure level at the outlet of the original scheme from 104.47dB to 99.71dB.

(2) Adding short blades is an effective measure to reduce the aerodynamic noise at the outlet of centrifugal fan. The optimal scheme is to add two short blades in the middle of adjacent blades, and the arc length of short blades adjacent to the compressed air surface is 1/4 times the original blade arc length, and the arc length of short blades adjacent to the leeward surface is 1/3 times the original blade arc length. The maximum aerodynamic noise at the outlet of this scheme can be reduced by 5.26 dB; However, the improvement of the aerodynamic performance of the fan by this optimization scheme is relatively limited.

(3) The aerodynamic performance of the double outlet design is significantly improved, and the outlet flow can be increased by about 20% in general; The double outlet design scheme can reduce the noise by reducing the low fan speed under the condition of satisfying the aerodynamic performance.

(4) The design of inclined volute tongue with an inclination angle of 15, 20 and 28 has little effect on reducing aerodynamic noise and improving aerodynamic performance.

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References

[1] Chen X. X. (2018) Study on Aerodynamic Optimization and Power Matching of Centrifugal Fan System on Sanitation Vehicles. Master degree's thesis, Shanghai Jiao Tong University, Shanghai.

[2] Heo M. W., Kim J. H., Cha K. H., et al. (2013) Parametric Study on Aerodynamic Performance of a Centrifugal Fan with Additionally Installed Splitter Blades. ASME Fluids Engineering Conference.

[3] Wang X. L., Yang D. H., Yang G. S., et al. (2013) Air Flow Simulation in High-Pressure Fan with Splitter Blade. Fluid Machinery, 805-806, 1730-1735.

[4] Yang C. W., Chang Z. Z., Zuo Y. F. (2010) Numerical Investigation of Centrifugal Fan with Long-short Blade. Fan Technology, 4, 9-13.

[5] Hu X. (2018) Study on Aerodynamic Performance Calculation and Noise Reduction of Fans with Uneven Blade Spacing. Master degree's thesis, South China University of Technology, Guangzhou.

[6] Li L., Wang R., Jing H. H. (2012) Three Dimensional Numerical Simulation of Internal Flow Field in Multi-blade Centrifugal Fan based on the Non-linear Turbulent Model. Fluid Machinery, 10,41-45.

[7] Li L., Zhang B., Fu L., et al. (2015) Analysis on internal vortex and pressure pulsation properties of road sweeper fan. Chinese Journal of Construction Machinery, 6, 486-491.

[8] Zhang B., Li L., Fu L., et al. (2014) Analysis of the Optimized Design and Numerical Simulation on the Centrifugal Fan of Sweepers. Machinery Design ＆ Manufacture, 9, 246-248.

[9] Huang J. A., Xiang Y., Jiang C. J. (2021) Research on Aerodynamic Noise Calculation and Noise Reduction Design of Multi-blade Centrifugal Fans. Noise and Vibration Control, 2, 56-61.

[10] Ran M. M. (2007) Analysis of Multi-blade Centrifugal Fan on CFD and Noise Prediction. Master degree's thesis, Huazhong University of Science & Technology, Wuhan.

[11] Mao Y. J., Qi D. T., Zhao C., et al. (2014) Research and Development of Fan Noise Prediction and Control Methods. Fan Technology, 3, 67-74.

[12] Sandra V.S., Rafael B.T., Carlos S.M., et al.(2008)Reduction of the aerodynamic tonal noise of a forward-curved centrifugal fan by modification of the volute tongue geometry. Applied Acoustics, 69, 225-232.

[13] Li D., Gu J.M. (2004) Practice and Analysis to Reduce the Fan Noise with Step-tongue Volute. Fluid Machinery, 2, 10-12.

[14] Chen Z.H., Chen K. (2014) Research on the effect of bell mouth structure on the performance of centrifugal fan.

Online Excellent Papers of Chinese Scientific and Technological Papers, 6, 578-584.

[15] Yu Z., Li S., He W.Q., et al. (2005) Numerical Simulation of Flow Field for a Whole Centrifugal Fan and Analysis of the Effects of Blade Inlet Angle and Impeller Gap. Hvac & R Research, 2, 263-283.

[16] Khelladi S., Kouidri S., Bakir F., et al. (2005) Flow Study in the Impeller-Diffuser Interface of a Vaned Centrifugal Fan. Journal of Fluids Engineering, 3, 495-502.

[17] Park S. O., Meakhail T. (2005) A Study of Impeller-Diffuser-Volute Interaction in a Centrifugal Fan. ASME Paper No.GT-2004-53068, 84-90.

[18] Zhou S.Q., Li H., Wang J., et al. (2015) Study on the Effect of Inlet Nozzle Installation on Performance of Forward-Curved Blade Centrifugal Fan. Journal of Engineering Thermophysics, 7, 1466-1470.

[19] Yang X., Wen X.F., Yuan M.J., et al. (2012) Experimental Research on Eccentric Inlet of a Multi −blade Centrifugal Fan with Dual Inlet. Fluid Machinery, 2, 1-4.

[20] Li C.X., Lei Y., Wang S. L., et al. (2006) Investigation on Flow Dynamics and Decreasing Vortex Noise Inside Volute of Centrifugal Fan. Proceedings of the CSEE, 17, 117-121.

[21] Li C.X., Wang S. L. (2009) Numerical and Experiment Investigation on Flow Characteristics inside Volute of a Centrifugal Fan with Anti-vortex Ring. Journal of Mechanical Engineering, 7, 278-283.

[22] Bai Y.H. (2019) Effect of Anti-vortex Ring Structure of Mine Ventilator on Total Pressure Efficiency of Fan. Mechanical Management and Development,7, 139-140

[23] Wu H.Y., Jian X.L., Chen Q., et al. (2020) Noise Analysis and Control of Centrifugal Fan for Space Station. Fan Technology, 2, 30-37.

[24] Yao X.G., Bai W.J., Yu W.C., et al. (1998) Experimental Study on Noise Reduction of Centrifugal Fan (I) — Effect of Impeller Type on Noise. Fluid Machinery, 2, 9-12

[25] Zhu M.L., Yang S.N., Zhu W.W., et al. (2001) Development of A Series Assembled Silencers for Low or Median Pressure Centrifugal Blower. Noise and Vibration Control, 2, 18-26.

[26] Khalid I., Salamat S. (2018) Comparison of Lattice-Boltzmann (Direct Noise Computation) Method and Hybrid Computational Aeroacoustic Approaches in Aircraft Noise Prediction. 4th Multi Disciplinary Student Research International Conference (MDSRIC).

[27] Brionnaud R., Modena M. C., Trapani G., et al. (2015) Direct Noise Computation with a Lattice-Boltzmann Method and Application to Industrial Test Cases. Aiaa/ceas Aeroacoustics Conference.

[28] Schfer R., Bhle M. (2020) Validation of the Lattice Boltzmann Method for Simulation of Aerodynamics and Aeroacoustics in a Centrifugal Fan. Acoustics, 4,735-752.

[29] Gorakifard M., Saluea C., Cuesta I., et al. (2021) Analysis of Aeroacoustic Properties of the Local Radial Point Interpolation Cumulant Lattice Boltzmann Method. Energies, 5, 1443.

[30] Stadler M., Schmitz M. B., Laufer W., et al. (2013) Inverse Aeroacoustic Design of Axial Fans Using Genetic Optimization and the Lattice-Boltzmann. Proceedings of ASME Turbo Expo 2013: Turbine Technical Conference and Exposition, 1-11.

[31] Stadler M., Schmitz M. B., Ragg P., et al. (2012) Aeroacoustic Optimization for Axial Fans with the Lattice-Boltzmann Method. ASME Turbo Expo 2012: Turbine Technical Conference and Exposition, 1-10.

[32] Sanjosé M., Hub S., Lrcher F., et al. (2021) Noise mechanisms in a radial fan without volute. Journal of Physics: Conference Series, 1,012009.

[33] Manoha E., Caruelle B. (2015) Summary of the LAGOON Solutions from the Benchmark problems for Airframe Noise Computations-III Workshop. Aiaa/ceas Aeroacoustics Conference.

[34] Luzzato C. M., Biermann J., Fouque R. (2019) The Aero-Acoustic Design and Optimization of a Ground Transportation HVAC System using Lattice Boltzmann Methods. NAFEMS World Congress.

[35] Sorgüven, E., Doğan Y. (2012) Acoustic Optimization for Centrifugal Fans. Noise Control Engineering Journal. 4, 379-391.

[36] Magne S., Sanjose M., Moreau S., et al. (2013) Tonal Noise Control of Centrifugal Fan Using Flow Obstructions - Experimental and Numerical Approaches. 19th AIAA/CEAS Aeroacoustics Conference.

[37] Dominic, L. D., Mélanie, et al. (2017) Aeroacoustic study of an axial engine cooling module using lattice-Boltzmann simulations and the Ffowcs-Williams and Hawkings Analogy. European Journal of Mechanics B/fluids, 10, 1-8.

[38] Perot F., Kim M. S., Goff V. L., et al. (2013) Numerical optimization of the tonal noise of a backward centrifugal fan using a flow obstruction. Noise Control Engineering Journal, 3, 307-319.

[39] Spalert P.R., et al. (1997) Comments on the feasibility of LES for wings, and on a hybrid RANS/LES Approach. Advances in DNS/LES, 1, 4-8.

[40] Spalart P. R. (2006) A new version of detached-eddy simulation, resisentant to ambiguous grid densities. Theoretical and computational fluid dynamics, 3,181-195.

[41] Chen B. B., (2018) Study on the Aerodynamic Performance and Noise of the Centrifugal Fan for Vacuum Cleaners, Master degree's thesis, Nanjing University of Aeronautics and Astronautics, Nanjing.