Numerical investigation of grease separation of multi-blades centrifugal fan with inner guides

Dongfang Zhao and Xueyi You*

Tianjin Key Lab of Indoor Air Environmental Quality Control Department, School of Environmental Science and Engineering, Tianjin University, Tianjin 300350, China

*Corresponding author’s e-mail: xyyou@tju.edu.cn

Abstract. To study the effect of inner guide vanes on the grease particle separation performance of multi-blade centrifugal fan (MCF), numerical simulations are executed under the working condition. The inner guide vanes are arranged in a ring with even space at the blade outlet. The turbulent airflow field is modelled with the renormalization group (RNG) k-ε turbulence model. For the particulate phase, discrete phase model (DPM) is employed to track greases particles migration. The comparison of grease particles separation efficiency suggests that the potentially benefit effects induced by inner guide vanes is efficient and reliable. The predicted results show that the total separation efficiency of MCF with inner guide vanes is higher by 4.5% than that of the original MCF for the particle of diameter between 1 μm to 10 μm. In addition, the separation efficiency of volute is higher than that of the original MCF and it mainly separates grease particles for the diameter in the range of 1 μm to 4 μm.

1. Introduction
Cooking is one of common daily activities in modern family. It is one of the most significant indoor particle matter sources [1-3]. Several studies [4-6] stated the potential health effects induced by the exposure to cooking emission, such as lung cancer and respiratory ailments. Therefore, high performance range hoods are required to remove particulate contaminants. The complete range hood contains elements like filters and a multi-blades centrifugal fan (MCF), which is used to cost power to discharge cooking oil fumes (COF). Generally, the filter can only filter out part particles in the COF. The particles unremoved by filter enter the MCF and are separated due to centrifugal inertia. However, considering the adverse effect of corrosion and energy consumption of rotating blades, the MCF is not used as the main part of grease particle separation. This can lead to a considerable part of particles emitted into ambient air, which causes severe air pollution and threatens people's health.

Particularly, China promulgated relevant standards, such as GB 18483-2001 (Emission standard of cooking fume), for catering industry and GB/T 17713-2011 (Range hood), for domestic. It has definitely regulated the range hood minimum standard for grease separation efficiency. Therefore, the research of separation performance improvement of range hood has already become extremely important. Moreover, to improve the separation performance, it must first be ensured that the discharge efficiency for COF is close to 100 percent as possible. Hence, there is lots of relevant research on MCF to improve its discharge performance. For example, Abanto and Reggio [7] used commercial software Fluent to predict the aerodynamic performance of MCF for a domestic kitchen hood. It was found that the dimensionless flow and load coefficients are shown to be in good agreement with the experimental data. Chen et al. [8] investigated the effect of exhaust airflow rate and mounting height on the range hood-driven flow by particle image velocimetry approach. It was
found that the spill length of the cooking fume increases with decreasing of the mounting height. Hariharan and Govardhan [9] proposed the parallel wall volutes for industrial centrifugal blower, and predicted the aerodynamic performance by commercial CFD code ANSYS CFX 14. It was found that the performance with parallel wall volute is improved up to 6%, compared with the rectangular volutes. Son et al. [10] investigated the effect of ration between inlet radius and bell mouth of centrifugal blower on exhaust airflow rate by numerical simulation. It was found that that the optimal ratio is about 0.86 to improve centrifugal blower flow rate, and it is best to have the ratio at about 0.09.

The MCF is the primary component of domestic range hood, and many authors have investigated the effect of structure parameters on its aerodynamic performance. However, few research works have been reported the influence of inner guide vanes on MCF separation performance. In addition, inner guide vanes technology is a high potential approach to improve exhaust airflow rate and separation efficiency of the MCF. Thus, the aim of present research is to validation the application of the inner guide vanes of the MCF for improving the grease particle separation performance by numerical simulation method.

2. Computational model

2.1. Airflow modeling

A commercial CFD scheme of ANSYS Fluent is used to simulate the internal airflow field. The RNG k-ε model is widely used for solving complex swirling and rapidly strained flows [11]. Thus, the RNG k-ε model is selected to solve the 3D unsteady Reynolds-averaged equations in this paper. To realize the wall information exchange between impeller and the adjacent fluid zone, the moving reference frame (MRF) and sliding mesh model (SMM) are widely used for fluid machinery. The MRF is mainly used to solve steady flow and its accuracy is lower than the SMM. Although the SMM can be only used for transient solution with high computation cost, it excellently solves the dynamic interaction between rotor and stator. Thus, the basic flow field inside the MCF is calculated by MRF until the result converges. Thereafter, the SMM is selected to solve the flow field to achieve high accuracy.

2.2. Particle phase modeling

The Euler-Lagrange approach, known as a discrete phase model (DPM), is employed to track greases particles migration. The Saffman’s lift force is taken into account in this study. The virtual mass force and other additional forces are neglected. Hence, the equation of motion of a particle can be written as

\[
\frac{du_p}{dt} = F_D(u_p - u_a) + g(\rho_p - \rho_a)\rho_p + F_a
\]  

(1)

where \( u_p \) and \( u_a \) is the velocity of particle and air, respectively, m/s; \( \rho_p \) and \( \rho_a \) is the density of particle and air, respectively, kg/m\(^3\); \( g \) represents the gravitational acceleration, m/s\(^2\); \( F_D \) is the drag force coefficient; \( t \) is the time, s; \( F_a \) is additional acceleration term, m/s\(^2\).

In addition, the interaction between particle and air is assumed to be two-way coupling, and the discrete random walk (DRW) method is employed to simulate the stochastic velocity fluctuations in flow field. The inlet and outlet are established as the pressure conditions. Non-slip wall conditions are applied to the boundaries, while standard wall functions are used in the near wall region. The Semi-Implicit Method for Pressure Linked Equations algorithm is adopted to solve the discrete equations. For the discretisation of pressure, momentum, turbulence kinetic energy and turbulence dissipation rate, the second order upwind format is employed. The effects of gravitation and wall roughness on the flow field are negligible.

2.3. Model validation

In this study, the air is treated as incompressible and Newtonian fluid. The structure parameters of the MCF studied in this paper are blade inlet angle 79° (\( \beta_1 \)), blade outlet angle 163° (\( \beta_2 \)), impeller inlet
diameter 210 mm, impeller outlet diameter 250 mm, arc blade number 60. The guide vanes are installed at blade outlet and arranged in a ring with even space. The space span of guide vanes is 225° as in Figure 1. There has 3° angle of attack for dropping influence of vortex separation along the blade tip, as in equation (2).

\[ \beta_3 = 180° - (\beta_2 - 3°) = 20° \]  

(2)

![Figure 1. The structure of inner guide vanes.](image)

![Figure 2. The distribution of sampling points.](image)

![Figure 3. Comparison of pressure at blade outlet on meridian with different grid numbers.](image)

The grid independence test is conducted on a computational domain with 3 groups of different grid numbers. 24 sampling points are extracted in blade outlet zone, and their pressures are compared in Figure 2. Figure 3 shows that the difference of pressure distribution for the grid number of 1.33 million and 2.24 million is very slight. Hence, the grid number of 1.33 million is selected for present numerical studies.

The numerical results of the exhaust airflow rate \( q_V \) are compared with experimental results reported in the reference [12], as shown in Figure 4. The simulation data is basically consistent with the experimental result and the numerical model is feasible to predict the flow characteristics of the MCF. However, there are relatively larger deviations between the simulation and experimental with the increasing of \( q_V \). This is because the resistance of wall surface and inlet filter is neglected.

In order to validate the DPM model, the experimental data reported in reference [13] is used to test the efficiency of this model. Figure 5 shows the scheme diagram of the experimental chamber. The supply air velocity was 0.225 m/s and the particle diameter and density were 10 μm and 1400 kg/m³, respectively. Figure 6 shows the comparison between the normalized particles concentration and experimental data at three different locations of center plane. A reasonable agreement between the simulation results and the experimental results can be seen from these figures, which means that the DPM is feasible.
3. Result and discussion

The size distribution of grease particle in COF reported in reference [14] is fitted into Rosin Rammler Equation. It is divided into 10 discrete intervals, and the parameters used in this study are shown in Table 1. The particles are assumed to be spherical and its density is 960 kg/m$^3$. A particle is deemed as deposited once its edge touches a solid wall surface and does not consider the re-suspension. The trap is selected as DPM boundary condition for blade and guide vanes surface, volute inside wall. And the separation efficiency defines as followings:

- Total separation efficiency

$$\eta_t = \frac{(Num_{in} - Num_{out})}{Num_{in}}$$  \hspace{1cm} (3)

- Blade intercepting efficiency

$$\eta_b = \frac{Num_b}{Num_{in}}$$  \hspace{1cm} (4)

- Guide vanes intercepting efficiency

$$\eta_g = \frac{Num_g}{Num_{in}}$$  \hspace{1cm} (5)

- Volute separation efficiency

$$\eta_v = \frac{Num_v}{Num_{in}}$$  \hspace{1cm} (6)

![](image.png)

Figure 4. $q_V$ with different orifice plate conditions.

Figure 5. The scheme diagram of experimental chamber.

Figure 6. Comparison of the normalized particle concentration between the results of simulation and experiment [13] at (a) $x=0.2$m, (b) $x=0.4$m and (c) $x=0.6$m.
where \( N_{in} \) and \( N_{out} \) are the particle number released at inlet and outlet of the MCF, respectively; \( N_{b}, N_{g} \) and \( N_{v} \) represent the particle number trapped by the blades, guide vanes and volute inside surface, respectively.

Table 1. Particle diameter distribution properties.

| Parameters   | \( D_{\text{min}} \) | \( D_{\text{max}} \) | \( D_{\text{mean}} \) | Spread diameter | Number of diameters |
|--------------|----------------------|----------------------|----------------------|-----------------|--------------------|
| Value        | 0.03\( \mu \text{m} \) | 10\( \mu \text{m} \)  | 4.6293\( \mu \text{m} \) | 1.1865          | 10                 |

The grease particle separation of the original multi-blades centrifugal fan (OMCF) and the modified multi-blades centrifugal fan with inner guide vanes (MCFG) is shown in Figure 7. From Figure 7(a), it is observed that the MCFG exhibits higher separation efficiency than the OMCF. In the particle diameter \( (D_p) \) range of 1 to 10 \( \mu \text{m} \), the mean total separation efficiency of the MCFG increases by 4.5\% compared with the OMCF. It indicates that the inner guide vanes significantly contribute to improve separation performance of the MCF. Figure 7(b) shows that \( \eta_b \) of the MCFG is lower than that of the OMCF. This is because the influence of the inner guide vanes at blade out makes the fluid velocity increasing in flow channel of impeller, and the residence time of particle decreases. However, when the particles pass through flow channel of guide vanes, about 10\% particles is intercepted by the guide vanes. In Figure 7(c), it is interesting noticed that \( \eta_v \) of the MCFG is significantly higher than that of the OMCF. There is a dramatic decrease for \( \eta_v \) at 3 \( \mu \text{m} \leq D_p \leq 10 \( \mu \text{m} \), which demonstrates that the guide vanes help to small diameter particles move to volute surface. Therefore, guide vanes are very useful measurement to improve separation efficiency of the MCF.

![Figure 7. Particle separation efficiency versus particle diameter.](image)

4. Conclusions

The present paper numerically studies the effect of inner guide vanes on grease particle separation performance of multi-blades centrifugal fan. The proposed inner guide vanes show excellent function to improve separation efficiency of the MCF. The total separation efficiency of the MCFG is 93.8\% at \( D_p = 5 \( \mu \text{m} \), which is higher by 11.3\% than that of the OMCF. Although the blade intercepting efficiency of the MCFG is lower than that of the OMCF, the volute separation efficiency increases dramatically for grease particles of diameter in the range of 1 \( \mu \text{m} \) to 4 \( \mu \text{m} \). The findings are helpful for the improvement of cooking oil fumes purification of range hood.

Acknowledgments

The research was financially supported by the National Key R&D Program of China through grant No. 2017YFC0211500.

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