

Research Article

Multiobjective Optimization Design for Skew and Sweep Parameters of Two-Stage Blades of Axial Fan

Wen-hui Yue,¹ Yong-ping Jin,² and Ze-jun Wen¹

¹ Engineering Research Center of Advanced Mining Equipment, Ministry of Education, Hunan University of Science and Technology, Xiangtan, Hunan 411201, China

² College of Mechanical and Electrical Engineering, Central South University, Changsha 410083, China

Correspondence should be addressed to Yong-ping Jin; jinyongping12@163.com

Received 11 March 2013; Accepted 4 April 2013

Academic Editors: M. Ahmadian, Y.-H. Lin, and B. Yu

Copyright © 2013 Wen-hui Yue et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Computer aided design and numerical simulation have been widely applied in optimization design of fan blades. In this paper, skew and sweep parameters of two-stage blades of an axial fan are optimized by using the particle swarm optimization algorithm. First, the skew and sweep parameters of two-stage blades of an axial fan are defined. Second, response surface methodology is used to study the relationship between the skew and sweep parameters of two-stage blades and the total pressure and the efficiency of the axial fan. The response surface model that describes the relationship between the skew and sweep of two-stage blades and the total pressure and the efficiency of the axial fan is established. Finally, with the skew and sweep of two-stage blades being design variables and the total pressure and the efficiency being the objectives, a particle swarm optimization algorithm is developed to solve this complex multiobjective optimization problem. The optimal result shows that the total pressure increases by 49.1 Pa and the efficiency increases by 1.55%. In addition, the aerodynamic performance of the axial fan is improved. This research has significance to optimization design of the axial fan.

1. Introduction

With the rapid development of computer technology, computer aided design and numerical simulation have been widely used in optimization design of fan blades. The total pressure which includes dynamic pressure and static pressure, the efficiency, and the aerodynamics performance of an axial fan may be improved by changing blades shape properly through optimization design. Benini [1], Yang et al. [2, 3], Samad and Kim [4], and Lei et al. [5] used the artificial neural network genetic algorithm to optimize stacking lines of blades. The optimal results show that a proper match of skew and sweep in a fan design can effectively increase the total pressure and the efficiency of an axial fan, improve the flow status of the suction surface of a blade, and decrease the secondary flow. Jin et al. [6] used the response surface methodology to optimize skew and sweep parameters of two-stage blades of an axial fan. But this research focused on the single stage blade parameters optimization design and the optimization objective is only for the efficiency of a

fan. It should be mentioned that there is rare research for the multiobjective optimization design of skew and sweep parameters of two-stage blades in an axial fan.

In the optimization of an aerodynamic performance of an axial fan, it is very important that the total pressure and efficiency of the fan need to be considered simultaneously. Therefore, such an optimization is a multiobjective optimization. In the multiobjective optimization process, all objectives are mutually related to each other and mutually conflict with each other in most cases. For the optimization design of an axial fan, an excessive high total pressure pursuit may lead to low efficiency and vice versa. It is impossible that several objectives achieve optimal value at the same time. For this purpose, the organization and coordination among these objectives should be considered and investigated accordingly. One of the goals of this research is to deal with the multiobjective optimization.

In this paper, the axial fan is used as the research target, and the computational fluid dynamics method is used to simulate the three-dimensional flow of the axial fan. First, the

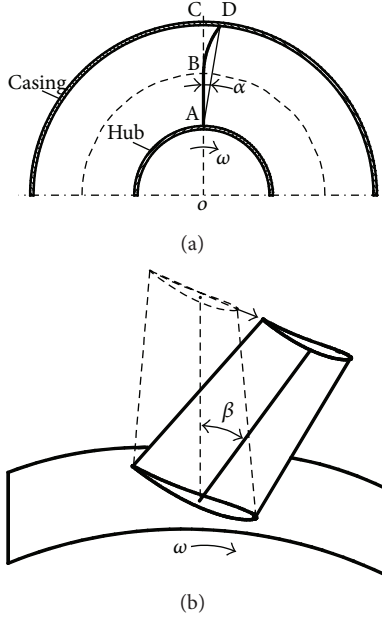


FIGURE 1: Definitions of blades skew and sweep.

modeling of an axial fan is introduced. Then a response surface methodology is used to study the relationship between the skew and sweep parameters of two-stage blades and the total pressure and the efficiency of the axial fan. After that, a particle swarm optimization algorithm is developed to solve the complex multiobjective optimization problem where the total pressure and the efficiency of the axial fan are the optimization objectives. Finally, some conclusions are presented.

2. Blades and Computational Model

2.1. Definition of Blades Skew and Sweep. The definitions of blades skew and sweep are illustrated as shown in Figure 1. In Figure 1(a), a stacking line of the blade (ABD) is composed of a line segment (AB) and an arc segment (BD), and point B lies in the point of 50% of the blade height. The angle α_i between line AB and line AD is called skewed angle of the blade, $i = 1, 2$, represent the first stage and the second stage blades, respectively. In Figure 1(b), the sweep corresponds to moving the blade section in the chord direction, and the angle is expressed as β_i , and $i = 1, 2$ represent the first stage blade and the second stage blade, respectively.

2.2. Computational Model. In order to study the relationship between the skew and sweep parameters of two-stage blades and the total pressure and the efficiency of axial fan, an axial fan is taken as a research task, and some specifications of this axial fan are given in Table 1.

The three-dimensional software SolidWorks is used to build the 3D model for a fan blade (see Figure 2). The current collector and streamlined shield are added in the front of the first stage impeller, and a diffuser is added in the back end of the second stage impeller to form a complete 3D model

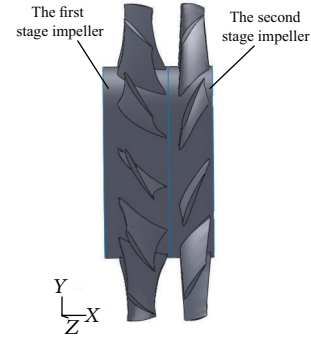


FIGURE 2: Impellers model.

TABLE 1: Specifications of axial fan.

Flow/(m ³ /s)	43
Rotational velocity/(r/min)	980
Impeller diameter/mm	1600
Hub ratio	0.6
Blades number of the first stage impeller	13
Blades number of the second stage impeller	11

of the axial fan. Furthermore, the mesh of the 3D model of the axial fan is generated by using unstructured tetrahedral mesh (TGrid). Because of the large volume of the fan, in order to improve the calculation efficiency, the meshing size of the current collector, streamlined shield, and diffuser is set to be slightly larger than that of the first stage impeller and the second stage impeller. In this paper, the volume meshing size for the current collector, streamlined shield, and diffuser is set as 38, for the first stage impeller set as 30, and for the second stage impeller set as 29. The total grid number of the axial fan is 916 653.

2.3. Boundary Conditions. Simulations of the three-dimensional flow of the axial fan are conducted by using the FLUENT software. The boundary conditions of the three-dimensional flow field model are as follows: the fluid is normal air; the fan inlet is set as mass-flow inlet. The fluid areas that include these between the current collector, the streamline cover, and the first stage impeller, between the first stage impeller and the second stage impeller, and between the second stage impeller and the diffuser are set as mixing plane. The two-stage blades of the axial fan and hubs are set as stationary walls, and the iteration is 1400 [7, 8]. The computational mesh and boundary conditions of the axial fan are shown in Figure 3.

3. Experimental Design and Analysis of Simulation Results

3.1. Experimental Design. To study the effect of the skew and sweep parameters of two-stage blades on the total pressure and efficiency of the axial fan, a proper experimental

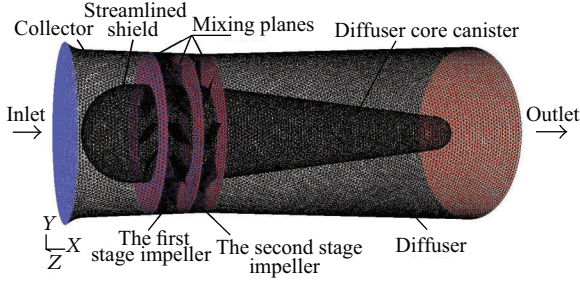


FIGURE 3: Computational mesh and boundary conditions of axial fan.

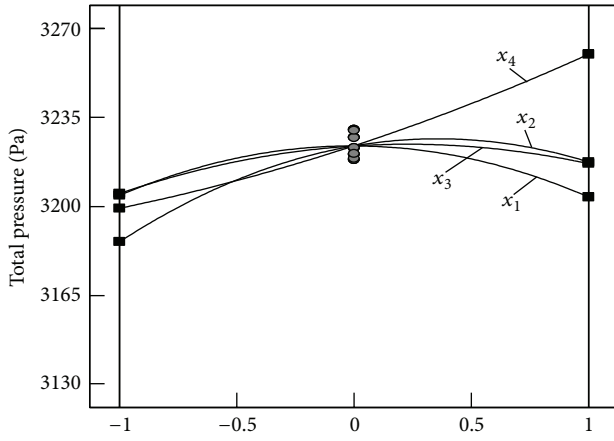


FIGURE 4: Effects of x_1 , x_2 , x_3 , and x_4 on the total pressure.

design method is important for this research. Compared with various methods of experimental design, this paper uses response surface methodology (RSM) to arrange the experiment scheme. This method not only can achieve the experiment requirements but also can effectively reduce the number of experiments, save time, and improve efficiency. Before conducting experiments, it is necessary to determine the scope of the change of all design variables through the single factor experimental design. The result of a single factor experimental design shows that α_1 , β_1 , α_2 , and β_2 have most significant effects on the total pressure and the efficiency of the axial fan. The variation range of each factor is decided by preliminary calculations [6]: α_1 from -15° to 15° , β_1 from -10° to 10° , α_2 from -12° to 12° , and β_2 from -8° to 8° (for the convenience in analysis, where x_1 , x_2 , x_3 , and x_4 represent the α_1 , β_1 , α_2 , and β_2 , resp.). The analytical factors and levels for RSM are shown in Table 2, and an experimental scheme is listed in Table 3.

3.2. Analysis of Simulation Results. The simulations of three-dimensional flow of the blades for 29 designed tests in the experimental scheme are carried out by using FLUENT software, and the simulation results for total pressure and efficiency are shown in Table 4.

Figure 4 shows the effect of x_1 , x_2 , x_3 , and x_4 on the total pressure of fan. It can be seen that the total pressure of the axial fan tended to increase firstly and then decrease

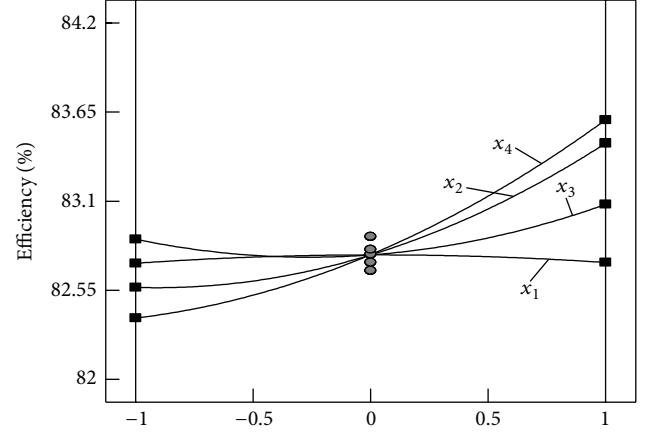


FIGURE 5: Effects of x_1 , x_2 , x_3 , and x_4 on the efficiency.

TABLE 2: Analytical factors and levels for RSM.

Factors	Coded value of each factor level		
	-1	0	1
$\alpha_1/(\circ)$	-15°	0°	15°
$\beta_1/(\circ)$	-10°	0°	10°
$\alpha_2/(\circ)$	-12°	0°	12°
$\beta_2/(\circ)$	-8°	0°	8°

with the increase of x_1 , x_2 , and x_3 . The total pressure will be increased along with the increase of x_4 . The result also shows that the relative importance of these four factors, from most significant to least significant, is x_4 , x_2 , x_3 , and x_1 .

Figure 5 shows the effect of x_1 , x_2 , x_3 , and x_4 on the efficiency of the fan. It can be seen that the parameter x_1 is insignificant on the efficiency of fan. The efficiency of the fan is enhanced along with the increase of x_2 and x_4 . The efficiency of fan tended to decrease first and then to increase with the increase of x_3 . Parameter x_4 has the most significant influence on the efficiency of the fan.

Figure 6 shows 3D response surface and contour graph of the effect of x_2 and x_4 on the total pressure and the efficiency of the fan.

At the same time, response surface model of the total pressure and the efficiency can be established by multiple regressions based on 29 experiments's results. They are given by the following:

$$\begin{aligned}
 f_{(\text{Total pressure})} = & 3223.79 - 0.31x_1 + 15.68x_2 \\
 & + 5.86x_3 + 32.42x_4 - 33.79x_1x_2 \\
 & + 0.23x_1x_3 + 3.11x_1x_4 - 0.15x_2x_3 \\
 & + 0.17x_2x_4 - 15.98x_3x_4 - 19.78x_1^2 \\
 & - 21.99x_2^2 - 12.84x_3^2 + 6.07x_4^2
 \end{aligned}$$

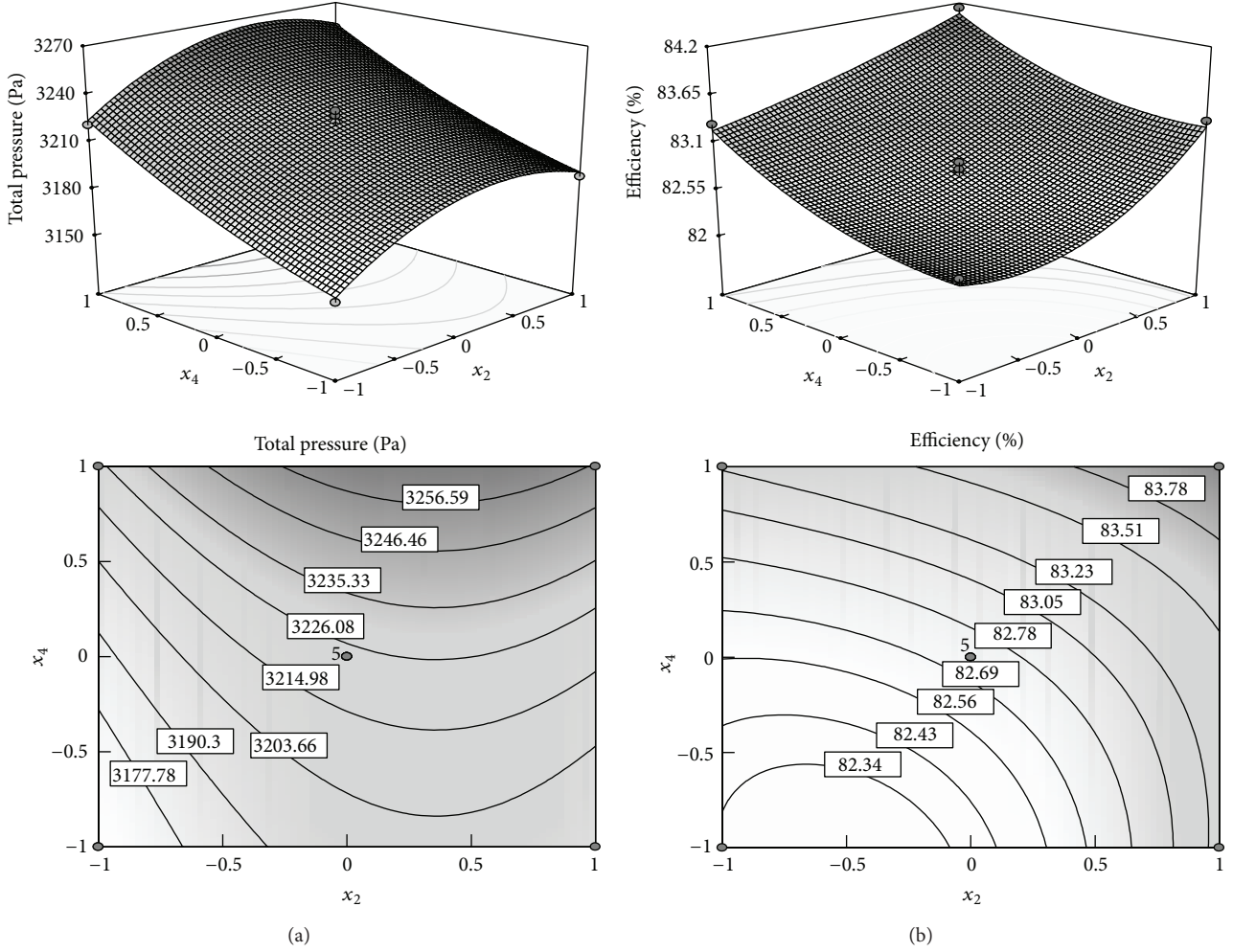


FIGURE 6: 3D response surface and contour graph.

$$\begin{aligned}
 & -2.03x_1^2x_2 - 6.71x_1^2x_3 + 1.02x_1^2x_4 \\
 & + 7.32x_1x_2^2 + 2.67x_1x_3^2 - 9.59x_2^2x_3 \\
 & - 0.36x_2^2x_4 + x_2x_3^2, \\
 f_{(\text{Efficiency})} = & 82.77 + 0.0025x_1 + 0.45x_2 + 0.11x_3 \\
 & + 0.61x_4 + 0.12x_1x_2 + 0.095x_1x_3 \\
 & - 0.12x_1x_4 - 0.065x_2x_3 - 0.035x_2x_4 \\
 & - 0.26x_3x_4 - 0.049x_1^2 + 0.24x_2^2 \\
 & + 0.2x_3^2 + 0.22x_4^2 - 0.16x_1^2x_2 \\
 & - 0.023x_1^2x_3 + 0.065x_1^2x_4 + 0.095x_1x_2^2 \\
 & + 0.072x_1x_3^2 - 0.1x_2^2x_3 - 0.19x_2^2x_4 \\
 & - 0.11x_2x_3^2.
 \end{aligned} \tag{1}$$

4. Multiobjective Optimization of Skew and Sweep Parameters and Analysis

4.1. Multiobjective Optimization. With the skew and sweep of two-stage blades being the variables and the total pressure and the efficiency of axial fan being the objectives, the formulation of multiobjective optimization can be written in the following form:

$$\begin{aligned}
 \text{Max} \quad & F(x) = [f_{\text{Total pressure}}(x), f_{\text{Efficiency}}(x)] \\
 \text{s.t.:} \quad & -1 \leq x_1, x_2, x_3, x_4 \leq 1.
 \end{aligned} \tag{2}$$

Because the total pressure and the efficiency of the axial fan are two different objectives, this optimization is a multiobjective optimization problem. In the multiobjective optimization process, the total pressure and the efficiency of the fan are mutually related to each other and mutually conflict with each other. For this purpose, the organization and coordination between the total pressure and the efficiency of fan should be considered and investigated in depth. In this study, particle swarm optimization algorithm is used

TABLE 3: Experimental scheme.

Number	x_1	x_2	x_3	x_4
1	0 (0°)	0 (0°)	1 (12°)	-1 (-8°)
2	1 (15°)	-1 (-10°)	0 (0°)	0 (0°)
3	0 (0°)	-1 (-10°)	0 (0°)	-1 (-8°)
4	0 (0°)	1 (10°)	0 (0°)	1 (8°)
5	-1 (-15°)	0 (0°)	1 (12°)	0 (0°)
6	-1 (-15°)	1 (10°)	0 (0°)	0 (0°)
7	1 (15°)	0 (0°)	-1 (-12°)	0 (0°)
8	0 (0°)	0 (0°)	0 (0°)	0 (0°)
9	0 (0°)	0 (0°)	0 (0°)	0 (0°)
10	1 (15°)	1 (10°)	0 (0°)	0 (0°)
11	-1 (-15°)	-1 (-10°)	0 (0°)	0 (0°)
12	0 (0°)	0 (0°)	0 (0°)	0 (0°)
13	0 (0°)	-1 (-10°)	1 (12°)	0 (0°)
14	0 (0°)	-1 (-10°)	0 (0°)	1 (8°)
15	0 (0°)	0 (0°)	0 (0°)	0 (0°)
16	0 (0°)	-1 (-10°)	-1 (-12°)	0 (0°)
17	0 (0°)	0 (0°)	-1 (-12°)	1 (8°)
18	1 (15°)	0 (0°)	1 (12°)	0 (0°)
19	0 (0°)	1 (10°)	0 (0°)	-1 (-8°)
20	0 (0°)	0 (0°)	0 (0°)	0 (0°)
21	1 (15°)	0 (0°)	0 (0°)	1 (8°)
22	0 (0°)	0 (0°)	1 (12°)	1 (8°)
23	0 (0°)	0 (0°)	-1 (-12°)	-1 (-8°)
24	-1 (-15°)	0 (0°)	-1 (-12°)	0 (0°)
25	-1 (-15°)	0 (0°)	0 (0°)	-1 (-8°)
26	1 (15°)	0 (0°)	0 (0°)	-1 (-8°)
27	0 (0°)	1 (10°)	-1 (-12°)	0 (0°)
28	0 (0°)	1 (10°)	1 (12°)	0 (0°)
29	-1 (-15°)	0 (0°)	0 (0°)	1 (8°)

to solve this multiobjective optimization problem. The so-called Pareto optimality method is used to find the potential optimization solution for maximizing the total pressure and the efficiency of the fan.

4.2. Particle Swarm Optimization Algorithm. Particle swarm optimization (PSO) is a population based stochastic optimization technique developed and inspired by social behavior of bird flocking schooling [9]. It is widely reported that the PSO algorithm is simple to implement and has fewer parameters when compared to other evolutionary algorithms [10–14]. PSO shares many similarities with evolutionary computation techniques. The PSO system is initialized with a population of random solutions and searches for optima by updating generations. This paper assumes that the particle swarm is composed of m particles in n -dimensional searching space; the i th particle has the following characteristics. The current location of particle

$$x_i = \{x_{i1}, x_{i2}, \dots, x_{in}\}, \quad i = 1, 2, \dots, m. \quad (3)$$

TABLE 4: Simulation results for total pressure and efficiency.

Number	Total pressure/Pa	Efficiency/%
1	3210.02	82.78
2	3212.74	82.49
3	3157.52	82.4
4	3253	84.14
5	3184.94	82.91
6	3226.04	82.87
7	3191.35	82.89
8	3222.89	82.77
9	3227.14	82.80
10	3172.47	83.30
11	3131.15	82.53
12	3230.17	82.88
13	3167.91	83.05
14	3221.29	83.32
15	3220.4	82.72
16	3175.07	82.91
17	3263.13	83.79
18	3190.11	83.25
19	3188.53	83.36
20	3218.36	82.67
21	3245.53	83.59
22	3242.9	83.49
23	3166.35	82.05
24	3187.09	82.93
25	3179.29	82.23
26	3172.44	82.48
27	3208.74	83.70
28	3200.97	83.58
29	3239.93	83.83

The current velocity of particle

$$v_i = \{v_{i1}, v_{i2}, \dots, v_{in}\}, \quad i = 1, 2, \dots, m \quad (4)$$

p_{pbest} is the best solution (fitness) that has been achieved so far

$$p_{pbest} = \{p_{i1}, p_{i2}, \dots, p_{in}\}, \quad i = 1, 2, \dots, m. \quad (5)$$

A global best position is defined as

$$p_{gbest} = \{p_{g1}, p_{g2}, \dots, p_{gn}\}. \quad (6)$$

At each iteration, all the particles move in the searching space to find the global optima. The velocity and position of each particle are adjusted by the following formulas:

$$\begin{aligned} v_{i,j}(t+1) &= \omega \cdot v_{i,j}(t) + c_1 \cdot r_1 \cdot [p_{pbest}(t) - x_{i,j}(t)] \\ &\quad + c_2 \cdot r_2 \cdot [p_{gbest}(t) - x_{i,j}(t)], \\ x_{i,j}(t+1) &= x_{i,j}(t) + v_{i,j}(t+1), \end{aligned} \quad (7)$$

where subscript j denotes the dimension of searching space, i is the total number of particles, t represents the current

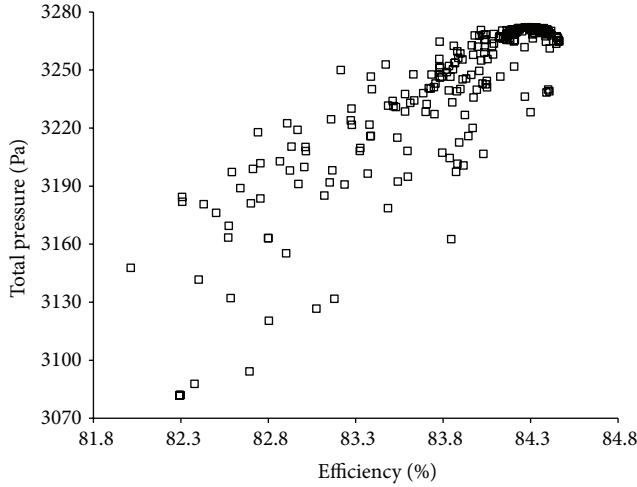


FIGURE 7: The optimizing process of the total pressure and the efficiency.

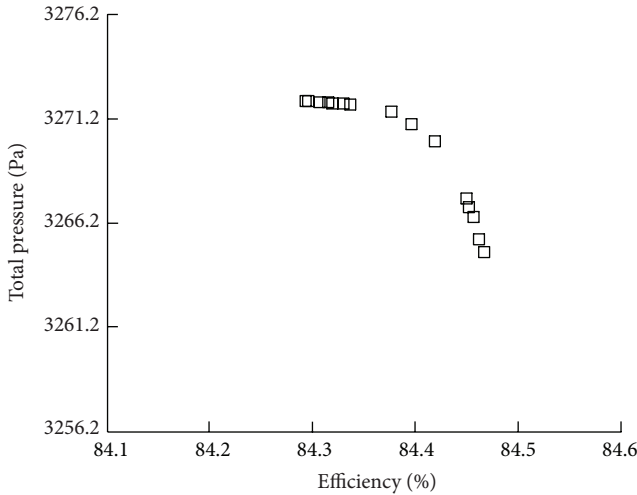


FIGURE 8: The relationship between the total pressure and efficiency corresponding to the Pareto optimal set.

iteration number, $r_1 \sim U(0, 1)$ and $r_2 \sim U(0, 1)$ are two independent random functions, c_1 and c_2 are acceleration constants, and ω is an inertia weight.

A procedure for the particle swarm optimization algorithm is as follows.

Step 1. Initialize n particles and randomly assign the velocity and position of each particle.

Step 2. Calculate each particle's value of fitness.

Step 3. Compare each particle's value of fitness with p_{pbest} , and if it is better, this particle will be taken as the current global best position.

Step 4. Compare each particle's value of fitness with p_{gbest} , and if it is better, the particle will be taken as the current global best position.

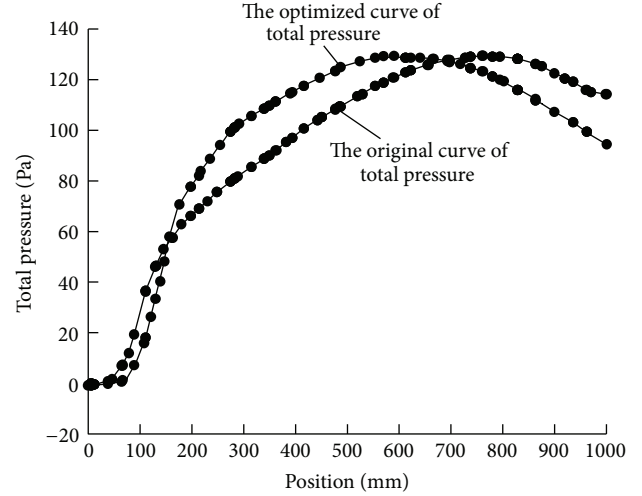


FIGURE 9: The total pressure distribution of original fan and optimized fan at the outlet of axial fan.

Step 5. Update the velocity and position of particle on the basis of (7).

Step 6. Repeat Step 2, until meeting the terminal condition.

4.3. Optimization Process and Analysis. Particle swarm optimization algorithm is used to solve this multiobjective optimization problem. In the particle swarm optimization algorithm, the initial 25 particles are generated randomly, and acceleration constants are set as $c_1 = 2$, $c_2 = 2$, and inertia weight $\omega = 1$. The algorithm converges after 270 iterations. The optimizing process of the total pressure and the efficiency is shown in Figure 7.

The relationship between the total pressure and the efficiency corresponding to the Pareto optimal set is shown in Figure 8. It is seen that excessive high total pressure pursuit may lead to low efficiency of the axial fan and vice versa. The change between the total pressure and the efficiency in the Pareto optimal set is very small. And each point of Pareto optimal set can be used as the optimized result.

Because each point of Pareto optimal set can be used as the optimized result, in order to compare with the original design, the total pressure and the efficiency of the original design are 3222.89 Pa and 82.77%, respectively; a point of Pareto optimal set is selected randomly as an example. The value of each factor of this point is $x_1 = -0.6988$, $x_2 = 0.9886$, $x_3 = -0.9144$, and $x_4 = 1$. At this point, the total pressure is 3271.99 Pa and the efficiency is 84.32%. Then we translate x_1 , x_2 , x_3 , and x_4 into the actual designed parameters: $\alpha_1 = -10.48^\circ$, $\beta_1 = 9.89^\circ$, $\alpha_2 = -10.97^\circ$, and $\beta_2 = 8^\circ$. The optimized result shows that the total pressure increase by 49.1 Pa and the efficiency increase by 1.55%, compared with the original design.

Figure 9 shows the total pressure distribution of the original fan and the optimized fan at the outlet side. It can be seen that the highest pressure point of the total pressure of the diffuser outlet is on the vicinity of central diffuser outlet.

Simultaneously, the total pressure of the tip, the flow in tip region, and the fluid accumulating on the tip are decreased, and the flow which increase in the heel of blades can reduce the loss of pressure of the axial fan and improve the total pressure and the efficiency.

5. Conclusion

The computational fluid dynamics method is used to solve the three-dimensional flow of an axial fan, and a multiobjective optimization method is proposed for the optimization design of two-stage blades. Response surface methodology is used to study the relationship between the skew and sweep of two-stage blades and the total pressure and the efficiency of the axial fan. With the skew and sweep of two-stage blades being design variables and the total pressure and the efficiency of axial fan being the objectives, particle swarm optimization algorithm is applied to solve this complex multiobjective optimization problem. The optimal result shows that the total pressure increases by 49.1 Pa and the efficiency increases by 1.55%, compared with the original design. In addition, the aerodynamic performance of axial fan is improved. It is demonstrated that the developed multiobjective optimization method can improve the overall performance of the axial fan.

Conflict of Interests

The authors do not have any conflict of interests with other people or company.

Acknowledgment

This research is supported by the Hunan Provincial Natural Science Foundation of China under Grant no. 11JJ8005.

References

- [1] E. Benini, "Three-dimensional multi-objective design optimization of a transonic compressor rotor," *Journal of Propulsion and Power*, vol. 20, no. 3, pp. 559–565, 2004.
- [2] L. Yang, O. Hua, and D. Zhao-Hui, "Optimization design and experimental study of low-pressure axial fan with forward-skewed blades," *International Journal of Rotating Machinery*, vol. 2007, Article ID 85275, 10 pages, 2007.
- [3] Y. Li, H. Ouyang, and Z. Du, "Optimized design based on skewed and swept blade technology," *Reneng Dongli Gongcheng/ Journal of Engineering for Thermal Energy and Power*, vol. 22, no. 6, pp. 605–609, 2007.
- [4] A. Samad and K. Kim, "Multi-objective optimization of an axial compressor blade," *Journal of Mechanical Science and Technology*, vol. 22, no. 5, pp. 999–1007, 2008.
- [5] H. Lei, C. Wu-li, D. Wen-jian, and Z. Hao-guang, "Multi-objective optimization of the circumferential stacking of axial compressor 3D blades," *Mechanical Science and Technology for Aerospace Engineering*, vol. 28, no. 6, pp. 716–720, 2009.
- [6] Y. Jin, D. Liu, and Z. Wen, "Optimization design for skew and sweep parameters of mine contra-rotating axial fan two-stage blades," *Meitan Xuebao/Journal of the China Coal Society*, vol. 35, no. 10, pp. 1754–1759, 2010.
- [7] Z. Z. Han, J. Wang, and X. P. Lan, *Simulation Examples and Application of FLUENT*, Beijing Institute of Technology Press, Beijing, China, 2004.
- [8] Y.-P. Jin, D.-S. Liu, and Z.-J. Wen, "Effects of blades number and axial clearance on the aerodynamic performance of mine contra-rotating axial fan," *Journal of Hunan University of Science & Technology*, vol. 25, no. 4, pp. 29–32, 2010.
- [9] J. Kennedy and R. Eberhart, "Particle swarm optimization," in *Proceedings of the 1995 IEEE International Conference on Neural Networks. Part 1 (of 6)*, pp. 1942–1948, December 1995.
- [10] Y. Karpat and T. Özel, "Multi-objective optimization for turning processes using neural network modeling and dynamic-neighborhood particle swarm optimization," *International Journal of Advanced Manufacturing Technology*, vol. 35, no. 3–4, pp. 234–247, 2007.
- [11] J. Srinivas, R. Giri, and S. Yang, "Optimization of multi-pass turning using particle swarm intelligence," *International Journal of Advanced Manufacturing Technology*, vol. 40, no. 1–2, pp. 56–66, 2009.
- [12] L. X. Liu, *Research of multi-objective particle swarm optimization algorithm [M.S. thesis]*, Hunan University of Science and Technology, Hunan, China, 2010.
- [13] D. Y. Sha and H. Lin, "A multi-objective PSO for job-shop scheduling problems," *Expert Systems with Applications*, vol. 37, no. 2, pp. 1065–1070, 2010.
- [14] W. Yang, Y. Guo, and W. Liao, "Multi-objective optimization of multi-pass face milling using particle swarm intelligence," *International Journal of Advanced Manufacturing Technology*, vol. 56, no. 5–8, pp. 429–443, 2011.

