The numerical simulation of air distribution in the hybrid electrostatic-fabric precipitator

Minkang Tang*, Ping Yang, Haiping Guo
School of resources and environmental engineering of Jiangxi University of Science and Technology
Email: tmkjjxust@126.com

Abstract: In this paper, the computational fluid dynamics software is adopted to simulate the fluid field of the cylindrical hybrid electrostatic-fabric precipitator, by doing that distributions of static pressure and flow velocity are gained. By increasing the opening rate of the internal circular collecting plate, the uniformity of the air can be improved, and then RMS identifying method is used to judge the air homogeneity. Finally, the basic characteristics of the toroidal electric field are gained, all of these provide a reference to design and improve the function of hybrid electrostatic-fabric precipitator.

1. Introduction
With the development of society, the environmental issue which has a great importance of mankind survival attracts an improving attention. The hybrid electrostatic fabric filter, an effective control of fine dust emission, has a promising future [1, 2]. The dust stream in electrostatic fabric filter is a complex three-dimensional flow. It is very difficult to make out the internal flow field with the conventional test precipitator. The distribution of internal airflow in the dust removal device can be analysed by computer simulation, and numerical simulation methods have the advantage of reproducibility when compared with the experimental research methods. Numerical simulation technology attracts more and more attention, while it is applied widely [3]. The purpose of this thesis is to deepen people's understanding of the electric bag filter performance in theory, intensify the effect of electric bag filter dust through the guidance of the CFD simulation and optimize the structure of the electrostatic fabric filter.

2. Model of the hybrid Electrostatic-Bag precipitator
The laboratory homemade hybrid electrostatic-bag precipitator by Jiangxi University of Science and Technology is used as the physical prototype, and the whole calculation model of hybrid electrostatic-bag precipitator is built by the Gambit software.

2.1. The physical prototype
The Laboratory homemade hybrid electrostatic-bag precipitator includes two parts, the electricity dust removal and bag dust removal, and both parameters of the parts are shown in table1.

* To whom any correspondence should be addressed.
2.2 Calculation Model

2.2.1 Simplify the Physical prototype

The main function of the diversion holes on the circular plate is to channel the air of the annular channels to bag dust removal area even, the arrangement of diversion hole is shown in figure 1. As there are many diversion holes, fine grid is needed in the precise computation. However, because the computer capacity is limited and direct calculation is very difficult, the holes can be equivalent to the gap strip in the case of the opening rate unchanged.

| Design value of dust removal                              | Design value of the bag     |
|-----------------------------------------------------------|----------------------------|
| Radii of external circular plate                          | 560 mm                     |
| Radii of the inner circular plate                         | 280 mm                     |
| Corona electrode number                                   | 12                         |
| Rows of the diversion holes                               | 4 rows                     |
| Radii of the big diversion holes                          | 40 mm                      |
| Radii of the little diversion holes                       | 25 mm                      |
| Distance of the inner and external circular plates         | 280 mm                     |
| Bag number                                                | 7                          |
| Length of the bag                                         | 800 mm                     |
| Center distance of the bag                                 | 50 mm                      |
| Distance of the outlaying bags and inner circular plate    | 50 mm                      |

| Name                                | Data                                      |
|-------------------------------------|-------------------------------------------|
| Air volume need handling            | $Q = 2600 \ \text{m}^3 \ \text{s}^{-1}$  |
| Cross-sectional area of the electric field | $S = 280 \ \text{mm} \times 800 \ \text{mm} = 0.224 \ \text{m}^2$ |
| Velocity of the electric field      | $v = \frac{Q}{S} \times \frac{1}{2} = 1.6 \ \text{m} \ \text{s}^{-1}$ |

The 3D model is built according to the structure characteristics of the hybrid electrostatic-bag precipitator, the geometry model can be divided into several parts: inlet, the electric field, bag dusting space, bag, internal circular collecting plate, and pure air box and ash hopper [5]. Local mesh division method is used to deal with the model, the bags and the bag space grids can be structural grids, the rest can be the unstructured grids (shown in figure 2 and figure 3).
2.2.2 Definite the boundary conditions

- Boundary conditions of air inlet;

Velocity is the condition of inlet boundary. Define velocity and scalar of the in the flow inlet boundary. Suppose the inlet gas of the model pipeline is a uniform fully developed turbulence and the inlet velocity is constant. Then the inlet turbulent kinetic energy and turbulent dissipation conditions are respectively:

\[ k = \frac{3}{2} \overline{u}^2 \]  
\[ \varepsilon = C_u^{3/4} \frac{k^{3/2}}{l} \]  
\[ l = 0.16 (Re_{D_H})^{1/6} \]

Where: \( I \) is the Turbulence intensity; \( \overline{u} \) is average velocity of the entrance (m/s); \( l \) is the turbulence (Turbulence length scale), \( l=0.07 \) L (m); \( C_u \) is Constant and \( C_u = 0.09 \). \( Re_{D_H} \) is the Reynolds number calculated by hydraulic radius (\( D_H \)); L is the associated scale; for the fully developed turbulent flow, L is generally the hydraulic diameter.
• Boundary conditions of outlet:
  Pressure condition of the pipe outlet is the boundary condition of the outlet.
• Filter bag.
  Boundary condition of the filter bag is porous jumping. In this paper, the hybrid filter bag is at the
  beginning, the coated filter bag is clean and air permeability is good, too.
• Boundary conditions of wall
  The wall is stationary, and is at the zero-gradient condition, the standard function of wall is adopted
  by the wall.
• Gas phase parameters
  No compressed air, at normal temperature.

3. Results and analysis of the simulation

3.1. Simulation of the convergence condition
Two-equation model RNG and SIMPLE algorithm is used for the simulation. Second-order upwind is
used for the flow differential.

Usually, there are two meanings for the convergence calculation. One is the approaching trend of
the exact solution of the solutions of differential equation; the other is the approximation of the
solution of algebraic equations to the true solution of the set of coefficients. Either in Iterative solution
of nonlinear problems or algebraic equations, iterative calculation is considered convergent if the
deviation of the consecutive solutions or the relative deviation of each node is less than a set allowed
values.

In the calculation process of this paper, the calculation convergence is monitored by the checking
residual changes of each variable dynamic. There are 500 iterations, iteration will stop at about 10^{-4}
middleweight convergence, after 500 iterations, variables will meet the convergence conditions at the
851^{th} iteration. Stop calculating, the Fluent console prompt solution is converged [6].

![Figure 4. The residual curve.](image)

3.2. Results of the model simulation
To analyze the internal flow of the hybrid electric bag, first of all, key section of the specific location
in the dust space should be selected, and the measurement points of the critical section should be
layout too. Analyze the airflow distribution of the whole equipment by observing the velocity
distribution of the critical section shown in figure 5, the values of the key section are shown in table 4.
Figure 5. Schematic diagram of the calculation section and the bags.

### Table 3. Value of the key section of X, Y, Z direction.

| X direction | Y direction | Z direction |
|-------------|-------------|-------------|
| X₁=170      | Y₁=-147.22  | Z₁=-1000    |
| X₂=-85      | Y₂=-73.6    | Z₂=-700     |
| X₃=0        | Y₃=0        | Z₃=-400     |
| X₄=85       | Y₄=73.6     | Z₄=0        |
| X₅=170      | Y₅=147.22   | Z₅=150      |

4. Analysis of the model simulation

4.1. Electric field

The analysis of speed distribution of electric field, bag dust removal area and hopper area were shown in figure 6-8. The electric field is unevenly distributed: the dust stream will move forward at a speed of 1.6 m s⁻¹ after it passed the entry. The stream will divided into two streams quickly when it hit the inner circle collecting plate. One will spread quickly to both sides of inner circle plate. Due to a fast speed, the flow will enter the bag at a speed of 2 m s⁻¹, in the case of it passes the first and second hole. It can be seen from figure 8 that only little air can reach the back-end of the electric field where the field strength is weak. Another part of the airflow diffuses into the dust hopper from the posterior of the electric field. The air velocity of the posterior of the dust hopper is fast, it can be in the range of 1-1.5 m s⁻¹. The airflow will form a notable vortex. The vortex of the dust hopper seriously impacted the whole equipment. Deposited dust will be brought to the bag by the vortex. This will not only increase the dust concentration, but will also increase the filter load. What’s more, it will cause erosion to the bag, and is not conducive to the operation. From figure 8 we know that the air enters the above box evenly and discharged from the outlet.

The flue gas velocity will reduce significantly after it enters the bag (from 1.6 m s⁻¹ to about 0.4 ~ 0.6 m s⁻¹), however, airflow distribution is more uniform. Cross section Y₁=-147.22, Y₃=0 is the velocity distribution map of plane X-Z. Air velocity increases gradually along Z-axis of the bag. The middle map of figure 6 is the velocity distribution map of the bag clearance, the airflow rising along the bag clearance, the velocity is between 1and 1.5 m s⁻¹, and what’s more, the velocity is relatively uniform. Such airflow can reduce secondary blowing dust in the bag room.
Nowadays, the most commonly used evaluation method is the RMS standards in the domestic. Generally, the air homogeneity of the electric field cut is judged, and the RMS standards are shown in table 4 [7].
Table 4. Criteria.

| σ       | σ≤ 0.10 | σ≤ 0.15 | σ≤ 0.25 | else               |
|---------|---------|---------|---------|--------------------|
| Criteria| excellent| fine    | qualified| unqualified        |

The relative RMS formula:

$$\sigma = \left( \frac{\sum_{i=1}^{n} (v_i - \bar{v})^2}{n \times \bar{v}^{-2}} \right)^{\frac{1}{2}}$$

(4)

Here: $n$ is the total number of the point; $v_i$ is the flow velocity of the i point, m s$^{-1}$; $\bar{v}$ is the mean flow velocity of the point, m s$^{-1}$.

As shown in figure 9, at X=-150, that is, diversion holes 1 and 2 close to the air inlet, the maximum speed of airflow is about 2.5 m s$^{-1}$, which can be accounted for two aspects: firstly, the distance of the guiding holes are too small, thus there is jet effect when air enters the bag; secondly, there is energy loss due to the friction effect when air flows along the circle, which will make the air velocity near the diversion holes 3 and 4 be less than the two front rows.

Figure 9. Velocity of the section where Z=-400.

4.2. The velocity distribution of the filter bag

As shown in figure 10 and 11, although the velocity of the filter bag concentrated between 0.5 and 1.7 m s$^{-1}$, the velocity distribution of the bags are not uniform. The velocity at the bottom of the bags is slow, and which is much faster at the top, particularly near the outlet. Local area is with a high speed, which has seriously impact on the service life of the filter bag.
4.3. The velocity distribution of the ash hopper

It can be seen from figure 12 and 13 that airflow velocity is mainly distributed between 0.2 and 0.9 m s\(^{-1}\), this is less than the design requirement. Even though scouring wear is small due to the slow flow speed, air speed along the ash hopper wall far away from the entrance is much greater than the one in the center of the dust hopper; the maximum speed is around 0.9 m s\(^{-1}\).

4.4. Optimize the model

There are 4 rows of diversion holes on the inner circle dust collection plate of the physical prototype, the collecting plate opening rate is relatively small, that is, area ratio of the effective collecting area of the inner circle collecting plate and the area of the diversion holes is large. And the larger the ratio is, the more effective the collecting area is, so is the ability of dust collecting of the electric field area. In addition, the speed of the electric field is 1.6 m s\(^{-1}\), the opening rate is small, and the collecting plate can help to protect the bag from the air scour and the electric field of corona discharge.

However, analysis of the simulation results shows that due to the uneven distribution of the airflow which is at the back-end of the precipitator field area, a re-allocation of the airflow in this part is needed [8]. Uneven distribution of airflow is caused by the speed of the inlet and the unreasonable set up of the circular collecting plate deflector. Therefore, to distribute the airflow of the electric field uniformly, the airflow of the backend of the electric field can run into the dust bag evenly, improvement in two aspects is needed: (1) increasing the opening rate; (2) reducing the flow velocity.

4.4.1 Increase opening rate

After the equivalent processing of the internal circular plate, the diversion hole and dust collection
plate in of the inner circle are in the same height, so the opening rate equals to the ratio of the openings length and the circumference of the inner circle dust collection plate.

The opening rate of prototype is:

\[
\zeta = \frac{80\text{mm}\times2+50\text{mm}\times2}{2\pi\times280\text{mm}} \approx 15\%
\]

Supposing the rate is 20% after increasing the diversion hole. By the calculation, the required length of the openings is 91.68 mm. In order to simplify the design, length of the openings is 100 mm.

4.4.2 Reduce the flow velocity

Airflow in the bag is mainly composed of two parts, one entered the bag from the deflector holes on the inner collecting plate, and the other entered the bag from the bottom of the bag. These two parts of air develops the windward side speed and the updraft speed at the end of the bag. If the speed of the windward side is too fast, there will be serious wear and tear to outer part of the bag. The ESP is a small one, the original wind speed of the electric field (1.6 m s\(^{-1}\)) is a little fast. The definite velocity should be decided by the air that needs to deal with.

4.5. Optimizations

Optimization program one: improve precipitator internal structure on the basis of the original model, distribute the airflow by opening hole on the inner circle plate (see figure 14), and the effect is notable as shown in Figure 15. The improved equipment reduced the load caused by run of air flow from the bottom of the bag to the dust removal area. It can be seen from Figure 16 that stream the bag mouth ran out upward vertically, the direction of the electric field point to the inner circle speed uniformly by the outer circle collecting plate.

Optimization program two: air diffusion area increases, the distribution around the inner circle board is uniform than the calculation of the original model. The filtration rate decreases along the Z axis. The turbulent flow decrease markedly. And the airflow of the bottom is gentle (see figure 17).

Optimization program three: the velocity of inlet airflow is 0.4 m s\(^{-1}\). This is not only being good to the airflow distribution of the whole equipment, the flow field is also smoother when compared with Option II (shown in figure 21).

After the simulation of re-meshing and iteration convergence, contrast of the flow field velocity distribution of the internal part of dust collector is shown in figure 15-18.

4.6. Comparison of optimization

Export the airflow velocity data of the key points of the electric field section where Z=-400 in Option II and Option III.

Export the key airflow data of section Z=-400 in Option II and Option III, the calculation of the data showed that the max air velocity of optimization two is 1.65 m s\(^{-1}\), the min is 0.10 m s\(^{-1}\), mean air flow rate is 0.472; relative RMS is 0.184656. In optimization three, the maximum flow velocity is 1.34 m s\(^{-1}\), the minimum flow velocity is 0.06 m s\(^{-1}\); mean air flow rate is 0.352; relative RMS is 0.094235. According to common standards of the current domestic electric field airflow uniformity judgment (see Table 4). Optimization three was adopted. That is: adjust the inlet flow rate is 0.4 m s\(^{-1}\), increase the entrance width of electrostatic fabric filter circular plate to 100 mm.

4.7. Velocity distribution of the improved bag gap

Rising velocity of bag clearance mainly refers to the flow velocity paralleled to the bag direction (Z axis) of the dust stream. This velocity decided whether the bag can get a normal and efficient operation by pulse gray or not. The faster the rising velocity is, the less possible the dust will deposit on the surface of the filter. Though the dust deposit on the filter surface, they will move again when pulse jet clean the bag, then captured by the filter and generate a secondary adsorption, resulting in a difficult
deashing [9, 10]. In order to study the variation of the equipment of the bag flow field, due to the special symmetry of the device, select the speed on $Y_2=-73.6$ section as the study object.

**Figure 14.** Distribution of the diversion holes.

**Figure 15.** Section velocity of program one ($v=1.0 \text{ m s}^{-1}$).
**Figure 16.** Vectogram of velocity where $Z=0$ of program one ($v=1.0 \text{ m s}^{-1}$).

**Figure 17.** Section velocity of program two ($v=0.8 \text{ m s}^{-1}$).

**Figure 18.** Section velocity of program three ($v=0.4 \text{ m s}^{-1}$).

**Figure 19.** Velocity cloud of the section where $Y_2=-73.6$ ($v=0.4 \text{ m s}^{-1}$).

**Figure 20.** Section velocity where $Y_2=-73.6$ ($v=0.4 \text{ m s}^{-1}$).
As can be seen from the figure 19 and 20, the maximum speed along the Y axis appears twice, the maximum 0.6 m s\(^{-1}\) appears at the two rows of symmetrical diversion holes of the collecting board, respectively. Airflow velocity distribution is more uniform after the air flow enters the filter space from the diversion holes on both sides, there is a maximum value at Y=0. The majority of the flow velocity distribute between 0.1 and 0.3 m s\(^{-1}\). According to the design, the air flow velocity should be less than 1 m s\(^{-1}\), which is conducive to dust settlement and form a loose layer of dust.

5. Main conclusion

5.1. After the analysis of the electric current whose field channels is toroidal, using CFD software, basic characteristics of the toroidal electric field are got:

- The flow velocity between internal and external circular collecting plate shows a gradient distribution, that is, the flow velocity gradually decreases along the center of the circle outward. Airflow velocity near the cylindrical dust collection plate is relatively small, so dust particles can stay in the electric field for a relatively long time, thus dust particles have enough time to charge in the electric field, which is conducive to the settlement of dust particles of the internal and external cylindrical dust collection plate.
- The electric field flow velocity near the entrance is relatively large, while the one away from the entrance is relatively small. The entrance aperture of deflector hole on the inner circle of the collecting plate is small, while the one away from the imported aperture is big, what’s more, the circumference symmetric structure is good to the gas flow evenly distributed when the airflow from the farm area transition to the filter bag dust area.
- The airflow along the inner circle collecting plates will affect the dust layer formation of the inner circle collecting board, thus reducing the collection efficiency of dust collection plate in the inner circle.

5.2. Bag area

In the bag area, the air flow rate introduced by the collecting plate deflector is bigger than the one enter from the bottom of bag, this is unfavorable to the bag close to the collecting plate. The longer the bag, the more obvious the trend which filtration velocity increasing along longitudinal axis is, resulting in the local area near the outlet side of the bag stay a long period of high filtration velocity state.

During engineering design, the above two parts seriously affect the service life of the bag; it is recommended that thicken these areas in the engineering design.

Acknowledgments

The project is supported by National Natural Science Foundation of China (51064008).

References

[1] Guo X L 2008 North Chin. Electr. Power Technol. 9 5
[2] Tang M K 2010 Chem. Ind. Press (Beijing)
[3] Bai H, Lu C, Chang C L 1995 J. Air Waste Manage. Assoc. 45 900
[4] Di J H 2005 Hebei Univ. Sci. Technol. (in Chinese) 2 160
[5] Meng G Z, Guo L J 2002 Chem. Mach. 29 197
[6] Wang Y F 2010 Donghua Univ.(Shanghai)
[7] Xiang X D 2002 Metall. Ind. Press (Beijing)
[8] Wei J P, Zhang Y H 2009 Shanxi Electr. Power 4 32
[9] Marzio P, Enrico N, Thomas J 2002 J. Fluid Mech. 458 419
[10] Wissink J G 2003 Int. J. Heat Fluid Flow 24 626