Simulation and optimization design of cyclone separator for waste plastic film

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Abstract. Waste plastic sorting and recycling is a kind of efficient and energy-saving way of domestic garbage treatment. In this paper, the Cyclone based Multistage Separation Process for waste plastic film is presented, and the principle and structure of cyclone separator are introduced. The fluid analysis software Fluent is used to simulate and analyze the cyclone separator of waste plastic film. The comprehensive analysis shows that the optimal wind speed of cyclone separator is 18m/s, and under this speed the separation effect of particles in cyclone separator is the best. Based on this, the cyclone separator for waste plastic film was optimized, the structure size of cyclone separator for waste plastic film with three different densities was obtained, and the calculation basis for the design and manufacture of cyclone separator for waste plastic film was provided.

1. Introduction

With the continuous advancement of China's urbanization process, the output of domestic garbage is increasing year by year. According to statistics, waste plastics account for about 10% of the total amount of waste in large and medium-sized cities [1-2]. As a pollution-free and efficient separation method, cyclone separation has been paid more and more attention. Cyclone separator is a centrifugal sedimentation separation equipment in industry. During the separation works, the fluid in the cyclone separator does centrifugal movement in it, and the centrifugal force is used to improve the sedimentation speed of particles in the fluid, so as to achieve efficient separation [3]. Combined with computational fluid dynamics (CFD) and numerical simulation methods, the internal flow in a cyclone separator for separating plastic particles has been simulated and analyzed by Linyan Wu et al [4]. Zhili Gong and his team [5] have analyzed and summarized the advantages and disadvantages of the REM model and k-ε model in the simulation of cyclone separator. Combined with body-fitting grid technology, Na Li et al [6] have come to the conclusion that the REM model has stronger simulation ability by analyzing the simulation results of standard k-ε model, REM model and RNG k-ε model for cyclone separator. And Jiangyun Wang et al [7] improved the RNG k-ε model in turbulence model and used it for fluid simulation in cyclone separators. At present, in the study of cyclone separator, the thin film is assumed to be particles for simulation, but the deformation of the thin film in the wind separation is ignored, which cause a large error between the theoretical analysis results and the actual conclusion, and then affects the separation accuracy and efficiency of the cyclone separator [8-10].
2. Structure and working principle of cyclone separator

Taking a standard cyclone separator as an example, I will briefly explain the basic structure and operation principle of the cyclone separator. As shown in Figure 1, the main body of the cyclone separator is a cylinder, and the lower part is a conical cylinder. The intake pipe is used for incoming separation gas, the exhaust pipe is used for flowing out the separated gas, the cyclone roof is used for connecting the cylinder and the exhaust pipe, and the ash discharging pipe is used for connecting the receiving device for separated impurities. After tangentially entering the cyclone separator from the intake pipe, the flow of gas with particle impurities is constrained by the cylinder wall, doing downward spiral motion, which is generally called external swirling airflow or downstream. The particulate impurities are thrown to the outer wall by the centrifugal force generated by the external swirling airflow, and then lose inertia. Under the action of gravity, they fall along the outer wall and pass through the ash discharging pipe to the collecting device. When the gas external swirling flow reaches the cone, it is affected by the cone. According to the principle of “angular momentum conservation”, its tangential velocity gradually increases. When it reaches the bottom of the cone, it forms a spiral upward internal swirling flow, which is discharged through the exhaust pipe.

![Figure 1. The construction of cyclone separator](image)

3. Cyclone multistage cleaning process of waste plastic film

On the basis of preliminary research and comprehensive literature research, a multi-stage cyclone sorting process for waste plastic film was put forward, and a multi-stage sorting device was designed based on the advantages of cyclone separator. A variety of waste plastic films of different species are recycled and crushed, and then enter the cyclone multi-stage sorting device through the air blower with suitable wind speed. Since the cyclone separator in the multi-stage separation device is designed and optimized according to the waste plastic film that needs to be sorted, the waste plastic film debris can be selected stage by stage according to different densities. Figure 2 shows the working principle diagram of cyclone three-stage separation system.

![Figure 2. The schematic of three-stage sorting in cyclone](image)
As shown in Figure 2, the cyclone three-stage separation system is composed of three cyclone separators in series. As described in the schematic diagram, it is mainly used for the separation of high, medium and low density plastics.

4. Simulation analysis of cyclone separator for waste plastic film

4.1. Cyclone separator simulation process
Simulation analysis of cyclone separator using fluid analysis software Fluent. Fluent is mainly used for the simulation of fluid, heat transfer and other fields. It has many characteristics, such as rich physical models, high efficient parallel computing function and convenient interface setting, etc. The simulation process of cyclone separator is shown in Figure 3:

![Diagram of simulation process](image)

Figure 3. The simulation process diagram of cyclone separator

In the simulation process of cyclone separator, the 3D model of cyclone separator is built using SolidWorks software. In the model after dividing the mesh, specific settings are made after calibrating the model boundary and completing the setting of material parameters. The determined two-phase model affects the accuracy of simulating the complex flow field in cyclone separator. And the choice of the solution method is related to the convergence of the solution process.

4.2. Model building and meshing
The 3D model of the cyclone separator was built using SolidWorks software, and was imported into the Fluent. After determining the fluid domain of cyclone separator that should be simulated, the mesh is divided. The fluid domain of cyclone separator after meshing is shown in Figure 4. The total number of grid nodes is 11167 and the number of cells is 63466.

![Mesh of cyclone separator](image)

Figure 4. The meshing of cyclone separator

4.3. Selection of flow field model
When simulating the flow field inside a cyclone separator, the commonly used turbulence models are usually the standard k-ε model, RNG k-ε model and RSM Reynolds stress model. Considering that the
RNG k-ε model with rotational effects has been proved to be more accurate in simulating the internal processes of cyclone separator in recent years, the RNG k-ε model was chosen as the gas phase model for simulation.

The k and ε equations of the RNG k-ε model are shown in Equations (1) and (2), they are:

$$\frac{\partial \rho k}{\partial t} + \frac{\partial (\rho U_j k)}{\partial x_j} = \frac{\partial}{\partial x_j} \left( \mu_{eff} \frac{\partial k}{\partial x_j} \right) + \rho G_k \rho - \rho \varepsilon$$  \hspace{1cm} (1)

$$\frac{\partial \rho \varepsilon}{\partial t} + \frac{\partial (\rho U_j \varepsilon)}{\partial x_j} = \frac{\partial}{\partial x_j} \left( \mu_{eff} \frac{\partial \varepsilon}{\partial x_j} \right) + \frac{\varepsilon}{k} \left( C_{\alpha} \varepsilon - C_{\alpha} \rho \varepsilon \right)$$  \hspace{1cm} (2)

Among them:

$$C_{\alpha} = 1.42 - \frac{\eta(1-\eta/\eta_s)}{1 + \beta \eta}, \ \eta_s = 4.28, \ \eta = \frac{5k}{S}, \ S = \sqrt{2S_i S_s}$$

$$C_{\mu} = 0.085, \ C_{\varepsilon} = 1.68, \ \sigma_k = \sigma_\varepsilon = 0.7169$$

4.4. Multi-phase flow model selection

To simulate the movement of solid impurities separated by cyclone separator in computer, it is important to improve the precision of particle phase simulation, so it is necessary to introduce the multiphase flow model. The commonly used multiphase flow models are DPM model, VOF model, Mixture model and Eulerian model.

The DPM model, namely the Discrete Phase model, can be used to simulate the discrete phase in the moving flow field, whose particle motion adopts the Lagrange method, and the continuous fluid calculation adopts the Eulerian method. DPM model can track particles with clear simulation ideas, and has advantages in simulating particle separation, smoke diffusion and coal combustion.

The DPM model studies the influence of gravity, inertial force and centrifugal force on particles, and parameters such as particle size and temperature can be set, which is suitable for particle tracking and motion analysis in the separator. Therefore, DPM model is selected for multiphase flow model.

4.5. Boundary condition setting

Setting the inlet plane of the cyclone separator as Inlet, the inlet gas is air at room temperature with a fixed speed and uniform flow, the speed is respectively set at 10m/s, 12m/s, 15m/s, 18m/s, 23m/s, 25m/s. Setting the exhaust plane and the lower cone plane of the cyclone separator as Outflow, whose velocity value could be calculated step by step through the internal velocity value. The other boundary surfaces of the cyclone separator are set as Wall to meet the no slip shear condition.

4.6. Solving algorithm selection

After setting the parameters of the cyclone separator, it is necessary to choose the appropriate discrete and pressure interpolation format to figure out the results. Commonly used discrete formats are upwind format, QUICK format, SIMPLEC, SIMPLE algorithm, and PRESTO! pressure interpolation format.

SIMPLEC algorithm is semi-implicit continuous pressure equation algorithm, which is a pressure-velocity coupling algorithm and is generally used in steady flow. As the development of SIMPLE algorithm, SIMPLEC algorithm synchronizes the improvement process of velocity field with pressure field, inherits the generality of SIMPLE algorithm and improves its convergence.

PRESTO! (Pressure staggering option) pressure interpolation format is used to disperse the momentum equations in numerical calculation, and it uses non-staggered mesh technology to store information such as velocity and pressure to the grid nodes for solution. Compared with other pressure interpolation formats in the software, for example, Standard format and Body force weighted format, the PRESTP! pressure interpolation format is suitable for solving high-speed rotating flow field and flow in highly distorted region. Using this, it is beneficial to improve the calculation accuracy and reduce the amount of calculation. Thus, we selected the SIMPLEC algorithm and use PRESTO! pressure interpolation format to solve the problem. The SIMPLEC algorithm has wide applicability and good
convergence, which is beneficial to analyzing and solving high-speed stable flow field in cyclone separators. And the PRESTO! pressure interpolation format is suitable for high vortex number problems and can be used to give the prediction of the mid-low valley phenomenon of tangential velocity and vortex phenomenon.

4.7. Analysis of simulation results

Usually the inlet velocity of cyclone separator is 10 to 25 m/s. We select six groups of wind speed those are 10 m/s, 12 m/s, 15 m/s, 18 m/s, 23 m/s and 25 m/s to simulate and analyze, and obtained the section clouds of particle volume fraction under the different wind speed condition. They are shown in figure 5. The volume fraction cross-section cloud drawing that can be analyzed to obtain the distribution of particles in the cyclone separator is a ratio between the particle volume and the gas volume in the cyclone separator.
6

Figure 5. The section clouds of particle volume fraction

The simulation results in Fig. 5 show that with the increase of wind speed, the volume fraction of particles in the cone increases gradually. When the wind speed is at 10-18 m/s, the volume fraction of particles in the cone increases obviously, and the aggregation area gradually extends from the outer wall to the inside of the cone.

From 18 m/s, the volume fraction of particles in the cone reaches a stable state. When the wind speed is at 10-18 m/s, the volume fraction of particles in the exhaust pipe changes obviously. It can be seen from the six groups of cross-section clouds drawing that the particles are distributed in each main part of the cyclone separator. To get more accurate analysis results, the data from cross-section clouds of particle volume fraction corresponding to the six wind speed values were counted as shown in Table 1.

| Wind speed (m/s) | Maximum volume fraction (%) | Cone | Main cylinder | Exhaust pipe | Total |
|------------------|-----------------------------|------|---------------|--------------|-------|
| 10               | 0.98700                     | 0.20600 | 0.01070 | 1.20370 |
| 12               | 0.99700                     | 0.00832 | 0.00832 | 1.01364 |
| 15               | 1.00000                     | 0.00732 | 0.00732 | 1.01464 |
| 18               | 1.00000                     | 0.00182 | 0.00182 | 1.00364 |
| 23               | 1.00000                     | 0.00203 | 0.15200 | 1.15403 |
| 25               | 1.00000                     | 0.00181 | 0.10200 | 1.10381 |

It can be seen from Table 1 that the maximum volume fraction of particles in the cone is 1% when the wind speed is higher than 15 m/s. The maximum volume fraction of particles in the main cylinder and exhaust pipe decreases gradually when the wind speed is between 10 m/s and 18 m/s, but increases gradually when the wind speed is between 18 m/s and 25 m/s. Comprehensively analyzing, it can be concluded that the separation effect will be the best when the wind speed is 18 m/s. Because the sum of the maximum volume fractions of in cyclone separator is the smallest, 1.00364; and the sum of particle volume fraction at the position of main cylinder and exhaust pipe is smallest, 0.00364. This shows that particles are mainly collected in the cone, which is conducive to separating through the ash discharge pipe under the cone.
5. Optimal design of cyclone separator

In the three-stage cyclone separation system, it is necessary to optimal design cyclone separator according to the properties of waste plastic film to be sorted and simulation optimal speed, and combined with the the calculation method of pressure loss $\Delta p$ and critical particle size in the separation theory of cyclone separator, deriving the calculation formula of minimum particle size $d_c$ (Critical diameter) that cyclone separator can separate:

$$d_c = \sqrt{\frac{9\mu B}{\pi n u_i \rho_p}}$$  \hspace{1cm} (3)

Among them:
- $\mu$ — gas viscosity;
- $B$ — breadth of intake pipe;
- $n$ — number of rotating rings around exhaust pipe in front of inner cylinder;
- $u_i$ — tangential initial velocity;
- $\rho_p$ — Densities of impurity particles.

As the inlet pipe width of general cyclone separator is proportional to the diameter $D$ of main cylinder, it is inferred that the diameter $D$ of main cylinder of cyclone separator is directly proportional to the critical particle size.

The indoor temperature was selected as 20℃ and the corresponding air density $\rho=1.21\text{kg/m}^3$, viscosity $\mu=1.81\times10^{-5}\text{Pa}\cdot\text{s}$, the density of waste plastic film is 1390kg/m$^3$, the inlet velocity is 18m/s.

As is designed above, when the waste plastic film to be sorted is medium density PE with a density of 1390kg/m$^3$, the optimized dimensions are as follows: the main cylinder diameter $D = 1840\text{mm}$, the cone height $H_2 = 3680\text{mm}$, the minimum cone diameter $D_2 = 920\text{mm}$, the inlet pipe height $h = 1104\text{mm}$, the inlet pipe breadth $B = 920\text{mm}$, and the difference between the exhaust pipe and the inlet pipe in the cyclone separator $s = 368\text{mm}$.

With the same method, when the waste plastic film to be sorted is high density PC with a density of 1900kg/m$^3$, the optimized dimensions are as follows: the main cylinder diameter $D = 2100\text{mm}$, the cone height $H_2 = 4200\text{mm}$, the minimum cone diameter $D_2 = 1050\text{mm}$, the inlet pipe height $h = 1260\text{mm}$, the inlet pipe breadth $B = 1050\text{mm}$, and the difference between the exhaust pipe and the inlet pipe in the cyclone separator $s = 420\text{mm}$.

When the waste plastic film to be sorted is low density PP with a density of 1040kg/m$^3$, the optimized dimensions are as follows: the main cylinder diameter $D = 1454\text{mm}$, the cone height $H_2 = 2908\text{mm}$, the minimum cone diameter $D_2 = 727\text{mm}$, the inlet pipe height $h = 872\text{mm}$, the inlet pipe breadth $B = 727\text{mm}$, and the difference between the exhaust pipe and the inlet pipe in the cyclone separator $s = 291\text{mm}$.

6. Conclusion

This paper introduces the principle and structure of cyclone separator, and puts forward the multi-stage cyclone separation process for waste plastic film. The fluid analysis software Fluent is used to simulate and analyze the cyclone separator for waste plastic film. The comprehensive analysis shows that the optimal wind speed of cyclone separator is 18m/s, and under this speed, the particle separation effect in cyclone separator is the best. Based on this, the cyclone separator for waste plastic film was optimum, the structure dimensions of cyclone separator when sorting three different densities of waste plastic film were obtained, and the calculation basis for the design and manufacture of cyclone separator for waste plastic film was provided.

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