The Orthogonal Experiments for Radial Jet Cyclone

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Abstract. Radial jet cyclone (RJC) is a new type of dust removal equipment based on the improvement of traditional cyclone which greatly improves the separation efficiency of small size particles and inevitably increases the pressure drop. In order to explore the comprehensive influence of the structure size and process parameters of the radial jet cyclone on its separation efficiency, this paper selected five main influencing factors: blade helix angle, blade length, vortex finder depth, airflow velocity and particle concentration to design a set of orthogonal experiments. Through analysis, the experimental results show that the flow velocity has the greatest influence on the pressure drop, followed by the blade helix angle, and the other three factors have a smaller influence. The insertion depth of the riser has the greatest influence on the separation efficiency. While the smaller the vortex finder depth is, the higher the separation efficiency. The other influencing factors are blade helix angle, airflow velocity, blade length and dust concentration.

1. Introduction
Cyclone is a kind of centrifugal separation equipment. Because of its simple structure, low cost and small energy consumption, it is widely used in air pollution control and gas-solid separation process of powder materials in industrial production. Modern efficient cyclone separators have high separation efficiency for particles larger than 5μm, but lower efficiency for dust smaller than 5μm, and are greatly affected by the amount of gas flow[1]. In order to improve the separation efficiency of cyclone for tiny particles, domestic and foreign researchers have done a lot of study: some researchers optimized the traditional cyclone structure size[2-6]. Elsayed introduced artificial neural network to optimize the overall geometry size cyclone separator, the cyclone performance is superior to the Stairmand type cyclone separator[3]. Some researchers have made innovations in the structure, and designed different forms of cyclone, such as a rotating particle invented by Brouwers, which can completely separate breathing fine particles of 0.1~5.0μm by coupling the centrifugal field and laminar flow field of cyclone separator[7,8]. A dynamic cyclone designed by China university of petroleum has a rotating exhaust pipe consisting of vertical rows of tubules or blades to replace the riser pipe in a traditional cyclone separator. This allows the secondary separation of fine particles in the rotating exhaust pipe to basically remove particles over 1.7μm[9]. A large number of numerical simulation studies have also been used to study the internal flow field of cyclone separator, which has played an important role in revealing its separation mechanism[10].

The radial jet cyclone studied in this paper is a new type of cyclone[11]. It has been innovatively designed in structure to improve the separation efficiency of ultra-fine particles. Zheng chenyu conducted mathematical modeling and calculation analysis of RJC[12], and obtained that the critical particle size of RJC was about 1μm. Zhou jielian and Liu xianjie conducted an experimental study on RJC and measured the separation efficiency of RJC. The results showed that the total separation
efficiency of talcum powder with an average particle size of 4μm was 93.9%, and the minimum captured particle size was 0.3μm[13].

However, RJC is a new kind of centrifugal separation structure with almost brand new design. There are 18 structural parameters, 4 dust physical parameters and 3 gas parameters affecting its separation efficiency and pressure drop. So many factors make it really hard to get the rule of its influence on the performance of RJC theoretically. While the experimental research and exploration is a process that needs a lot of time and energy. This study adopts the method of orthogonal experiment, the predecessors' research results and the theoretical calculation results of the radial jet cyclone. On the basis of choosing the blade helix angle, blade length, vortex finder depth, air flow velocity and particle concentration five main factors which may have important effects on separation efficiency and pressure drop, we build up a set of orthogonal experiment.

2. The Structure and Separation Theory of RJC

The structure of traditional cyclone is as figure 1[14].

![Figure 1. The structure of a traditional cyclone](image)

Gas flow with small particles entry into the cyclone through Inlet. Then form a downward spiral flow, the effect of centrifugal force make particles moving towards wall, once the particles hit the wall, we consider that they do not follow the movements of the air flow anymore, but fell along the wall to be captured in the solids hopper, while the downward spiral motion of airflow reverse when reaching the bottom of the cones. The airflow form nan upward spiral airflow and get out of the cyclone through Vortex Finder. If the particles could not get to the wall through the downward spiral airflow, we consider they will reverse upward movement together with airflow, meaning escaped. Two obvious defects can be seen from the structure and principle of the traditional cyclone:

When the dusty gas enters from the inlet, the downward spiral airflow will have a certain collision with other airflows that enter later. In this way, the distribution of the spiral air flow is not uniform, which is not conducive to the separation of particles.

In the dusty gas moving spirally downward, the particles near the cyclone centre need to travel a long distance to strike the wall, which means it is difficult to be separated.

Aiming at the improving the above disadvantages of traditional cyclone, we designed a new type of radial jet cyclone, hoping to improve the separation efficiency. The structure of RJC is shown in figure 2 and the inner structure of RJC is shown in figure 3.
After entering the radial jet cyclone from the Inlet, the dusty gas enters the jet turning section uniformly after passing through the rectifying section. The effect of the horizontal section blade in the jet turning section is to make the movement direction of the dusty gas become horizontal and radial to the RJC wall. The outer wall and inner wall of the turning section in the radial jet cyclone are concentric circle transition, so the particles in the gas arriving at the turning section can be approximately considered as entering the spiral blade section with the circular motion of the gas at this stage. Under the action of twisted spiral blades, the velocity direction of dusty gas changed, and the particles continued to move towards the outer wall under the action of centrifugal force generated by the downward spiral motion. In addition, the circular distribution of multiple spiral flow channels plays a regular role in the flow of dusty gas, so that the dusty gas can steadily enter the cylinder section and cone section similar to the traditional cyclone to continue to separate. The separated particles will eventually fall into the Solids Hopper, while the purified gas will be discharged from the Vortex Finder.

It can be seen from the structure of RJC that, compared with the traditional cyclone, the dusty gas enters into RJC and passes through the rectifier first, and then through the symmetrical distribution of the spiral blade passage, the airflow is evenly distributed at the exit of the spiral blade, without any collision. At the same time, we greatly reduce the distance between dusty gas and the wall surface through the setting of internal spiral blades, which will directly improve the separation efficiency of particles.

3. The Orthogonal Experiments
According to previous research results, the cutting particle size of a 140mm RJC for talc powder is about 2μm. It can be seen that the cutting size is far less than that of a tradition cyclone which is 23.8μm. Meaning the separation efficiency is much higher than that of the traditional cyclone[15]. But also it is not hard to see from its structure, flows through the RJC circuit is more complex, and contains diffusion, shrinkage process that all will make the pressure drop increase. However, the pressure drop is also one of the important performance indexes. In order to optimize the structure of the RJC design and find a suitable work condition. We choose five important parameters from its many structure, technical parameters: the blade helix angle, blade length, vortex finder length, airflow velocity and particle concentration to design a set of L16 (4^5) orthogonal experiments. Hope to find...
the main factors which influence the RJC performance. The selected experimental factors and levels are shown in table 1:

**Table 1. The Factors and their levels for the orthogonal experiments**

| Levels | blade helix angle (A) | vortex finder length (B) | particle concentration (C) | airflow velocity (D) | blade length (E) |
|--------|----------------------|--------------------------|---------------------------|----------------------|-----------------|
| 1      | 15°                  | 50mm                     | 10g/m3                    | 15m/s                | 5mm             |
| 2      | 20°                  | 100mm                    | 13g/m3                    | 20m/s                | 6.5mm           |
| 3      | 25°                  | 150mm                    | 16g/m3                    | 25m/s                | 8.5mm           |
| 4      | 30°                  | 200mm                    | 19g/m3                    | 30m/s                | 10mm            |

**Figure 4.** The whole experiment equipment and process

**Figure 5.** The photo of whole experiment equipment and process

The whole experiment equipment is as shown in figure 4 and figure 5:

In the experiment, talcum powder with a median particle size of 4 m was selected as the test particle which’s density is 2800kg/m3. The particle size distribution was measured by Master Min laser particle size analysis, as shown in figure 6. In the experiment, Testo 425 hot-wire anemometer was used for velocity measurement, and ALNOR AXD530 pitot tube and u-tube differential pressure meter were used for pressure measurement. The data after consolidation are shown in table 2.
Figure 6. The particle size distribution of talcum powder

Table 2. Formatting sections, subsections and subsubsections.

| Experiment Number | Factors | Left Behind | Bag Filter | Total | Vortex Finder | $\Delta P_1$ | $\Delta P_2$ | $\Delta P_3$ | Pressure Separation Drop | Separation Efficiency |
|-------------------|---------|-------------|------------|-------|---------------|--------------|--------------|----------------|----------------------------|-----------------------|
| 1                 | 15      | 50          | 10         | 15    | 5             | 27.8         | 3.8          | 138.4         | 68.2                       | 380                   |
|                   | 2       | 100         | 13         | 20    | 6.5           | 37.6         | 5.2          | 142.8         | 81                | 500                   |
|                   | 3       | 150         | 16         | 25    | 8.5           | 45.2         | 9.8          | 150.2         | 88.4                       | 580                   |
|                   | 4       | 200         | 19         | 30    | 10            | 54.2         | 11.2         | 146.8         | 80.2                       | 820                   |
|                   | 5       | 50          | 13         | 25    | 10            | 44.4         | 5.6          | 138           | 92.2                       | 510                   |
|                   | 6       | 100         | 10         | 30    | 8.5           | 52           | 6            | 142.4         | 85.8                       | 710                   |
|                   | 7       | 150         | 19         | 15    | 6.5           | 42           | 8            | 144.4         | 94.4                       | 350                   |
|                   | 8       | 200         | 16         | 20    | 5             | 43.8         | 11.2         | 148.4         | 99.4                       | 450                   |
|                   | 9       | 50          | 16         | 30    | 6.5           | 61.2         | 4.4          | 147           | 85.8                       | 510                   |
|                   | 10      | 100         | 19         | 25    | 5             | 54.8         | 4.2          | 152           | 92.6                       | 390                   |
|                   | 11      | 150         | 15         | 20    | 10            | 47.8         | 8.4          | 146.8         | 87               | 320                   |
|                   | 12      | 200         | 13         | 15    | 8.5           | 42.6         | 5.2          | 139.2         | 88.4                       | 280                   |
|                   | 13      | 50          | 19         | 20    | 8.5           | 46.6         | 4.2          | 145.6         | 92.8                       | 250                   |
|                   | 14      | 100         | 16         | 15    | 10            | 39.2         | 8.8          | 153.6         | 91.8                       | 190                   |
|                   | 15      | 150         | 13         | 30    | 5             | 48.2         | 11.2         | 142.4         | 78.6                       | 490                   |
|                   | 16      | 200         | 10         | 25    | 6.5           | 43           | 13.6         | 158.2         | 82                | 340                   |

In the experiments, we measure three pressure point to calculate $\Delta P_1$, $\Delta P_2$ and $\Delta P_3$. The sum of these three makes the total pressure drop. And the Separation Efficiency is calculated by:

Separation Efficiency = ($\text{Total} - \text{Bag Filter} - \text{Left Behind}$) / ($\text{Total} - \text{Vortex Finder}$)

As can be seen from the experimental results, the separation efficiency of the number 1 experiment reached 96.56%, which was much higher than that of the traditional cyclone of the same size. Meanwhile, the pressure drop of the number 4 experiment reached 3090Pa, which is much higher than that of the traditional cyclone of the same size. In order to analyze the influence of various factors on separation efficiency and pressure drop, we performed range analysis on the results of orthogonal experiment.
4. Range Analysis

4.1. Range Analysis of Separation Efficiency
The range analysis of the orthogonal experiment results for the separation efficiency is shown in table 3.

| Experiment Number | Experiment Factors | Separation Efficiency |
|-------------------|--------------------|-----------------------|
|                   | 1(A) | 2(B) | 3(C) | 4(D) | 5(E) |                      |
| 1                 | 15   | 50   | 10   | 15   | 5    | 96.56%               |
| 2                 | 15   | 100  | 13   | 20   | 6.5  | 95.06%               |
| 3                 | 15   | 150  | 16   | 25   | 8.5  | 90.67%               |
| 4                 | 15   | 200  | 19   | 30   | 10   | 87.90%               |
| 5                 | 20   | 50   | 13   | 25   | 10   | 94.02%               |
| 6                 | 20   | 100  | 10   | 30   | 8.5  | 93.36%               |
| 7                 | 20   | 150  | 19   | 15   | 6.5  | 92.19%               |
| 8                 | 20   | 200  | 16   | 20   | 5    | 89.29%               |
| 9                 | 25   | 50   | 16   | 30   | 6.5  | 94.87%               |
| 10                | 25   | 100  | 19   | 25   | 5    | 95.68%               |
| 11                | 25   | 150  | 10   | 20   | 10   | 91.52%               |
| 12                | 25   | 200  | 13   | 15   | 8.5  | 94.62%               |
| 13                | 30   | 50   | 19   | 20   | 8.5  | 95.76%               |
| 14                | 30   | 100  | 16   | 15   | 10   | 92.31%               |
| 15                | 30   | 150  | 13   | 30   | 5    | 88.11%               |
| 16                | 30   | 200  | 10   | 25   | 6.5c | 88.19%               |
| I1                | 3.7019 | 3.8121 | 3.6964 | 3.7568 | 3.6965 |                        |
| I2                | 3.6886 | 3.7641 | 3.7180 | 3.7162 | 3.7031 | T'=92.51%             |
| I3                | 3.7668 | 3.6248 | 3.6714 | 3.6856 | 3.7440 |                      |
| I4                | 3.6437 | 3.6001 | 3.7153 | 3.6425 | 3.6574 |                      |
| R                 | 0.1231 | 0.2120 | 0.0466 | 0.1143 | 0.0866 |                      |

It can be seen from the range analysis table that the vortex finder length has the greatest influence, followed by the blade helix angle, airflow velocity, blade length and dust concentration. In this experiment, the higher the separation efficiency the better, so the optimal combination of A3B1C2D1E3 can be obtained.

The influence of blade helix angle and airflow velocity on the separation efficiency was expected, because the larger the spiral velocity of airflow, the greater the centrifugal force will have on the particles, thus gets the better the separation efficiency. This phenomenon reflected in the range analysis table is consistent with our expectation. The biggest factor, however, was the vortex finder length. Moreover, in our hypothesis, a longer vortex finder length can reduce the generation of short-circuit flow to a certain extent and prevent particles from escaping directly from the blade outlet to the vortex finder. The experimental data show that shorter vortex finder length has better separation efficiency, which will be the focus of our further research.

4.2. Range Analysis of Pressure Drop
The range analysis of the orthogonal experiment results for pressure drop is shown in table 4.
Table 4. Range Analysis of pressure drop

| Experiment Number | Factors | Pressure Drop |
|-------------------|---------|---------------|
|                   | 1(A)    | 2(B) | 3(C) | 4(D) | 5(E) |               |
| 1                 | 15      | 50   | 10   | 15   | 5    | 1300          |
| 2                 | 15      | 100  | 13   | 20   | 6.5  | 1880          |
| 3                 | 15      | 150  | 16   | 25   | 8.5  | 2360          |
| 4                 | 15      | 200  | 19   | 30   | 10   | 3090          |
| 5                 | 20      | 50   | 13   | 25   | 10   | 1880          |
| 6                 | 20      | 100  | 10   | 30   | 8.5  | 2520          |
| 7                 | 20      | 150  | 19   | 15   | 6.5  | 1160          |
| 8                 | 20      | 200  | 16   | 20   | 5    | 1670          |
| 9                 | 25      | 50   | 16   | 30   | 6.5  | 2160          |
| 10                | 25      | 100  | 19   | 25   | 5    | 1760          |
| 11                | 25      | 150  | 10   | 20   | 10   | 1320          |
| 12                | 25      | 200  | 13   | 15   | 8.5  | 930           |
| 13                | 30      | 50   | 19   | 20   | 8.5  | 920           |
| 14                | 30      | 100  | 16   | 15   | 10   | 710           |
| 15                | 30      | 150  | 13   | 30   | 5    | 1930          |
| 16                | 30      | 200  | 10   | 25   | 6.5  | 1360          |
|                   | I1      | 8630 | 6260 | 6500 | 4100 | 6660          |
|                   | I2      | 7230 | 6870 | 6620 | 5790 | 6560          |
|                   | I3      | 6170 | 6770 | 6900 | 7360 | 6730          |
|                   | I4      | 4920 | 7050 | 6930 | 9700 | 7000          |
|                   | R       | 3710 | 790  | 430  | 5600 | 440           |

T′=1684.375

As can be seen from table 4, for the pressure drop, the flow velocity has the largest influence, followed by the blade helix angle, while the other three factors have a small influence. In this experiment, the smaller the pressure drop the better, so the optimal combination of A4B1C1D1E2 can be obtained.

According to the principle of traditional cyclone, the higher the airflow velocity is, the higher the pressure drop is. That is consistent with our experimental results. For the blade helix angle, the smaller the blade helix angle is, the longer the airflow stays in the RJC and the longer the distance it travels. In that way for sure we will get a greater pressure drop. However, in the traditional cyclone, with the increase of vortex finder length, the cyclone energy consumption increases, so that the total pressure drop of the cyclone separator increases. In our experiment, the vortex finder length has no significant influence on the pressure drop, which may be related to the structure of our unique vortex finder structure. The influence of vortex finder’s structure and length will be studied in following researches.

5. Conclusion and Prospect
According to the structural characteristics of RJC, this paper designs a set of 18 orthogonal experiments with 5 factors and 4 levels to evaluate the influence of those 5 factors on the separation efficiency and pressure drop of RJC. The experimental results show that RJC has better separation efficiency than traditional cyclone. The maximum separation efficiency was 96.56% for talc with median particle cutting size of 4μm. While the corresponding pressure drop is 1300 Pa. Obviously the pressure drop is higher than the traditional cyclone separator. However, it can be seen from the experimental results that the maximum pressure drop surprisingly reached 3090Pa, while the corresponding separation efficiency is only 87.90%. To some extent, the structural characteristics of RJC subvert the concept that the higher the separation efficiency is, the greater the flow pressure drop is.
Among the 5 influencing factors we selected, the length of the spiral blade and the concentration of particles (which is always within the range of dilute phase) did not have a significant impact on the separation efficiency and pressure drop, which can be temporarily excluded in future studies. The influence of blade helix angle and airflow velocity on separation efficiency and pressure drop is consistent with our expectation. Obviously higher separation efficiency will also lead to the increase of pressure drop. The balance of these two influencing factors is a key point of our future research.

What surprised us was the effect of the vortex finder length, which not only played an important role in the separation efficiency, but also, contrary to our assumption, the shorter vortex finder length did not cause short-circuit flow, but got us a higher separation efficiency. At the same time, it did not have a great impact on the pressure drop. This will be the focus point of our next researches, and we hope to improve the separation efficiency of the RJC as much as possible under the control of the overall pressure drop through reasonable design of vortex finder structure.

6. References

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