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Study on Application and Operation Optimization of Hydrocyclone for Solid-liquid Separation in Power Plant

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Abstract—**Hydrocyclone plays a vital role in the progress of WFGD in the power plants. Such as the choosing of particle size of limestone, dewatering of gypsum slurry, recycling of waste water. This paper introduced the theory and application of hydrocyclone in WFGD process, and also expounded and researched separately on the relationship of the performance and the structural parameters, characteristic parameters, operation parameters. From this essay some useful conclusions can be obtained, such as the results of design optimization and the performance optimization. These conclusions are very helpful in getting an economic performance of the whole process.**

Keywords: Hydrocyclone, operation parameter, performance optimization,separate efficiency, structural parameter

1 Introduction

In today's world, the most threatening problem to society is the change in both the terrestrial and aquatic environments caused by different kinds of pollutions. Just like gypsum slurry and wastewater, the offspring of the system of the WFGD (Wet Flue Gas Desulfurization). It includes the water, Chloride ion, gypsum, coal ash, and so on. So it must be recycled and separated. In general, hydrocyclones are widely used to separate particulates from water at high throughput because their advantages like simple structure, low cost, large capacity, and small volume, require little in the way of maintenance and support structure [1]. And it plays an important role in the FGD of power plant, therefore a higher level of the performance is required and performance optimization became to the great work of it.

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2 Theory

2.1 Structure

Hydrocyclones belong to a class of fluid-solid classifying devices that separate dispersed material from a fluid stream. Fluid is subjected to a high-intensity centrifugal force which is created by placing the slurry in a curving path in a cylindrical annulus in a tangential inlet section. The unit converts the initially linear motion of a fluid into continuously varying angular motion, thereby subjecting the dispersed particulates to centrifugal acceleration and enhancing the rate of settling of particles, according to their differing density, size, and shape. The structure of it is diameter of the hydrocyclone (D), height (H), diameter of the overflow (D_o), thickness of the overflow (d), diameter of the underflow (D_u), diameter of the inlet (D_i), height of the overflow in cyclone chamber (h), cone angle (θ), etc(Fig.1).

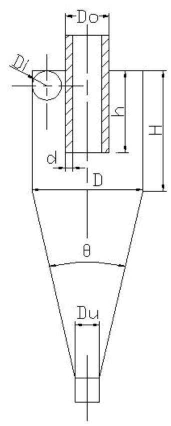

Fig.1 Sketch of hydrocyclone's structure

2.2 Operation principle

In accordance with the definition of Bradley [2], hydrocyclone is the device that it can be rotated by the fluid pressure. If the fluid with static pressure, initial velocity enters along the tangential to the hydrocyclone, generally, in cylindrical coordinates, the velocity (v) of the hydrocyclone can be decomposed into radial velocity (u_r), tangential velocity (u_t) and axial velocity(u_z),

$$u^2 = u_r^2 + u_t^2 + u_z^2 \tag{1}$$

Excluding the case of loss, and its spin angular momentum will be maintained. That is,

$$u_t r^n = C \tag{2}$$

n–Index, 0.5∼0.9, decide by the operation condition.
It can be seen that the tangential velocity will increased, the hydrostatic pressure will be into the dynamic pressure with the reduced radius of gyration. In other words, the fluid has had a rotating movement. The Serous granules are disjoined two parts, one of it moves to the hydrocyclone wall in the role of centrifugal force, at the same time, other part moves to the inside of the cyclone chamber by the role of radial velocity flow. Coarse grain attains the higher speed by the centrifugal force. When the velocity is bigger than the radial velocity, the particles transferred towards the wall, fell into the underflow region, taken by the underflow pipe from Chamber for the coarse-grained product. When the velocity is smaller than the radial velocity, the particles transferred to the inside of the chamber, entered into the overflow region, taken by the overflow tube from Chamber for the fine product. And when the velocity is equal to the radial velocity, the particle will be swing at the radial of r. If the flow region r on the decline, they will flow into the underflow area, otherwise they will enter into the overflow. If the axial velocity is amount to zero, one half of the gypsum slurry will be into the overflow, and another will enter the Chamber. The size of particle is separation grading, which is the basic principles of hydrocyclone classification.

3 Application of hydrocyclone

3.1 Application of gypsum slurry hydrocyclone

Gypsum is the by-product of WFGD. The solid material of Slurry mainly contained the gypsum, limestone, salts mixtures and the coal ash. The disposal process is divided into two steps: separation of primary and secondary dehydration, the primary separation completed by the gypsum hydrocyclone, secondary dehydration machine is vacuum dehydration equipment [3], just like the red part of the Fig.2.
The slurry is transferred to the gypsum hydrocyclone by the pump from the absorber tank. The overflow product of the gypsum hydroclone is the fine particles (fine gypsum, no reacted limestone, no dissolved impurities of the limestone and fly ash). And the underflow contains coarse gypsum particles, ultimately flows into the vacuum dryer. The solid material of the underflow is normally 50% (Wt), the free water of it will separated by the vacuum dryer.

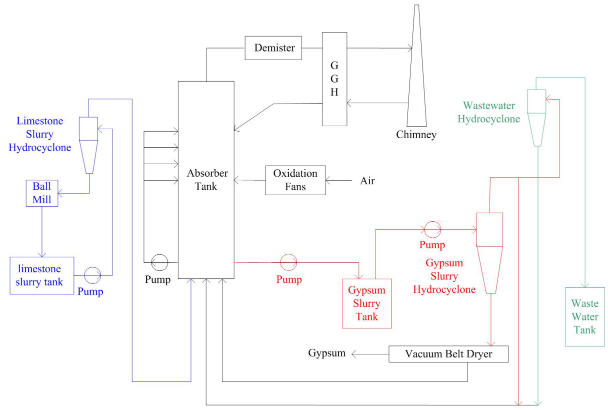

Fig.2 Sketch of WFGD system in power plant

3.2 Application of limestone slurry hydrocyclone

First of all, the limestone were sent to wet ball mill and milled to slurry with the special size, and then transported to limestone hydrocyclone, the underflow which was separated by the limestone (including coarse particles) returned to the wet ball mill for further grinded. Overflow materials (the concentration of it is between 20% and 30% (Wt)) will be stored in the slurry tank, and then pumped to the absorber tank, just like the blue part of the Fig.2.
The result of the higher of the limestone slurry concentration is more wear and tear to the pumps and pipelines, it will consumes more power for the pumps if the slurry concentration is too lower. At the same time, the utilization of limestone, reactivity, abrasion of the pumps and pipelines rely on the limestone particle size. Therefore, a suitable hydrocyclone will plays an important role to improve the quality of gypsum, the utilization rate of the limestone, reduce the abrasion of the pumps and pipelines and reduce the operation costs.

3.3 Application of wastewater hydrocyclone

The object of the solid volume flow is generally between 1% and 3% (Wt), the small solid particles mainly include absorbent which has not been completely reacted, the small gypsum crystal, etc. The most of the overflow will be into the absorber tank, the slurry which has not fully reacted is to function with the SO_2, and small crystals of gypsum slurry pool to the big crystals, it will impact the next stage of the formation of gypsum crystals, just like the green part of the Fig.2. A part of the overflow must discharge from the systems. On the one hand, the waste-water hydrocyclone retaining the limestone and small gypsum particles which has not reacted, on the other hand, it can eject the waste waters, while maintaining the concentration of the chloride ion in the WFGD system.

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4 Main parameters optimization

Hydrocyclones play an important role in the entire WFGD system and it is one of the main devices in this system. Optimization of the cyclone includes structural parameters, operating parameters, as well as physical parameters.

4.1 Structural parameter optimization

Structural parameters are needed to establish in the design progress and manufacturing progress, and it also determines the advantages and disadvantages of the separation performance. So the choice of structural parameters plays a decisive role in this progress. The structural parameters include the inlet, column paragraph, cone, underflow tube and tail pipe section.

4.1.1 Influence of the inlet

Inlet contains the cross-section shape of the imports, the imports shape of flow path, the number of import tubes, the size of the import section, etc.
The issue of angular momentum is decided by the cross-section shape. In order to obtain larger initial angular momentum and stabilize the field of the cyclone flow, the entrance form is normally adopted the rectangular cross-section.
The production capacity has a close connection with the import shape and the change of the cross-section. Involute curve flow channel cross-section is satisfactory than the conventional flow channel cross-section, such as an improvement, but not the best. By comparison, linear gradient flow channel cross-section might be more reasonable, it can play a positive role in guiding for our future design and application.

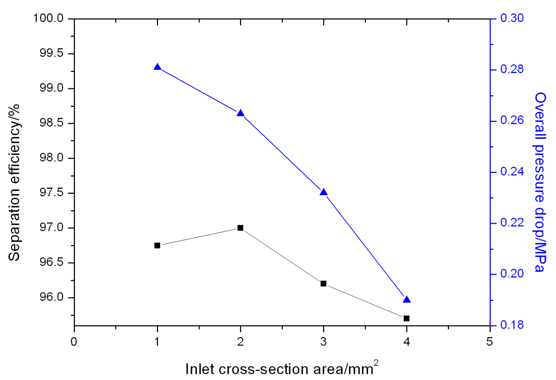

Fig.3 Relationship of the pressure drop and separate efficiency

The relations of the import section size and the classification performance can be analyzed by the following experimental data [4]: the horizontal cross-sectional area size is 19mm, the tangential size is 4.0mm, 4.5mm, 5mm and 5.5mm, the split ratio and flow rate maintain the same conditions, the overall pressure drop and separation efficiency of the experimental results in Fig.3.
We can see that the overall pressure drop can effectively reduce and the separation efficiency did not significantly lower when the section size of inlet increases. This feature will guide to achieve the low-pressure operation. And also we can reduce the power consumption of the pumps. Thereby it can increase the energy efficiency and the plant power product. It is a great guiding significance for the economy operation.

4.1.2 Influence of the cylinder

Column paragraph includes column diameter, length and cylinder diameter of overflow pipe, the depth of the insert, thickness and so on.
Hydrocyclone diameter is decided by the factor of separation performance and the traffic demand. In general, the larger size of hydrocyclone, the lower separation performance and the higher processing capacity (Fig.4). We should select the large cylinder as far as possible to meet the separation performance, thus reducing the quantity of hydrocyclone is to become a fact, thereby we can reduce the investment of operation and maintenance costs for the equipment.

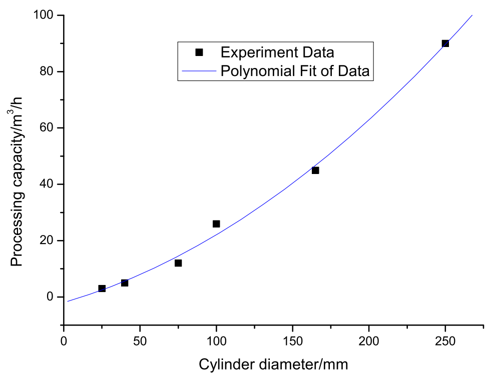

Fig.4 Membership functions for diameter and processing capacity [5]

In general, the hydrocyclone is constitutive of the cylinder and the cone section. Cylindrical region of space is considered as a pre-separation section, and the cone-shaped region of space as the main separation region, that is, the real separation process is completed in the conical section [4]. Liang-yin Chu and his group's research show that there is also a separation of behavior in the cylinder chamber. The meaning of it is that the separation behavior is occurred in the section of cylinder and the cone. The production capacity and reduced separation overall efficiency were monotone increasing and the overflow concentration was of the downward trend while the improving of the length of cylinder (Fig.5). But the size of the separation particle will become small if the length of column is too long or too short. When the column length increased from 0.4D to 1.6D, the amendment separation size of grain will be of the upward trend, when the column length increased from 1.6D to 2D, separation particle size d_{50} will reduce instead. So the column length should be longer to the best of its abilities when we design [6].

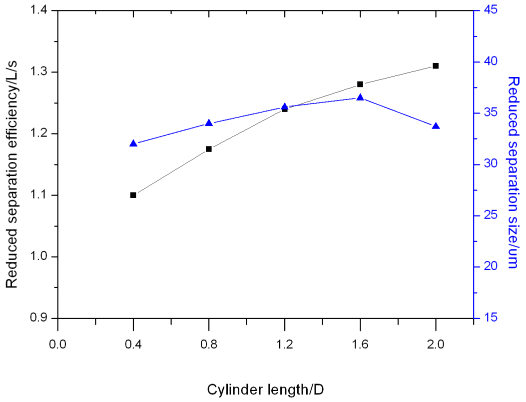

Fig.5 Relationship of the column's length with the reduced separation efficiency and granularity [6]

As everyone knows that short-circuit flow is one of the flow characteristics, and also it is one of important reasons that coarse particles are into the overflow and the coarse particles and the fine particles are mixed. And the existence of short-circuit flow and the quantity of the flow are directly related to the structure size of the overflow. The pressure drop will reduce and the production capacity will increase if the diameter of the overflow pipe fills out, but at the same time, it will also increase the separation size of the particles, lead to decline of the separation ability. In general, the diameter of the overflow pipe is equal to D/8-D/2.3 is appropriate . The increase of thickness of the overflow pipe will lead to the small size of separation chamber, cause hydrodynamic loss decreases, so that the rotating fluid flow more stable, it can reduce the activities scope of short-circuit flow and reduce the influence of the hydrocyclone performance by short-circuit flow [7].

4.1.3 Influence of the cone section

The structural parameters of cone part include the number of cone, the angle of cone and underflow diameter.
According to different applications, the structure is provided with a variety of forms. In accordance with the number of cone, the hydrocyclone is divided into single and double cone cyclone. And the hydrocyclone of power plants generally chooses the single cone cyclone. The meaning of that is the combination form of cone section and cylindrical section.
Cone angle is an important structural parameter, the distribution of convection, moment of momentum, the size of the separation efficiency have greatly affected with the change of the cone angle. The bigger the cone angle is, the higher fluid resistance becomes. Under the same import pressure, due to increasing of the fluid resistance, its production capacity will decline. So the large cone angle cyclone has the bigger tangential velocity than small cone angle cyclone, but it owns a shorter residence time than the other one. Therefore, the result of it is that the separation size of particle increases, the total separation efficiency decreased with the cone angle increasing.

4.1.4 Influence of the underflow tube

Flow diameter is very correlative with the performance of hydrocyclone classification [8]. In practice, due to the different of separation density or particle classification size of the stream, the different diameter of the underflow tube is required.

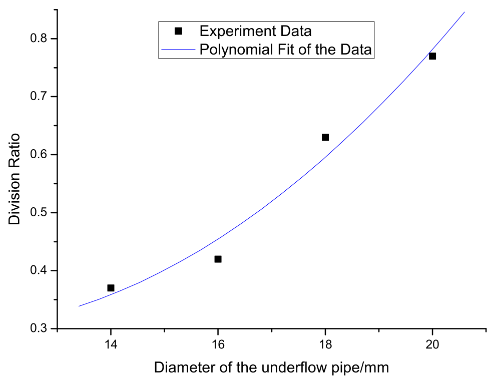

Fig.6 the Relationship of underflow pipe's diameter and division ratio [9]

The increasing of the underflow tube will enhance the production capacity accordingly, but at the same time, it will reduce the cut size and increase the separation efficiency and the division ratio (Fig.6). Like the following equation [10].

$$lgd_{50} = 4D - 5.76D_u + 3.66D_i + 2.99c_w - 6Q - 6 \quad (3)$$

With the decline of the underflow tube diameter, a corresponding flow mass of solids increasing will appear. When the mass concentration of solid reaches a certain limit, the jam phenomenon will occur. For example, in the process of gypsum hydrocyclone, they used to replace a smaller diameter of the underflow tube in order to achieve the requirements of the concentration at the end of flow. But the jam phenomenon is to reappear. For the sake of preventing the occurrence of this phenomenon, we can follow the law of the documentation to find out the suited size for the design, the documentation recommends the best diameter of it is (0.07∼0.10) D. It is also possible to change the other parameters to meet the requirements of the concentration in practical applications.

4.1.5 Influence of the tail pipe section

Main factor of tail pipe section is the length of tail pipe, and the diameter of tail pipe is equal to the diameter of the underflow tube. The effect of it is to maintain stability of the inside flow, while it maintains the stability of the entire flow field, so the length of tail pipe should meet the stability of the flow field as the standard.

4.2 Physical parameter optimization

Hydrocyclone optimization of physical parameters is accordant with the entire process of WFGD, so the premise of optimizing is that its changes must be associated with the other parameters. It includes feed mass concentration of solids, the size of solid-phase particle, viscosity of feed slurry, density of suspension, and all of these will affect the classification efficiency.
The transformation of the concentration is complex, if we increase the effective viscosity of the feed slurry, the accuracy of separation will reduce, the flow resistance will change, and it will bring on pressure drop, thereby it can enhance the cut size. To achieve the separation of smaller particles, the low concentrations and high pressure drop should be contented. The appropriate feed concentration is generally not exceeding 30% (Wt).
The research results showed that the total production capacity increased with the increase of medium viscosity, media viscosity will not affect the capacity of viscosity when $Re > 5000$. But the split ratio will impacted by medium viscosity [11]. Therefore, it's a good choice for an appropriate increasing in medium viscosity.
Due to the concentrated capability, there are some difference with the separation density and the suspension density. In general, the separation density is bigger than the suspension density, and the dispersion is around 0.2kg/L [12]. It is very difficult to be the same in practice, but we may change the other parameters to close the difference. The composition of the particle size is basically a fixed value in design, but the change of density requires a process of adjustments, frequent adjustments would cause a great loss of media. Therefore, the requirement is that the density of material should to remain steadily.

4.3 Operation parameter optimization

The feed pressure and the installation angle are the key factor of the performance classification, this is the main entry point of optimize the operating parameters.
Operation pressure is needed to obtain the optimal operation of the effect traffic under the lowest pressure of imports in a certain condition in order to achieve the purpose of energy conservation. In the operating of hydrocyclone, any change of the pressure in hydrocyclone will reduce the efficiency. The result of the imports increasing is that it will bring on the elevation of the classification efficiency and production capacity [13], at the same time, cut size will decline and the load of the power plant will increase. So import pressure should be maintained at a constant level.
The installation angle has little effect on its classification performance in the power plants. Vertical installation is collected at the most of situation, for example, the Krebs hydrocyclone. The recently studies have shown that production capacity of the cyclone will augment along with the increasing of the installation angle [14], particle size classification will be increased too. We can know that changing the installation angle and reducing its installation height is a good way to enhance production capacity of hydrocyclones from the Literature [15], and also it can abate the chance of the wear and blockage.

5 Conclusion

Hydrocyclones play an important role in the process of water-saving and water treatment in the WFGD system, so how to ensure its operation and energy saving have become a significant issue, this article did some study about the applications and performance optimization of the hydrocyclones, etc. And it has analyzed the relationship of the separation efficiency and the structure of hydrocyclone performance, operation and physical parameters with the actual situation in WFGD. Structural parameters optimization is often established by the designers and the staff, and it is the keystone with the entire optimization process. Physical parameters optimization needs to meet the all parameters of the FGD process, because the premise of optimizing is associated from the other parameters with reasonable configuration properties. Therefore, the circumspection is needed in the process of the operating optimization. The optimization of operation parameters is controlled by the operators, the main operation parameters which required to be established are the pressure and the angle of the installation. Designers and operators can make use of these findings to guide the practice.

Nomenclature

ε'	Reduced separation efficiency (%)
u_r	Radial velocity (m/s)
u_t	Tangential velocity (m/s)

u_z	Axial velocity (m/s)
C_e	Solid weight concentration of feed (%)
C_u	Solid weight concentration of underflow (%)
R_e	Reynolds number
G(d)	Grade efficiency (%)
$G(d^{'})$	Reduced grade efficiency (%)
GGH	Gas gas heater
d_{50}	Cut size (μm)
c_w	Mass fraction of the feed stream (%)
Q	Production capacity (m^3/h)
ρ	Density (kg/m^3)
v	Velocity (m/s)
r	Radial position (mm)

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