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Experimental Study on Low-resistance Venturi Water Film Cyclone with Vibrating String Grid

Zuyun Chen [1,2)*]***, Shipeng Zhao*** [1,2)]***, Zhenbiao Rao*** [1,2)] ***and Rumeng Zhang*** [1,2)]

[1)] School of Resource and Environmental Engineering, Jiangxi University of Science and Technology, Ganzhou, China. * Corresponding Author. E-Mail: welczy@163.com
[2)] Jiangxi Key Laboratory of Mining & Metallurgy, Environmental Pollution Control, Ganzhou, China.

ABSTRACT

With the increasing stringency of environmental standards, the removal of fine dust has become a goal of research scholars. In this paper, new type of low-resistance Venturi water film cyclone with vibrating string grid was proposed after synthesizing the advantages of various dust removal technologies. The combined effects of mechanism and influence of dust removal were studied from both vibrating fiber grid in Venturi dust collector and dust collector with water film. The structure optimization of the composite dust collector was experimentally studied. When the pressure of water film reaches 0.3MPa, the water film basically covers the inner wall of the cyclone dust collector and the dust removal efficiency is close to 97.32% of the experimental results. The optimal gas velocity of throat tube is 28.48 m/s in order to match with low-resistance Venturi water film cyclone with vibrating string grid. When the wind speed of throat pipe exceeds forming resonance frequency in water film of vibrating string grid, the effect of secondary film-making abates and the dust removal efficiency decreases. The dust removal efficiency under the condition of changing the gas velocity of the throat pipe was measured and dust removal modes in unconditional, spray, water film and single vibrating string grid conditions were combined. The low-resistance Venturi water film cyclone with vibrating string grid has the characteristics of extremely high dust removal efficiency, simple structure and low cost and is of great social significance in protecting the environment and improving theory and applications of the dust removal existing devices.

KEYWORDS: Venturi, Water film, Cyclone, Vibrating string grid, Dust removal efficiency.

INTRODUCTION

With the rapid development of industrialization, environmental pollution caused by coal combustion is becoming increasingly serious. The resistance of the Venturi dust collector ranges from 2.5 to 25 kPa and it can remove 99.9% of particles larger than 10μm. Regarding the major industry boiler, heating boiler, small and medium-sized boiler in power plant, the water film dust collector is still the practical mainstream dust removal equipment and is widely used (Robertas et al., 2018). According to incomplete statistics, the water film dust collector has occupied a half of the total number of coal-fired boiler dust collectors (Mohammad et al., 2020; Purvil et al., 2019). The water film dust collector plays an important role in the field of boiler flue gas purification, but it has high resistance and high energy consumption and cannot meet the requirements of air pollutant discharge standards. The dust removal technology of wet vibrating string grid is an efficient dust removal technology which was developed on the basis of the wet layer purification theory (Chen, 2018). The vibrating string grid produces high-frequency vibration, which greatly increases the collision probability between dust, droplets and strings, thus effectively improving the dust removal efficiency under the action of high-speed air flow (Chen, 2016; Wa'il, 2007; Mateusz, 2019). The dust removal mechanism of wet vibrating string grid was studied and the influencing factors of its dust removal efficiency were analyzed. It was concluded that the dust removal efficiency of vibrating string grid was related to the material,

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vibration frequency, over-current section area, layer number and spray parameters of vibrating string grid (Bashar et al., 2009; Chen, 2016).With the increasing strict environmental protection standards, the dust removal technology by Venturi, wet vibrating string grid and water film cyclone is difficult to meet the needs of controlling fine dust due to their respective shortcomings (Lehner, 1998). Based on the theory and advantages of dust removal by Venturi, wet vibrating string grid and water film cyclone (Charinpanitkul et al., 2011), a new type of composite dust collector, which is the low-resistance Venturi water film cyclone with vibrating string grid, was proposed by adding vibrating string grid in Venturi tube in this paper. The Venturi water film cyclone with vibrating string grid was made in order to carry out the experiments. Its dust removal characteristics and configuration optimization were theoretically and experimentally analyzed.

The Venturi water film cyclone with vibrating string grid is a kind of high-efficiency dust collector, which is composed of Venturi tube, vibrating string grid and centrifugal water film cyclone (Chen, 2014; Chen, 2017). The Venturi tube consisted of contraction tube, throat tube, water spraying device and expansion tube (Suhail, 2010). It has the advantages of high efficiency of dust removal, small volume and low investment. The dust removal technology with wet vibrating string grid is an efficient dust removal technology that is developed on the basis of the wet layer purification theory (Lehner, 1993). Under the action of high-speed air flow, the wet string grid produces high-frequency vibration (Hu, 2018; LIU, 2018), by which dust and droplets increase greatly the collision probability with string grid (Zhao, 2018; Cheng, 2018).

The-low resistance Venturi water film cyclone with vibrating string grid has the characteristics of extremely high dust removal efficiency, simple structure and low cost and is of great social significance in protecting the environment, reclaiming resources and effectively collecting fine dust. This paper attempts to establish the technology of the new composite dust removal system and improve the theory and applications of the dust removal existing devices.

Analysis of Dust Removal Mechanism of Water Film Cyclone and Structure of Venturi Water Film Cyclone with Vibrating String Grid

Analysis of Dust Removal Mechanism of Water Film Cyclone

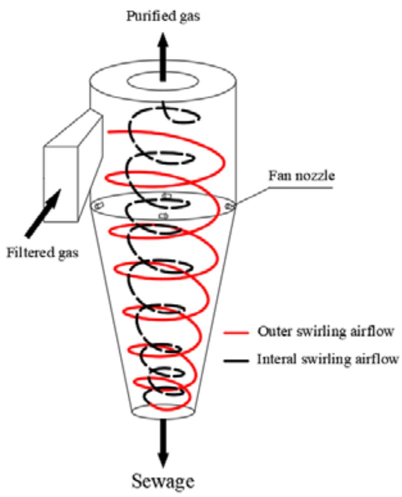
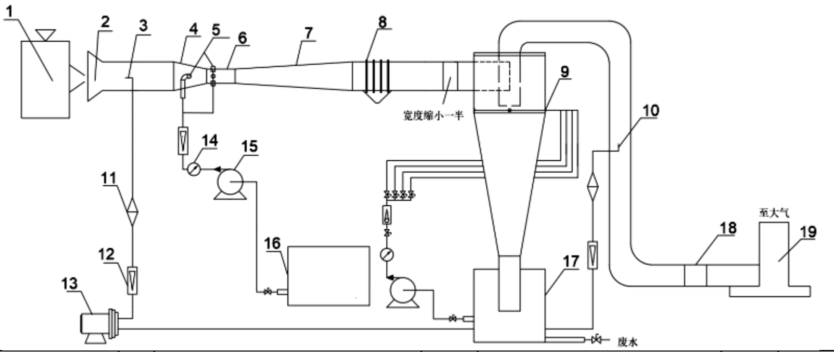


Figure (1): Dust removal mechanism of water film cyclone

Compared with the dust collector of cyclone (Zhang, 2004), the working efficiency of dust collector of water film cyclone is significantly improved due to the addition of water film. The filtered gas that comes from vibrating string grid in the Venturi enters the cyclone to form an outer swirly air flow. Due to the centrifugal force generated by the spiral movement of the air flow, dust droplets and unmoisturized dust are thrown toward the wall of the barrel and are captured by a water film made by four flabellate nozzles. The secondary dust is effectively removed, the sewage is discharged from the bottom of cyclone and the internal swirly air flow formed at the same time is discharged from the top outlet of the barrel of cyclone to obtain purified gas, as shown in Fig. 1.

Structure of Venturi Water Film Cyclone with Vibrating String Grid

The model of low-resistance Venturi water film cyclone with vibrating string grid is made in this experiment, as shown in Fig. 2. This experimental model is mainly composed of dust generator, dust removal by low-resistance Venturi vibrating string grid, water film cyclone, extraction fan, water supply device, measurement system… and so on. In the composite dust collector, the dust-containing air flow can be purified firstly by low-resistance Venturi vibrating string grid, and tangentially entered into the water film cyclone of dust removal system. Secondly, the dust in air flow is separated by the cyclone tube centrifuge and captured by water film. Finally, the purification gas comes into being.



1	Dust generator	**2**	Current collector	**3**	Inlet sampling head	**4**	Shrink tube
5	Spray nozzle	**6**	Throat pipe	**7**	Expansion tube	**8**	Vibrating string grid
9	Water film cyclone dust collector	**10**	Outlet sampling head	**11**	Filter box	**12**	Float flow meter
13	Air-extracting pump	**14**	Pressure gauge	**15**	Water pump	**16**	water tank
17	Sewage collection tank	**18**	Air volume regulator	**19**	Fan		

Figure (2): Schematic diagram of low-resistance Venturi water film cyclone with vibrating string grid

Operating Parameters Affecting Dust Removal Efficiency

Through the optimal experiment on low-resistance Venturi water film cyclone with vibrating string grid, it is determined that the optimal water supply mode is radial external spray. The best parameters are as follows: the gas velocity of the throat tube: 24m/s; spray water quantity: 2.3L/min and the plates of vibrating string grid: two with a clearance of 0.8mm. On this basis, the dust removal efficiency by water film is measured through changing the water supply pressure in the cyclone cylinder, as shown in Fig. 3 and Table 1.

Table 1. Measurement results of dust removal efficiency under different water supply pressures

Water supply pressure of water film (MPa)	0	0.1	0.2	0.3	0.4	0.5
Dust removal efficiency (%)	95.26	96.34	96.94	97.32	97.38	97.40

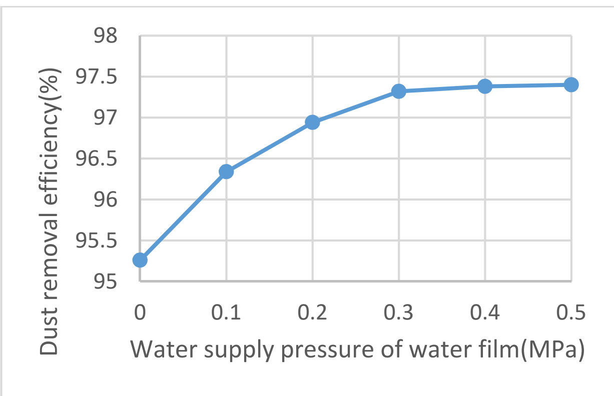


Figure (3): Effect of water supply pressure of water film on dust removal efficiency

The dust removal efficiency by the composite dust collector increases firstly and then tends to be stable with the increase of the water supply pressure of the water film and the dust removal efficiency increases 2.06% by the water film in the cyclone cylinder, see Fig. 3 and Table 1. The main reason is that the water film area is thin in the initial stage of pressure and it does not cover the inner wall of the cyclone cylinder. As the water supply pressure increases, the water film area increases. When the pressure of water film reaches 0.3MPa, the water film basically covers the inner wall of the cyclone cylinder and the dust removal efficiency is close to 97.32%. When the water supply pressure of the water film is further increased the water film area is basically unchanged and the dust removal efficiency tends to be stable. Therefore, the efficiency of dust removal and water consumption are taken into account. The optimal water supply pressure of the water film should be 0.3MPa.

Effect of Gas Velocity of Throat Pipe on Dust Removal Efficiency

Because the gas velocity in throat pipe affects greatly the dust removal system of water film cyclone, it is necessary to consider the influence of gas velocity of throat pipe on the dust removal efficiency in the whole device. Other factors have little influence on the cyclone water film dust removal and are therefore not considered. The gas velocity of throat pipe is changed to seek the matching wind speed between the dust removal system of low-resistance Venturi vibrating string grid and that of water film cyclone. The highest efficiency of the dust collector is the best matching wind speed and the measured results are shown in Fig. 4 and Table 2.

Table 2. Efficiency measurement results under different conditions with or without water film

Throat air velocity (m/s)	Without water film (m/s)	Water film pressure 0.3 MPa (m/s)	Venturi vibrating fiber grid dust removal system (m/s)
9.12	93.24	93.48	90.92
14.56	94.32	94.69	93.07
20.08	94.96	95.67	94.64
24.36	95.85	96.82	95.68
28.48	94.62	97.28	94.58
33.16	93.57	96.38	93.55
40.48	89.22	91.87	89.18
9.12	93.24	93.48	90.92
14.56	94.32	94.69	93.07

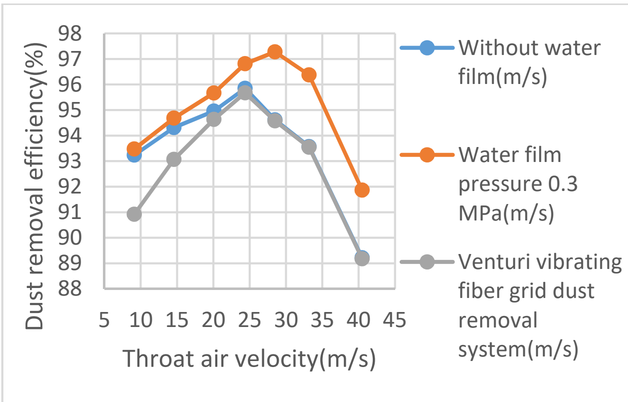


Figure (4): Gas velocity of throat pipe influence on dust removal efficiency under different conditions with or without water film

The dust removal efficiency increases firstly and then decrease with the augment of the air velocity of throat pipe by the low-resistance Venturi vibrating string grid under the condition of no water film, as shown Fig.4

and Table 2. When the wind speed of throat pipe is low, the dust removal by cyclone has a certain effect. When the wind speed of throat pipe continues to increase, the dust removal efficiency descends. When the wind speed of throat pipe reaches 24.36 m/s, the dust removal efficiency by cyclone coincides with that by low-resistance Venturi vibrating string grid, which indicates that the cyclone has basically no effect on dust removal. When the water supply pressure of water film is 0.3MPa in the cyclone, the dust removal efficiency by Venturi water film cyclone with vibrating string grid is higher than that by the Venturi anhydrous cyclone with vibrating string grid.

When the gas velocity of throat tube is low, the influence of water film on the total dust removal efficiency is low. When the gas velocity of throat tube increases, the effect of water film is more obvious. The main reason is that when the gas velocity of the pipe is low, a rotary air flow does not form in the cyclone and the dust-containing air flow does not have sufficient contact with the water film, which makes the dust removal efficiency low.

When the gas velocity of throat reaches 28.48 m/s, the swirly effect is obvious. The full contact with the water film occurs and the dust removal effect is best. When the gas velocity of throat tube is further increased, the stability and uniformity of the water film will be destroyed and the dust removal effect decreases. Therefore, the best matching wind speed of throat tube between the low-resistance Venturi vibrating string grid system and the cyclone water film system is 28.48m/s.

Inlet Average Dust Concentration Effect on Dust Removal Efficiency

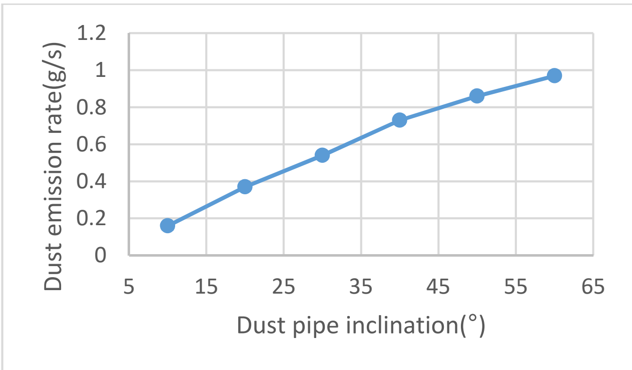


Figure (5): Inclination angle of dust conduction influence on dust concentration

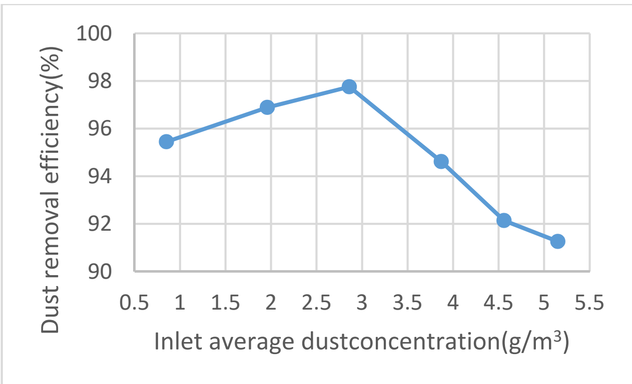


Figure (6): Inlet average dust concentration influence on dust removal efficiency

Due to limited experimental conditions, the inlet sampling head of the device is close to the dust generator and a certain error can't be avoided in dust sampling. Therefore, the average value is obtained by multiple measurements. The inclination angle of the dust guide tube in the dust generator is adjusted to change dust emission rate for the experiment, in case that the gas throat pipe velocity is 28.48m/s. In addition, under other optimal configuration conditions, different inlet average dust concentrations and corresponding dust removal efficiency values are obtained. The experimental results are shown in Fig.5, Fig.6 and Table 3.

The dust emission rate increases with the augment of the inclination angle of dust conduction tube and the increase range gradually decreases, as shown in Fig.5 and Table 3. The dust emission rate tends to be stable after reaching the maximum value, mainly because it is limited by the structure of the dust conduction tube and the dust emission power. With the increase of the average dust concentration at the inlet (as shown in Fig.6 and Table 3), the dust removal efficiency firstly increases and then decreases. When the dust concentration means 2.86g/m^{3}in the inlet gas pipe, which reaches saturation, the dust removal efficiency reaches 97.76%. The main reason is that the structure of the dust collector is limited. When the dust concentration continues to increase in the inlet gas pipe, the excess dust cannot collide with the water mist and a large amount of unwetted dust passes through the string gap, resulting in a rapid decline in dust removal efficiency. Therefore, according to the experimental results, the maximum allowable dust concentration in the inlet gas pipe is 2.86g/m^3 in the composite dust collector.

Table 3. Experimental data of inlet average dust concentration

Number	Dust pipe inclination (°)	Dust emission rate (g/s)	Inlet average dustconcentration (g/m)	Dust removal efficiency(%)
1	10	0.16	0.85	95.45
2	20	0.37	1.96	96.89
3	30	0.54	2.86	97.76
4	40	0.73	3.87	94.62
5	50	0.86	4.56	92.14
6	60	0.97	5.15	91.26

Comparative Analysis of Dust Removal Efficiency under Various Methods

Experimental Study on Dust Removal Efficiency by Single Method

It is necessary to compare the dust removal methods and to analyze the dust removal efficiency of various dust removal methods, after the optimum structure and best operation parameters of the composite dust collector are fixed. The dust emission rate is 0.286g/s and the measured air density is g=1.175kg/m^3. The dust removal efficiency under the condition of changing the gas velocity of the throat pipe is measured, respectively, in unconditional, spray, water film and single vibrating string grid conditions. The measurement results are shown in Fig.7 and Table 4.

Table 4. Efficiency measurement results under under single dust removal methods

Throat air velocity (m/s)	Unconditional device (%)	Throat air velocity (m/s)	Spray (%)	Throat air velocity (m/s)	Dryvibrating fiber grid (%)	Throat air velocity (m/s)	Water film (%)
9.43	36.24	9.29	63.21	9.12	56.23	9.24	59.26
14.89	43.65	14.72	71.85	14.56	49.74	14.66	64.52
24.83	52.14	24.66	78.22	24.36	53.16	24.59	73.45
28.92	58.64	28.76	84.33	28.48	58.92	28.62	80.22
33.63	53.27	33.43	74.22	33.16	54.09	33.37	74.16
40.81	46.93	40.61	60.17	40.48	47.22	40.56	65.57

It can be seen from Fig. 6 and Table 4 that the dust removal efficiency firstly increases and then decreases with the increase of wind speed of the throat pipe in the dust collector, under single dust removal methods. The main reason is that with the increase of wind speed of throat pipe, the more obvious the swirly flow is, the more strongly centrifugal separation will affect dust particles. However, further increase of wind speed of the throat pipe will significantly enhance the role of turbulence and part of the previously separated dust particles will be picked up again, reducing the dust removal efficiency. The arrangement order of dust removal efficiency is as by spray > water film > dry vibrating string grid > unconditional device. The dust removal efficiency by dry vibrating string grid decreases gradually with the increase of wind speed of throat pipe, so the effect is the worst. Dust removal effect by spray is the best under a single dust removal method and the dust removal efficiency can reach 84.33%.

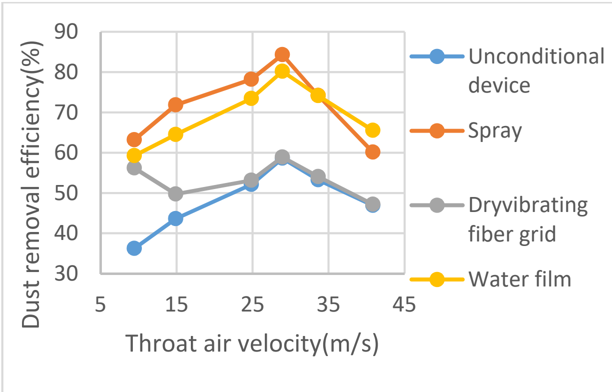


Figure (7): Wind speed of throat pipe effect on dust removal efficiency under single dust removal methods

Experimental Study on Dust Removal Efficiency by Combined Method of Dust Removal

The dust removal efficiency by combined method of dust removal is measured at different wind speeds of throat pipe, and the measurement results are shown in Fig.8 and Table 5.

Table 5. Efficiency measurement results under combined dust removal mode

Throat air velocity (m/s)	Spray + vibrating fiber grid + water film (%)	Throat air velocity (m/s)	Spray + vibrating string grid (%)	Throat air velocity (m/s)	Spray + water film (%)	Throat air velocity (m/s)	Spray + vibrating fiber grid + water film (%)
9.12	93.48	9.12	84.76	9.47	79.25	9.12	93.48
14.56	94.69	14.56	88.43	14.87	83.64	14.56	94.69
24.36	96.82	24.36	94.23	24.68	86.49	24.36	96.82
28.48	97.28	28.48	92.15	28.73	90.08	28.48	97.28
33.16	91.28	33.16	88.74	33.45	86.23	33.16	91.28
40.48	88.17	40.48	86.12	40.79	84.75	40.48	88.17

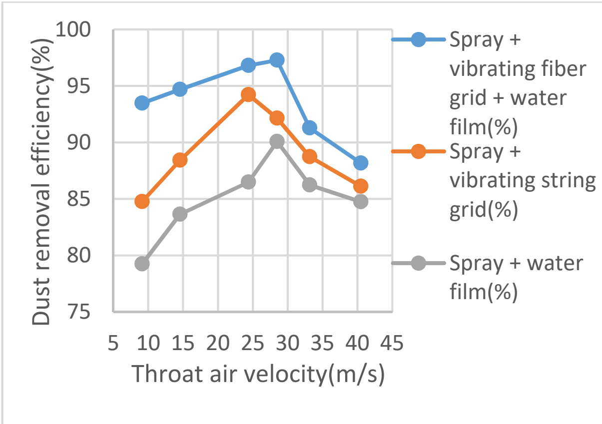


Figure (8): Wind speed of throat pipe effect on dust removal efficiency under combined dust removal mode

The dust removal efficiency by dust collector under the combined dust removal mode firstly increases and then decrease as the wind speed of throat pipe increases, according to Fig.8 and Table 5. The main reason is that the collision condensation of water mist and dust-containing air flow is enhanced and the water film resonance of wet vibrating string grid is strengthened. Besides, the capture efficiency of water film dust removal is improved with the increase of wind speed of throat pipe.

When the wind speed of throat pipe exceeds forming resonance frequency in water film of vibrating string grid, the effect of secondary film-making abates and the dust removal efficiency decreases. The order of dust removal efficiency under combined dust removal mode is spray + vibrating string grid + water film > spray + vibrating string grid > spray + water film. When the wind speed of throat pipe is 28.48m/s, the combined dust removal efficiency by spray + vibrating grid + water film is the highest and the most stable, with a maximum efficiency of more than 97%.

Experimental Analysis on Removal Dust Classification Efficiency

The classification efficiency of removal dust is supposed to be further analyzed in order to gather data about the dust particle size range by dust collector. The best parameters are that spray water quantity is 2.3L/min and the plates of vibrating string grid are two with a clearance of 0.8mm, under the condition of radial external spraying, according to the experimental results. When the gas speed of throat pipe is 20.09m/s, 24.36m/s and 28.48m/s, respectively, dust removal efficiency experiments are carried out. The classification efficiency of dust removal is measured by low-resistance Venturi water film cyclone with vibrating string grid and the graded dust removal efficiency of dust particle size is obtained as shown in Fig. 9 and Table 6.

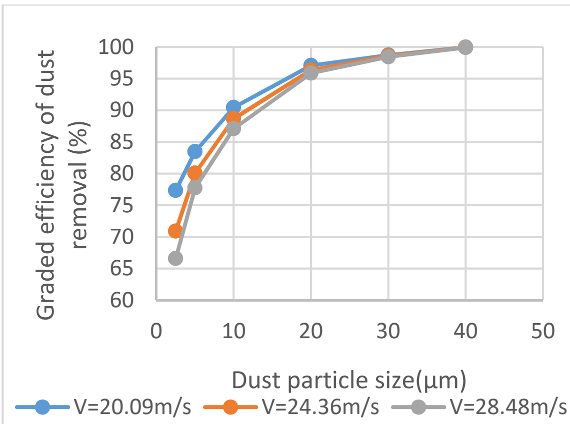


Figure (9): Graded dust removal efficiency under different gas speeds of throat pipe

Table 6. Measurement results of classified dust removal efficiency

Dust particle size (μm)	**Graded efficiency of dust removal (%)**	**Graded efficiency of dust removal (%)**	**Graded efficiency of dust removal (%)**
Throat air velocity	20.09	24.36	28.48
2.5	77.34	70.89	66.59
5	83.48	80.06	77.74
10	90.45	88.67	87.08
20	97.08	96.37	95.88
30	98.73	98.62	98.46
40	99.96	99.95	99.93

The graded dust removal efficiency increases rapidly with the aggrandizement of particle size. Then, it starts to increase slowly at 20μm particle size and finally tends to 100% at about 40μm particle size under the same gas velocity of throat pipe in the low-resistance Venturi water film cyclone with vibrating string grid, according to Fig. 9 and Table 6. The classification efficiency of the same particle size dust decreases with the increase of gas velocity of throat tube. When the gas velocity of throat pipe is 20.48 m/s, the collecting efficiency of respiratory dust reaches 83.48% in the low-resistance Venturi water film cyclone with vibrating string grid. The reason is that in the case of low gas speed, the residence time of the dust-containing gas in the throat pipe and the diffusion pipe is prolonged and the contact collision probability between the pipe water mist and the dust-containing air flow increases, which is beneficial to condense the fine dust into larger particles, where it is captured by the vibrating string grid.

CONCLUSIONS

According to the optimization experiment of operating parameters of the low-resistance Venturi water film cyclone with vibrating string grid, the following findings and conclusions are drawn.

(1) With the increase of wind speed of throat pipe, the collision condensation of water mist and dust-containing air flow is enhanced. Meanwhile, the water film resonance of wet vibrating string grid is strengthened. The dust removal efficiency of water film is improved. When the optimum water supply pressure of water film is 0.3MPa, the dust removal efficiency of the water film to the device increases by 2.06% and is close to 97.32%.

(2) Compared with different dust removal methods, the order of dust removal efficiency is as by spray > water film > dry vibrating string grid > unconditional device, under single dust removal mode. The order of dust removal efficiency is as spray + vibrating string grid + water film > spray + vibrating string grid > spray + water film, under combined dust removal mode.

(3) The graded dust removal efficiency increases rapidly with the aggrandizement of particle size. Then, it starts to increase slowly at 20μm and finally tends to 100% at about 40μm under the same gas velocity of throat pipe in the low-resistance Venturi water film cyclone with vibrating string grid.

(4) High-pressure nozzle atomization can reduce water consumption, improve humidity of dusty air and accelerate condensation of dust and water mist at both throat and vibrating string grid. The dust removal efficiency is high by low-resistance Venturi water film cyclone with vibrating string grid, the structure of which is simple and of low cost, with which fine dust can be effectively collected.

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