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Effect of the bottom-contracted and edge-sloped vent-pipe on the cyclone separator performance

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Abstract

The influence of the bottom-contracted and edge-sloped vent-pipe on the separation efficiency and pressure drop of a cyclone separator under different vent-pipe insert depth and different orientation of the sloped edge were studied in a visual cold circulating fluidized bed (CFB) experimental setup according to a commercial 100 MW CFB boiler with a scale of 20:1. And the correlative results were also compared with the traditional linear-pipe-shaped cyclone separator. Results indicate that the cyclone inlet stream velocity has a strong influence on the separation efficiency and pressure drop, and the results are similar to that of the conventional cyclone. Namely, both separation efficiency and pressure drop increase with increasing cyclone inlet stream velocity. The separation efficiency of the modified cyclone separator increases firstly and then decreases with the increasing of the vent-pipe insert depth. However, there is not a very clear rule of the effect of vent-pipe insert depth on the pressure drop for modified cyclone separator. Both the separating efficiency and the pressure drop change with the orientation of the sloped edge, and they have the same rule of change, the maximum at 90° and the minimum at 270°. Due to the configuration of the bottom-contracted and edge-sloped vent-pipe is suitable with the flow field inside cyclone separator, the separation efficiencies of the modified cyclone separator are usually higher than those of traditional cyclone separators.

Keywords: Cyclone separator; Separation efficiency; Pressure drop; Bottom-contracted and edge-sloped vent-pipe; Circulating fluidized bed

1. Introduction

As a key equipment for circulating fluidized bed (CFB) boilers, gas–solid cyclone separator, which helps the circulation of the solids in the furnace, has strong effects on the combustion efficiency, the circulation rate, the desulfurization efficiency, and so on. With the scale-up of CFB boilers, the volume and capacity of cyclone separator increase. However, large cyclone separators not only result in some manufacturing, installation and operation problems, but also have relatively lower separation efficiency [1,2]. During the last two decades experimental and theoretical investigations were conducted in order to achieve the less size, greater compactness and high separation efficiency of the gas–solid cyclone separator.

At the aspects of design and the overall arrangement of the separator, Foster Wheeler Company firstly developed the cooling type high temperature cyclone separator that is formed from flat rather than curved tubing panels to eliminate the fabrication complexity issue. The arrangement shows the separator to be positioned adjacent to the furnace which provides a “compact” configuration. But it was too complex for manufacturing and installation of the tubes and the refractory wall [3]. Ahlstrom Pyropower Company developed a square water-cooled cyclone separator with upward exhaust exit for high temperature separation and applied to its compact CFB boiler design [4]. Kvaerner Power Company’s CYMIC boilers use high efficiency cylindrical cyclones located inside the furnace and constructed of membrane walls and light refractory for erosion protection [5]. Greenfield Research Incorporated of Canada developed and patented a novel compact gas–solid separator which can achieve both high efficiency and compactness [6]. In addition, many separators have shown that the separation efficiency of inertial separators can, to some extent, meet the demand of some CFBB such as the U-beams separator of Sweden’s Studsvik Corporation [7], the slots separator of Germany’s Steinmuller Corporation [8], the slotted-tube impact separator of China’s Xi’an Jiaotong University [9] and the finned tube impact gas–solid separator of China’s Zhejiang

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Nomenclature

h vent-pipe insert depth (mm)
u cyclone inlet stream velocity (m/s)

Greek letter
α orientation of the sloped edge (°)

University [2]. Besides, the new configuration of the double-inlet square cyclone separator with two furnaces developed by Clean Coal Combustion Laboratory of Chongqing University is very suitable to the scale-up of the CFB boilers [10].

At the aspects of inner configuration, the France's Stein Corporation developed a cyclone separator of with an offset mounted exhaust pipe [11]. A type of square cyclone separator with downward exhaust exit was developed and granted a Chinese patent [12]. Its separation efficiency was shown as good as that of the traditional cyclone of circular cross-section separator and its particle cut-diameter was around 15 μm [13]. Moreover, authors have carried out many investigations on the effect of cylinder height and diameter [14], the cone opening size [15], the vent-pipe diameter, length, insert depth and offset [16–22] on the separator performance. And these results lay important foundations for optimizing and scale-up of cyclone separators.

As we know, however, the inside stream flow field of a single-inlet cyclone separator has not axial symmetry. The tangential velocity and radial velocity at the different angles in cyclone separator are also not uniform [23,24]. Thus, the shape of vent-pipe will certainly has an influence on the stream flow and may result in an effect on the separation efficiency and pressure drop of cyclone separators.

In the present work, an attempt has been made to investigate experimentally the effect of the bottom-contracted and edge-sloped vent-pipe on cyclone performance in a CFB loop.

2. Experimental setup and methodology

2.1. Experimental setup

In order to improve the comparability of experimental setup with practical CFB boilers, we set up a set of visual cold experimental apparatus with Plexiglas according to a commercial 410 t/h CFB boiler with a scale of 20:1 (Fig. 1). The main dimensions of the experimental setup are listed in Table 1.

Fig. 1. Visual experimental system of large-scale CFB.

Table 1
Main dimensions of the furnace and separator

Item	Dimension (mm)
Furnace height	3500
Furnace depth	650
Furnace width	680
Cyclone outside diameter	450
Cyclone cylinder height	900
Cyclone cone height	900
Cyclone vent-pipe diameter	200

2.2. Experimental methodology

In this work, the effects of the bottom-contracted and edge-sloped vent-pipe on the separation efficiency and pressure drop of cyclone separator under different vent-pipe insert depth and different orientation of the sloped edge (Table 2) were studied and the results were also discussed by comparing with the traditional linear-pipe-shaped cyclone separator. Note that the orientation of the sloped edge represents the angle between the two directions of the sloped edge and the inlet stream. Besides, the angle is described in clockwise when looking down the vent-pipe. The modified vent-pipe is shown in Fig. 2.

In the present work, the cyclone inlet stream velocity and the flux of high pressure air of L-valve were measured by hot-wire anemoscope and rotameters, respectively. Pressure signals in the furnace and cyclone separator were firstly transferred to electric signals by Kangyu KYB14 type differential manometers, and then they were collected by the ADAM4000 data acquisition system. The separation efficiency is indirectly calculated by measuring the change in the amount of bed material by unit of time in the return leg (Fig. 3).

Table 2
Experimental conditions

The vent-pipe insert depth (mm)	550	450	350	250
The orientation of the sloped edge (°)	0	90	180	270

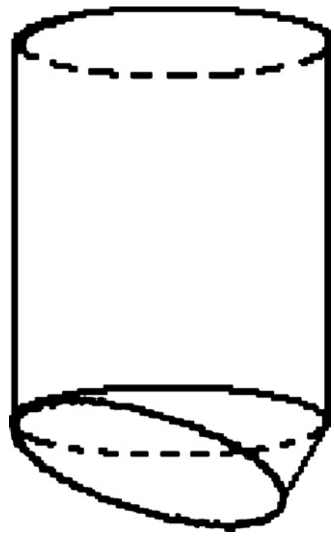

Fig. 2. Schematics of the modified vent-pipe.

3. Results and discussion

3.1. Separation efficiency

3.1.1. The relationship between separation efficiency and vent-pipe insert depth

Fig. 4 represents the relationship between material accumulating velocity in material collecting and measuring device and vent-pipe insert depth under various cyclone inlet stream velocities. It shows that the cyclone inlet stream velocity has a strong influence on the separation efficiency. Besides, the separation efficiency of the modified cyclone separator increases firstly and then decreases with the increasing of the vent-pipe insert depth. And the maximum of separation efficiency appears when the value of vent-pipe insert depth is 450 mm.

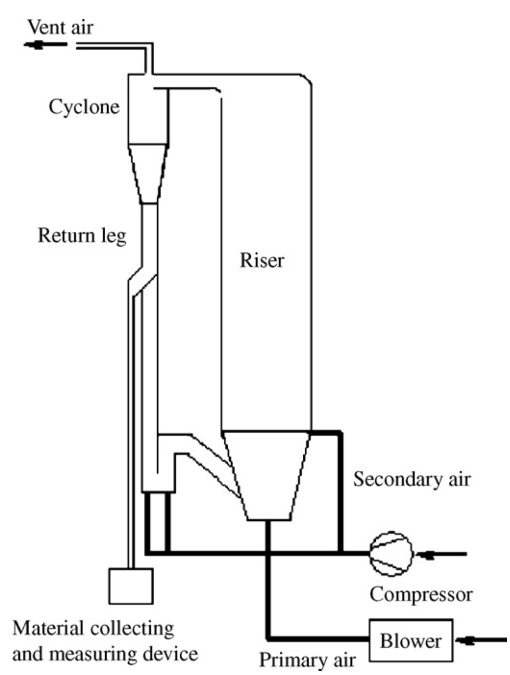

Fig. 3. Schematics of experimental setup.

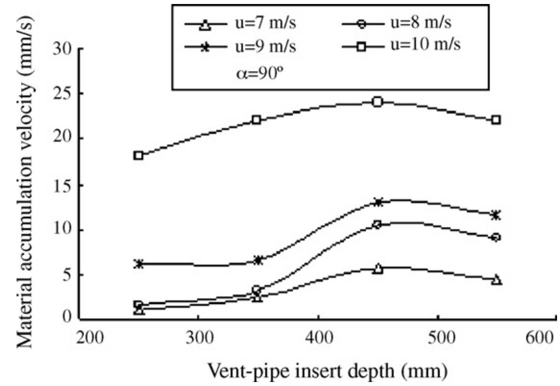

Fig. 4. The relationship between material accumulating velocity and vent-pipe insert depth under different cyclone inlet stream velocities.

As we know, the flow field inside the cyclone separator is related with the insert depth of vent-pipe. The main reason of the separation efficiency rising with the increasing of vent-pipe insert depth is that increasing insert depth reduces the probability of short-circuiting flow. Moreover, both the flow time and the flow line of vortex motion will increase with increasing the insert depth of vent-pipe. As a result, more particles will be separated. However, when the vent-pipe is inserted extremely deep, the ascending inner vortex and the descending outer vortex will be influenced and the flow field inside the cyclone separator will become turbulent which may lead to more and more coarser particles exiting at the top with the carrier gas by the re-entrainment of the ascending inner vortex.

3.1.2. The relationship between separation efficiency and orientation of the sloped edge

The effect of orientation of the sloped edge on the cyclone separation efficiency under various cyclone inlet stream velocities is shown in Fig. 5. The separation efficiency of the modified cyclone separator increases with increasing cyclone inlet stream velocity and the result is similar to that of the conventional cyclone. In addition, the separation efficiency changes with the orientation of the sloped edge, being the maximum at 90° and the minimum at 270°.

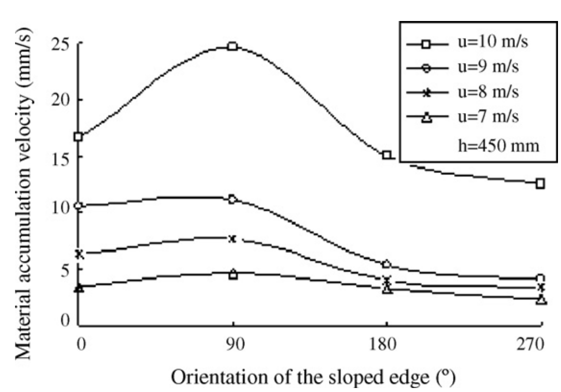

Fig. 5. The relationship between material accumulating velocity and orientation of the sloped edge under different cyclone inlet stream velocities.

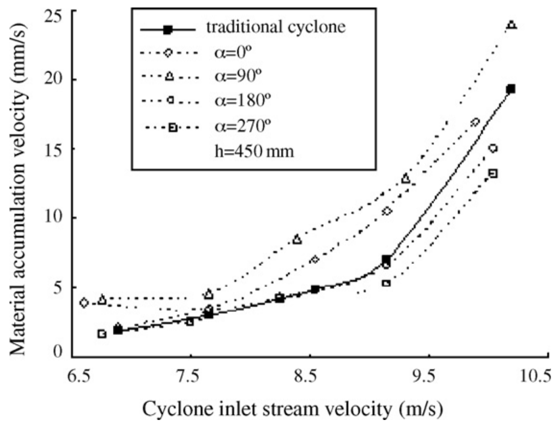

Fig. 6. Comparison of separation efficiency between the two different cyclone separators.

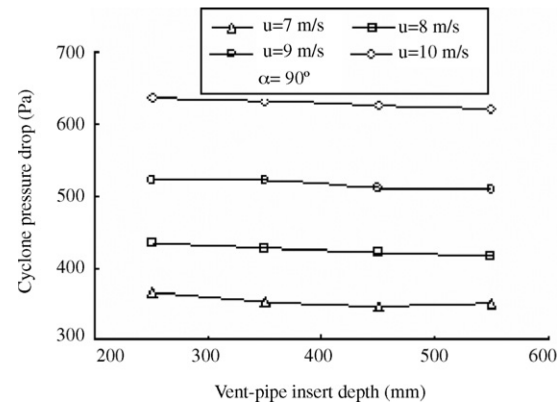

Fig. 7. The relationship between pressure drop and vent-pipe insert depth under different cyclone inlet stream velocities.

As we know, the inside stream flow field of a single-inlet cyclone separator has not axial symmetry. The tangential velocity and radial velocity of the different angle in cyclone separator are always not uniform. From numerical results we found that the maximum of stream tangential velocity appears when the orientation of the sloped edge is within 90–180°. The higher tangential velocity implies the higher descending axial velocity of the outside quasi-free vortex. Thus, it is not easy to come into being the short-circuiting flow. Furthermore, there is a separating flow vortex near the bottom zone of the vent-pipe when the orientation of the sloped edge is within 270–0°, and the change of the orientation can destroy this separating flow vortex. Especially, it is a conical surface in the region near the bottom of vent-pipe when the orientation of the sloped edge is 90°. All these configurations help to improve the flow field in the cyclone and results in the increasing of separation efficiency.

3.1.3. Separation efficiency comparison between two different cyclone separators

Separation efficiency comparison between the modified cyclone with bottom-contracted and edge-sloped vent-pipe and the traditional linear-pipe-shaped cyclone under the same operation conditions is shown in Fig. 6.

From Fig. 6 we can find that the separation efficiency of the modified cyclone is not absolutely higher than that of traditional cyclone. Only when the orientation of the sloped edge is 0° or 90°, the separation efficiency of the modified cyclone is obviously higher than that of traditional cyclone. The separation efficiency of the modified cyclone is higher than that of traditional cyclone only under some cyclone inlet stream velocities when the orientation of the sloped edge is 180°. However, the separation effect of modified cyclone almost cannot catch up with that of traditional cyclone when the orientation of the sloped edge is 270°.

3.2. Pressure drop

3.2.1. The relationship between pressure drop and vent-pipe insert depth

Fig. 7 shows the relationship between pressure drop and vent-pipe insert depth under various cyclone inlet stream velocities. As shown in the Fig. 7, there is not a very clear rule of the effect of vent-pipe insert depth on the pressure drop for modified cyclone separator. Nevertheless, the experimental data indicates that with increasing the insert depth of vent-pipe, pressure drop has a slightly decrease.

With the increasing of the insert depth of vent-pipe, more friction loss of the pipe wall consumes the entrance kinetic pressure, and the vortex intensity will be attenuated to zero at an extreme condition. At this moment, the consumed kinetic pressure calculated by energy equilibrium equation is much less than that without friction loss or with the maximal vortex intensity. Hence, there is no any whirling motion after stream entering into vent-pipe when increasing the insert depth of vent-pipe. Simultaneously, the stream has a very high static pressure. And the kinetic pressure consumption of this kind of vent-pipe is quite low. As a result, the total pressure drop decreases.

3.2.2. The relationship between pressure drop and orientation of the sloped edge

The relationship between the pressure drop and the orientation of the sloped edge under various cyclone inlet stream velocities is shown in Fig. 8. It shows that the pressure drop changes with the orientation of the sloped edge, being the maximum at 90° and the minimum at 270°. And the change rule is similar to that of separation efficiency. As described before,

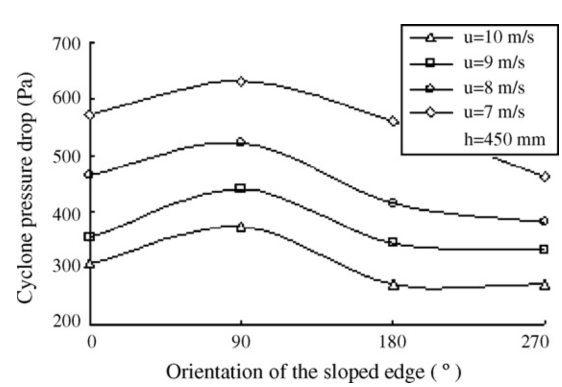

Fig. 8. The relationship between the pressure drop and orientation of the sloped edge under different cyclone inlet stream velocities.

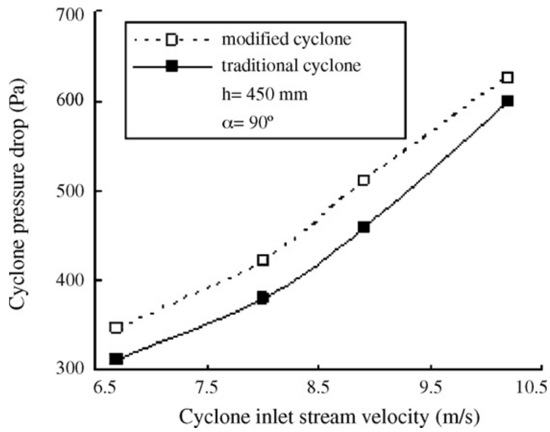

Fig. 9. Comparison of pressure drop between the two cyclone separators.

there is a higher stream tangential velocity when the orientation of the sloped edge is within 90–180°, especially for the orientation of the sloped edge is 90°. This configuration helps the stream flow and cannot bring remarkable resistance. As a result, the vortex intensity in the cyclone is enhanced and the kinetic pressure loss is indirectly increased.

3.2.3. Pressure drop comparison between two different cyclone separators

The comparison of pressure drop between the modified cyclone and the traditional cyclone under the same operation conditions is shown in Fig. 9. It indicates that the pressure drop of the modified cyclone is about 10% higher than that of the traditional cyclone.

4. Conclusions

In the present work, the influence of the bottom-contracted and edge-sloped vent-pipe on the separation efficiency and pressure drop of cyclone separator under different vent-pipe insert depth and different orientation of the sloped edge were studied in a visual cold CFB experimental setup. And the correlative results were also compared with the traditional linear-pipe-shaped cyclone separator. Some significant conclusions were summarized as follows:

(1) The cyclone inlet stream velocity has a strong influence on the separation efficiency and pressure drop. The results are similar to that of the conventional cyclone. Namely, both separation efficiency and pressure drop increase with the increasing of cyclone inlet stream velocity.
(2) Due to the configuration of the bottom-contracted and edge-sloped vent-pipe is suitable with the flow field inside the cyclone separator, the separation efficiencies of the modified cyclone separator are usually higher than that of the traditional cyclone separator.
(3) The separation efficiency of the modified cyclone separator increases firstly and then decreases with increasing the insert depth of the vent-pipe. And the maximum appears when the value of vent-pipe insert depth is 450 mm under this experimental condition. However, there is not a very clear rule of the effect of vent-pipe insert depth on the pressure drop for modified cyclone separator.
(4) Both the separating efficiency and the pressure drop change with the orientation of the sloped edge, and they have the same change rule, the maximum at 90° and the minimum at 270°. This also indicates that the increasing of separation efficiency through the change of configuration of vent-pipe is with the cost of increasing the cyclone pressure drop. However, when the key problem is the separation efficiency, this kind of cyclone separator with the bottom-contracted and edge-sloped vent-pipe is clearly more suitable.

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