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Development of a cyclone separator with high efficiency and low pressure drop in axial inlet cyclones

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ABSTRACT

This study was aimed at optimizing the configuration of a vortex finder to improve the separation efficiency and reduce the pressure drop of cyclone separators. Six types of cone-shaped vortex finders were designed and tested for their performance on gas–solid separation at different flow rates and particle concentrations. The experimental results demonstrated that the reflux cone and gaps (straight and spiral) in a vortex finder could improve separation performance of the cyclone separator through reducing the pressure drop and increasing the overall separation efficiency and grade efficiency. The new cyclone separator with the vortex finder (Type D) that had both reflux cone and spiral gap (15° dextrorotation) configurations had the best separation performance, which reduced the pressure drop by 73% and increased overall separation efficiency by 9% as compared to the cyclone separator with the basic vortex finder (Type A). This new cyclone separator removed 99% particles with a diameter bigger than 10 μm. Our study indicated that the modified vortex finders (especially with both reflux cone and spiral gap configurations) have great potential for their application in gas-solid separation for natural gas cleaning.

1. Introduction

Many industrial processes, such as natural gas transportation, petroleum refining, and environmental cleaning, involve the separation of particles from air streams. Fabric filters and cyclone separators have been widely used for gas–solid separation in natural gas stations. Since natural gas is transported at pressures as high as 12 MPa, cyclone separators with an axial inlet used in natural gas transportation are required to have a smaller pressure drop than those used in other fields. The pressure drop must be less than 0.05 MPa of operation pressure. Cyclone separators are also required to remove 99% particles with a diameter bigger than 10 μm at designed flow rates.

Since cyclone separators have been extensively used in various industries, a considerable number of experimental and theoretical studies have been performed on cyclone separators, which are aimed at enhancing separation efficiencies and reducing pressure drops. These efforts can be classified into two ways: one way is to optimize the configurations and geometric dimensions of the cyclone separators, and the other way is to add additional parts to the cyclone separators. To enhance separation efficiencies and reduce the pressure drop, a number of studies have focused on the effects of geometry dimensions of cyclone separators such as the gas inlet width and height, the cyclone cylinder and the vortex finder. The vortex finder is especially important and significantly affects the cyclone performance. The size and configuration of the vortex finder play a critical role in defining the flow field inside the cyclone, including the pattern of the outer and inner spiral flows.

Many researchers studied the influence of the vortex finder size on pressure drop and separation efficiency of a cyclone separator [1–6]. It has been concluded that the separation performance, including separation efficiency and pressure drop, could be improved by optimizing the vortex finder size. However, the effect of optimizing the vortex finder size on pressure drop was limited. Lim et al. [7] evaluated the performance of a cyclone with different vortex finders to examine the effect of the vortex finder shape on the collection efficiency. They found that the cone shapes or lengths of cone-shaped vortex finders were not an important factor affecting the particle collection efficiencies. Raoufi et al. [8] obtained detailed flow information using CFD simulation inside those cyclones tested by Lim et al. [7] and revealed that the vortex finder shape and dimension influenced its performance. Elsayed and Lacor [9] optimized the cyclone separator geometry to minimize pressure drop using mathematical models and CFD simulations. Their research findings demonstrated that inlet dimensions and the vortex finder diameter strongly affected the cyclone performance. Hsiao and Chen [10] studied the effect of geometric configurations, especially the vortex finder length, on the collection efficiency of axial flow cyclones. In their study, an increase of vortex finder length could either lead to the creation of bypass flow to the cyclone outlet or increase the particle residence time due to the additional turning of the upward vortex. Chen et al. [11] studied the influence of a vortex finder with different configurations on the cyclone separator performance. They found that the configuration of the bottom-contracted and edge-sloped vent-pipe was suitable for the flow field inside the cyclone separator. The

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separation efficiencies of the modified cyclone separators were higher than that of the traditional cyclone separator. Conrad et al. [12] invented various vortex finders with different damping devices to reduce the pressure drop of the cyclone separator, but the configurations of damping devices were complicated. However, some studies reported that the vortex finder configuration and size did not play an important role in pressure drop [13–15].

Although many researchers have succeeded in developing new configurations and optimizing the size of vortex finders to reduce pressure drop and improve separation efficiencies of cyclone separators, the cyclone separators with existing vortex finder configurations do not satisfy the requirement that the pressure drop must be less than 0.05 MPa of operation pressure. Therefore, the objective of this study was to obtain a new cyclone, which can be used in natural gas transportation with low pressure drop and high separation efficiency. The effects of different vortex finder configurations on the cyclone separator performance at different flow rates were investigated.

2. Experiment

2.1. Configuration of the cyclone separator and vortex finder

The cyclone separator used in this study had an axial inlet with eight guide vanes, and its detailed geometry and dimensions are shown in Fig. 1. The vortex finders with different configurations are shown in Fig. 2. All these vortex finders had the same dimensions. The basic vortex finder (Fig. 2a) was modified for different configurations by adding a reflux cone at the bottom and/or gaps inside.

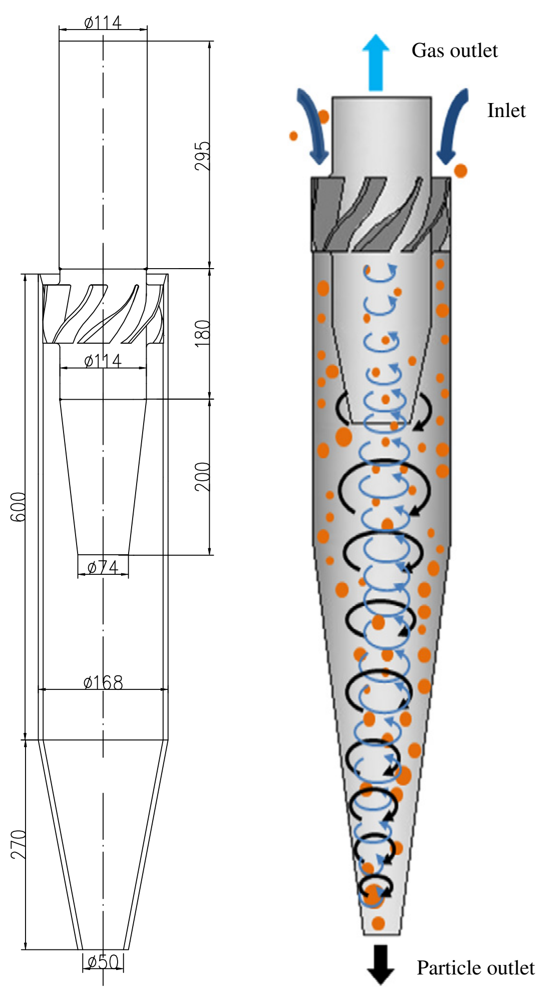

Fig. 1. Geometry and inside flow of the cyclone separator.

2.2. Experimental setup and procedure

The experimental setup is shown in Fig. 3. The experiments were carried out at atmospheric pressure and ambient temperature. A powder dispersion generator, BEG-1000 by Palas, was used to feed particles continuously into the inlet gas. The Pitot tube was used to measure the cross-section gas velocity in the tube. A Welas-2000 aerosol spectrometer by Palas was used for online measurement of particle concentrations and particle size distributions based on particle numbers at a sampling flow rate of 5 L/min. The range of measured particle concentrations was measured from 0 to 10^5 particles/cm^3 and the particle size distribution was between 0.3 and 40 μm. Sampling nozzles with different diameters were used for different flow rates. To reduce the sampling errors caused by the resident swirling flow at the outlet of the cyclone separator and to avoid the particles preferentially going to the outer walls, a rectifier was used (the same rectifier was used by Dirgo and Leith [16] and Lim et al. [7]) in the outlet of the cyclone separator.

Calcium carbonate was used as the experimental solid particle with a physical density of 2700 kg/m^3. The particle concentration ranged from 100 to 500 mg/m^3, the particle size ranged from 0.6 to 40 μm, and the average particle diameter was approximately 9.86 μm. The flow rate of cyclone separator ranged from 214 to 428 m^3/h. The overall efficiency was defined as the inlet and outlet particle concentration difference divided by the inlet particle concentration. The grade efficiency curve was obtained immediately by comparing particle size distributions at the inlet and outlet of the cyclone separator. Pressure drops between the inlet and outlet tubes of the cyclone separator were measured by a differential pressure gauge.

3. Results and discussion

The measured static pressure drops of the cyclone separator between the inlet and outlet for different vortex finders and different flow rates are shown in Table 1. The cone-shaped vortex finder (Type A) with a reflux cone (Type B) reduced the pressure drop of the cyclone separator by at least 36.6%. Similar research findings were also reported by Lim et al. [7] and Raoufi et al. [8]. The reflux cone caused partial air flow reflux and thus reduced energy dissipation of the swirl flow, which was attributed to the significant pressure drop in the Type B vortex finder. The difference between Type B and Type C vortex finders was that the cone of Type C has 18 straight gaps (Table 1). Fig. 4 shows the air direction of the vortex finder for the Types C, D, E and F. Further reduction on pressure drop was observed with Type C, which was due to the fact that a small portion of air flowing through the vortex finder destroyed the boundary layer of the inner swirl flow in the vortex finder and thus restrained energy dissipation effectively. The Type D vortex finder had spiral gaps (15° dextrorotation) instead of the straight gaps in Type C to add flow areas and thus caused more air flow through the vortex finder. The pressure drop of the cyclone separator with the Type D vortex finder was 38.6% lower than that of Type C. The direction of spiral gaps of Type E was 30° in dextrorotation, but the pressure drop with Type E was higher than that of Type D, which indicated that there was an optimum value for the spiral degree. Type D and Type F have spiral gaps in the opposite direction. Type F used the same direction in the spiral gap and guide vanes while Type D was the opposite. As a result, the former had less air following into the vortex finder, which led to more pressure drop compared to Type D. Table 1 shows that the pressure drop of the cyclone separator with the Type D vortex finder was the lowest at the same flow rat.

Fig. 5 shows the overall separation efficiencies of the cyclone separators with different vortex finders at flow rates of 214, 321, 375, and 428 m^3/h. It was found that the reflux cone (the Type B vortex finder) contributed to a 5.2–6.7% increase in the overall separation efficiency of the cyclone separator at different flow rates. The improvement on separation efficiency by reflux cone was because it can prevent the separated particles from escaping from the vortex finder entrance. In