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Prediction of the maximum-efficiency inlet velocity in cyclones

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ABSTRACT

The separation efficiency of cyclones is closely related to the inlet velocity, and the maximum-efficiency inlet velocity (MEIV) maximizes the separation efficiency. In current separation models, particles centrifuged on the wall are considered captured, and their further motions are no longer considered. We propose that particles centrifuged on the wall impact the wall and then rebound. If the energy in these particles is sufficient, they will rebound into the upward gas flow. Within the fast upward gas flow, particles quickly move into the vortex finder and escape from the cyclone. A faster inlet velocity imparts more energy to the particles. Therefore, an excessive inlet velocity causes rebounded particles to escape, decreasing efficiency. The particle motion discussed above is the reason for the MEIV phenomenon, which is different from previous explanations. Newton's law and the hard sphere model were used to describe the particles' motion. Taken together, a new approach to forecast MEIV was established. The effects of various particle characteristics on the MEIV of cyclones, which have not been considered by previous models to forecast the MEIV, are taken into account in this new approach. We observed good consistency between the prediction of the new model and experimental data.

1. Introduction

The cyclone separator is an important dedusting device widely used in many industries. To meet more stringent emission requirements for both environmental protection and safeguarding downstream equipment, cyclone performances must be improved. Cyclone separator performance includes two aspects, separation efficiency and pressure drop, both of which are significantly affected by the inlet velocity. Investigations [1–3] on pressure drop have shown that increasing the inlet velocity led to an increase in pressure drop. Many experiments [1,4–9] have determined a critical inlet velocity with respect to the separation efficiency. When the inlet velocity is smaller than the critical value, separation efficiency increases with the increase in inlet velocity; when the inlet velocity exceeds the critical value, the efficiency decreases with the increase in inlet velocity. The critical inlet velocity yields the maximum separation efficiency. In this paper, the critical inlet velocity is called the maximum-efficiency inlet velocity (MEIV). An inlet velocity exceeding the MEIV decreases the separation efficiency and increases the pressure drop, leading to poor performance. Therefore, the optimal design and use of cyclones is very important for the accurate prediction of the MEIV.

There has been a gap between the experimental results and the prediction of models for separation efficiency regarding the effect of inlet velocity on separation efficiency. According to the models for separation efficiency set up by Leith and Licht [10], Dietz [11], Mothes and Löffler [12], Li and Wang [13] and Zhao [14], separation efficiency continuously increases with increases in inlet velocity. The theory proposed by Avci and Karagoz [15] predicted that the effect of inlet velocity on separation efficiency diminishes at high flow rates. These theories have a common defect in that the MEIV of a cyclone cannot be forecasted. Although Azadi [16] and Swamee [17] built approaches to optimize inlet velocity, these approaches were based on models containing the defect mentioned above, and their results were therefore not the MEIV of the cyclone.

As early as 1974, Kalen and Zenz [4] established a theoretical–empirical approach to forecast the MEIV based on the flow pattern in cyclones analogized as the flow through a coiled pipe bearing a narrow slit along its inner length to allow gradual gas dissipation. By direct analogy to saltation in horizontal conveying lines, Kalen and Zenz [4] thought that if the gas velocity in this coiled pipe was greater than the saltation velocity of the particles, the particles would have little chance of reaching and remaining on the outer diameter of the coil, which would lead to a decrease in separation efficiency. Therefore, the theoretical approach to calculate the saltation velocity in the coiled pipe was deduced using the dimensions of the cyclone and inlet velocity. According to the experiment, when the

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inlet velocity was 2 to 2.5 times the saltation velocity, a decline in overall collection efficiency occurred. Combining this theoretical approach to saltation velocity with experimental data, the approach to predict the MEIV was as follows:

$$v_{MEIV} = 231.6\left(\frac{4g\mu_g\rho_p}{3{\rho_g}^2}\right)\left(\frac{b/D}{1-b/D}\right)b^{0.2}. \tag{1}$$

Shi and Wu [5] tested the MEIVs of cyclones with different inlets and found that the MEIV increased with an enlarging inlet, which could not be correctly predicted by Eq. (1). According to the experiment, Shi and Wu [5] introduced another parameter KA (KA is the ratio of cyclone area to inlet area) into Eq. (1) and set up another model that predicted the increasing MEIV with an enlarging inlet:

$$v_{MEIV} = 19KA^{1.4}\left(\frac{4g\mu_g\rho_p}{3{\rho_g}^2}\right)\left(\frac{b/D}{1-b/D}\right)\left(\frac{b}{D}\right)^{0.2}. \tag{2}$$

However, some common characteristics between the two models can be observed. Significantly, both give more attention to the effect of cyclone dimensions and features of the gas on the MEIV, but less attention to the effect of particle features. Only particle density is included in both equations. This may cause some phenomena observed in experiments to not be predicted by these models. For example, Wang [7] tested and compared the separation performances of fluidized-bed catalytic cracking (FCC) fine catalyst and shale ash. The results shown in Table 2 reveal that in the same cyclone separator and with the same gas, these two powders with almost the same density yielded rather different MEIVs, which was attributed to the disparity of particle characteristics by Wang [7]. However, the predicted MEIVs for these powders by both Eq. (1) and Eq. (2) were similar.

The goal of the present research is to establish a novel model to predict the MEIV of cyclones that gives more attention to the effect of particle characteristics. First, the gas flow in cyclones will be analyzed. Then, a different view on the motion of particles in cyclones will be put forward. Furthermore, Newton's law and the hard sphere model will be used to describe the particle motion. As a result, a new approach to forecast the MEIV will be set up. Finally, the availability and usability of the new approach will be evaluated by comparing the experimental data with the predictions of the other two approaches.

2. Gas flow

2.1. Tangential velocity

A gas's swirling motion consists of an outer vortex and an inner vortex in the separation space of the cyclone. The outer vortex is a near loss-free swirl, and the inner vortex is a near solid-body rotation (see Fig. 1) [18]. In some cyclones, the tangential velocity at the wall can be significantly higher than the inlet velocity due to constriction of the inlet jet [18]. The relationship between them is given by Meissner and Löffler [12]:

$$\frac{v_{in}}{v_{\theta w}} = \beta = -0.204\frac{b}{R} + 0.889. \tag{3}$$

2.2. Axial velocity

According to the axial velocity, the gas flow in a cyclone consists of the downward gas flow in the outer part and the upward gas flow in the inner part. Hoekstra [19], Hu [20] and Liu [21] measured the velocity field and found that the values of axial velocity in the two parts were significantly different. The upward gas flow was much faster than the downward gas flow. In the cylinder section of a cyclone, the diameter of the upward gas flow is slightly larger than that of the vortex finder and is not affected by the axial position, except right under the vortex finder wall. However, the cone section of a cyclone is determined by the axial position, which shrinks more when the axial position approaches the particle outlet.

We used the commercial CFD (computational fluid dynamics) code, FLUENT 6.1, to investigate the widths of the downward gas flow in the outer part of the cylinder section in cyclones with various geometries and inlet velocities. For the fluid dynamics models, the RSM (Reynolds stress model) was applied to calculate the gas flow field in the cyclone. The pressure equation was discretized by the PRESTO (pressure staggering option) scheme. The SIMPLEC (semi-implicit method for pressure linked equations consistent) algorithm was used for pressure-velocity coupling, whereas for the momentum, turbulent kinetic energy and dissipation rate, as well as for Reynolds stresses, the QUICK (quadratic upwind interpolation of convective kinematics) scheme was selected for the sake of second order accuracy. The simulation was unsteady. A period of 0.0002 s was selected as the time step size to balance the accuracy and workload.

The CFD simulation showed the gas velocity profiles inside the cyclone. Here, we focused on the radial profiles of the axial gas velocity

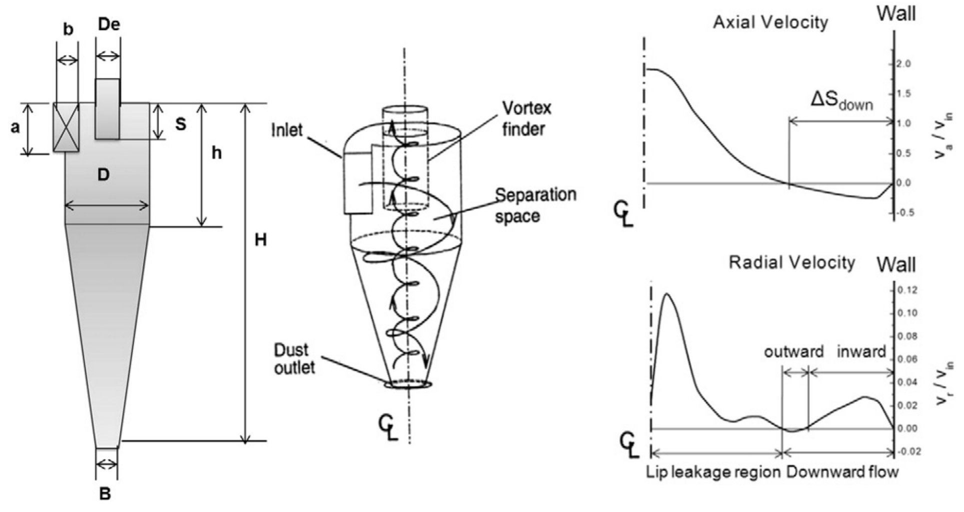

Fig. 1. Schematic illustration of the flow pattern in a cyclone with tangential inlet.