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Enhancement of cyclone solid particle separation performance based on geometrical modification: Numerical analysis

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ABSTRACT

Computational fluid dynamic (CFD) methods are used to investigate the enhancement of the solid-gas separation efficiency by adding tangential chambers to the conical section of a conventional cyclone separator. It is shown that the addition of the tangential chamber enhances the separation of the particles near the conical section wall, and hence the overall separation efficiency, particularly for small particles (1–3 μm). This enhancement occurs with only an 8% increase in the pressure drop between the inlet and outlet of the cyclone. The effects of the inlet velocity and the number of the tangential chambers on the separation efficiency are studied to find the optimum conditions. It is shown that the increase in the velocity enhances the efficiency at the expense of an increase in the pressure drop (the increase in the inlet velocity from 14 to 20 m/s doubles the pressure drop). The model also shows that the addition of one tangential chamber produces a lower dissipation rate of turbulence in the cyclone as compared to multiple chambers, and hence a higher separation efficiency. The efficiency of the proposed geometrical modification is also compared against the conventional cyclone design and that with another geometrical modification reported in the literature (i.e., a cyclone with an elongated conical length). The results reveal that the proposed modification in this paper enhances the separation efficiency for small particles (less than 3 μm) up to 50% compared to the conventional and the elongated designs and 15% for large particles (larger than 6 μm) compared to the conventional design. The proposed modification was also compared to the conventional design in terms of the erosion rate of the cyclone walls, which is increased by 50%.

1. Introduction

Natural gas is becoming one of the most desired fossil fuel energy sources. Two main reasons have led to the rapid increase in the demand for natural gas (NG) [1]: (1) natural gas is a more efficient energy source than oil (e.g. gas energy content is 51.6 kJ/gas compared to 43.6 kJ/g contained in petroleum) [2]; and (2) the amount of CO_2 emitted during NG combustion is lower than that of oil or other common fossil fuels. The increasing demand for natural gas has led to many technical innovations within the natural gas supply stream to reduce the overall energy consumption and greenhouse gas emissions. More specifically, a prodigious number of technological advances has been made in the treatment processes for the removal of solid particles (such as fine sand particles and black powder [3]), a key process to reduce pitting on the downstream equipment.

One of the most efficient methods for solid particle removal from the gas stream is the cyclone separator (which is used extensively in the NG industry). A cyclone relies on the centrifugal forces to guide the particles towards the walls, reducing the momentum of the particles and hence causing their separation at the bottom, while the clean gas is removed from the top of the cyclone. During this process, however, small particles rebounding from the walls reduce the efficiency as they can be carried away by the gas to the clean side of the cyclone. The most significant factor affecting the centrifugal force, and hence the particle separation/collection efficiency, is the particle momentum. Of course, an increase in the inlet velocity enhances the separation efficiency, but at the expense of an increased pressure drop in the cyclone and thus requires higher energy for transportation in the downstream processes. Another way to increase the velocity of the particles is to decrease the diameter of the cyclone at the bottom, referred to as the conical section, which enhances the impact of the finer particles to the wall. At the end of the process, however, there are always very small particles escaping with the clean gas. There have been numerous studies based on either active methods, such as applying magnetic (e.g., attracting black powder mixed with the gas stream [4,5]), mist injection [6] or electrical field (e.g., attracting charged particles mixed with

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the gas stream [7,8]), or passive methods such as geometrical modifications (e.g., varying the conical section dimensions [9,10] of the cyclone) that have been proposed to reduce the number of these escaping particles. The latter is the focus of this paper in which the proposed geometrical modifications reported in the literature are discussed in the following paragraphs. These studies include numerical modeling (and some experimental studies) to show the enhancement in the particle separation efficiency as a result of any geometrical modifications [11–22].

Park et al. [11] investigated numerically the separation efficiency using cyclones in series. In their study, one cyclone separator is divided into three sections. Each section is composed of a different diameter decreasing from the top cyclone to the bottom. This setup allows for larger particles with higher inertial forces to be separated without interfering with the smaller ones which are separated at a later stage. Their results showed that the first cyclone segregates particles in the range of 4.5–11.0 µm, whilst the second setup traps the particles in the size of 3.4–7.9 µm, and the third cyclone collects the particles in the range of 1.8–4.3 µm. This design provides an overlap in terms of the particle size between the three stages, so if a certain particle size is missed in the earlier stage it will be trapped in the following stages. However, the series configuration of the cyclones increases the pressure drop across the setup as compared to one cyclone. Kim et al. [12] implemented helical guiding vanes inside the cyclone to experimentally study their effect on the separation efficiency. Their design with 6 revolutions of helical vanes at the inlet flow rate of 15 L/min led to a 27% enhancement in the separation efficiency of 4 µm particles. Despite the general enhancement in the efficiency, the design provides a complexity in the manufacturing process of the cyclone. In addition, only a certain size of the particles follows the same helical path as provided by the fixed design proposed by Kim et al. [12]. For the sizes outside this range, the particles impact the vanes leading to an increased turbulence inside the cyclone. Brar et al. [13] numerically studied the effects of increasing the conical length of the cyclone on the separation efficiency. This approach increased the separation efficiency by 9.5% for 3 µm particles by increasing the major cyclone cylinder length by 5.5 times of the cyclone diameter. Moreover, the proposed increase in the conical length reduces the pressure drop by 34% as compared to the conventional design. They also showed that by further increase in the conical length (6.5 times of the cyclone diameter) the separation efficiency increases by 11% while the pressure drop reduces to 29% of the conventional design. This is due to the longer conical section which means a larger angle between the main barrel and the conical section walls, which makes the flow transition of the gas smoother before it redirects towards the exit. Xiang et al. [14] also experimentally investigated the effect of the dimensions of the conical section on the separation efficiency. At the inlet flow rate of 30 L/min, their experimental results showed that reducing the opening at the bottom of the conical section from 19.4 mm to 11.6 mm enhances the 4 µm particle separation efficiency from 70% to 86%. By increasing the inlet flow rate to 40 L/min, the efficiency for the same size of the particles was further increased to 92%. Similar to previous geometrical modifications, this reduction in the cone diameter increases the pressure drop through the cyclone separator by 15%. In another study, Chuah et al. [15] studied numerically the effect of the conical dimensions on the cyclone performance. By reducing the bottom conical diameter from 19.4 mm to 11.6 mm, they achieved a 40% increase in the efficiency for 1.5 µm particles. Despite this enhancement in the separation efficiency, the main disadvantage of this method is an increase in the pressure drop by 42%. Similarly, Wasilewski [16] investigated the effect of an additional counter cone at the bottom of the cyclone on the separation efficiency. He studied numerically and experimentally 15 different geometrical configurations of the proposed counter cone. In each of the studied configurations, the maximum separation efficiency was enhanced by 3%. However, the maximum pressure drop showed an increase of 4.1%. In a similar study, Misiulia et al. [17] conducted a numerical study on the effect of four deswirler on the separation efficiency. Their design reduced the pressure drop by 43% at the cost of increasing the separation cutsize from 1.5 µm to 1.72 µm. Furthermore, Parvaz et al. [18] studied the use of vortex finders (in an eccentric way) and their impact on the flow pattern inside the cyclone. Their numerical results indicate that increasing the eccentricity up to 10% increases the pressure drop by 32%. Similarly, the separation efficiency was enhanced by 3% for 1 µm particles at 4% eccentricity. Similarly, Demir et al. [19] conducted a numerical analysis on the effect of the conical heights on the pressure and velocity fields inside the cyclone separator. They conclude that the conical height should be limited to 1.5 times the barrel diameter to obtain the least frictional losses in the separator.

Another important parameter affecting the separation efficiency in the cyclone separators is the length of the down comer (which has also been referred to as the vertical tube in literature [20]). Bryant et al. [21], Zhu and Lee [22] and Mothes [23] emphasized that the down comer controls the natural vortex length of the flow and particle capture. Qian et al. [20] studied the enhancement of the cyclone separation efficiency by numerical investigation of the influence of the prolonged vertical tube attached to the bottom of the conical section at the dust outlet. Their study showed that an increase of 0.5 m in the length of the vertical tube increases the separation efficiency by a maximum value of 15% for 3 µm particles. Another example is the CFD analysis conducted by Bogodage and Leung [24] on the effect of the down comer height on the efficiency. Their results showed that increasing the down comer height by 381 mm increases the separation efficiency by 20% for particles smaller than 3 µm. A similar study conducted by Gil et al. [25] showed the effect of the increase in the down comer height (without the use of the hopper) enhancing the separation efficiency to 87% for particles smaller than 5 µm.

Although most proposed geometrical modifications provide a significant enhancement in the solid-gas separation in cyclone scrubbers, alternative methods aiming to further increase the efficiency in “existing” cyclone separation systems must be further explored. The aim of this study is to increase the separation efficiency of fine particles by including tangential collection chambers at the conical section in addition to the existing bottom collection chamber. Using a CFD model, the optimum number of the tangential collection chambers that yield the maximum collection efficiency for a range of particle sizes is identified, along with the corresponding pressure losses. Using this model, we identify that the solid-gas separation efficiency in cyclones can be increased by 50% by adding the tangential chamber.

2. Computational setup

2.1. Computational domain

In this study, a cyclone with the dimensions shown in Fig. 1 is analyzed numerically. The inlet velocity of the gas-dust mixture is assumed to be $V_i = 14$ m/s (unless mentioned otherwise). To verify the results of the numerical model (explained in Section 3), the separation efficiency is verified against the experimental values obtained by Ji et al. [26] for the same cyclone dimensions. After verification, the model is used to study the effect of the addition of the tangential chamber on the separation efficiency. The proposed additional tangential chamber is introduced to create an additional collecting pot for all sized particles. In this method, solid particles in the gas stream reach the conical section by which their rotational velocity increases. Hence, the particles experience larger centrifugal forces pushing the particles much faster towards the conical section walls.

Fig. 2 shows the 3-D model of the conventional cyclone under investigation with the additional tangential chamber. The tangential chamber is placed in the middle of the conical section. Since the centrifugal forces on the particles are inversely proportional to their rotational radius, the centrifugal forces applied on the particles would increase due to the reduced rotational radius of the conical section. Thus,