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Numerical optimization and experimental investigation of the aerodynamic performance of a three-stage gas–solid separator

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ABSTRACT

The present research investigates and optimizes the aerodynamic performance of a newly designed compact size three stage mobile gas–solid separator. This separator is designed to collect solid particles with different characteristics at a minimum pressure drop. The minimum particle diameter to be completely collected is 1 μm at solid loading 20 g/m^3. The first stage of the separator is a settling chamber which is designed to collect coarse particles (particles down to particle diameter 100 μm). The second stage is a cyclone separator where medium to fine particles (particles down to particle diameter 15 μm) are to be collected. Particles escaping the cyclone separator are collected in the third stage which is a bag filter.

A separator conceptual aerodynamic design is first performed to obtain overall separator dimensions. CFD simulation is used in order to optimize the separator aerodynamic performance and reduce the separator size. The separator is then constructed and experimentally investigated. Comparison between CFD results at design point and measured separator total pressure drop shows good agreement.

Keywords: Aerodynamic; Gas–solid Separator; Settling chamber; Cyclone; Bag filter; Dust collector

1. Introduction

Gas–solid separators are used in many industrial applications to collect solid particles from gas streams. Different separation techniques are available for the collection of solid particles. Each one has its own favorable range of application. An overview of the different separation techniques with their range of operation is presented by Perry et al. (1997) and Rousseau (1987). The present research is dealing with the investigation of a proposed efficient and compact design for a mobile separator.

Compact size mobile separators are usually used in working areas to collect solid particles during different industrial operations (e.g. material cutting). These separators are commercially available in different designs. A fan draws ambient air with solid particles via a hood and flexible pipe into the separator. A suitable separator design is used to collect the particles depending on their characteristics. Bag filters are commonly used because their separation technique only depends on the size of the filter medium (Rousseau, 1987). Particles larger than the filter size are collected independent of particle density, shape, and particles size distribution.

Despite the favorable separation characteristics of bag filters, they cause significant pressure drop during operation due to cake formation. Increasing the operating pressure drop increases the energy consumption and reduces the ability of the filter to clean the working area. During bag filter operation, for an incompressible cake, the pressure drop, Δp, across the filter cake and filter medium can be expressed as (Dorf, 1998)

$$\Delta p = \left[\frac{(a_f m_c)}{A_{cake}} R_m\right] \mu v_s \tag{1}$$

where μ and v_s are the viscosity and the superficial velocity of the filtrate, m_c is the total mass of solids in the cake, R_m is the filter-medium resistance, A_{cake} is the surface area of the cake, and a_f is defined as the specific cake resistance. Eq. (1) shows that increasing the solid loading in the bag filter hence

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the total mass of solids in the cake m_c increases the operating pressure drop. Chen and Hsiau (2009a,b) reported that increasing the filtration velocity decreases the cake porosity and hence increases the pressure drop and the filter collection efficiency. They showed experimentally that increasing the cake thickness by 1 mm results in 0.7% increase in collection efficiency. The pressure drop also increases by 10.4 mm H_2O at a superficial gas velocity of 0.32 m/s and solid loading 200 g/m^3. The increase in pressure drop due to cake formation can be minimized either by increasing the bag filter surface area or decreasing the rate of solid particles diffusion on the bag filter surface. Increasing the filter area increases the overall separator size and the cost of replacing the filter cloth at regular intervals of time. Decreasing the rate of particles diffusion on the bag filter surface can be achieved by installing pre-separation stages before the bag filter. Pre-separation stages also reduce the erosion of filter medium and the frequent need of bag filter cleaning. Multi-stage separation is usually used in fluidized bed reactors. Wang et al. (2009) used cyclone separator together with a bag filter to collect particles in a fluidized bed reactor. Yang et al. (2009) used two cyclone separators in series to collect particles in circulating fluidized bed system. Qi et al. (2008) used three cyclones arranged in series with a bag filter to collect solid particles in a fluidized bed system. Optimizing of the separation system is not discussed by Wang et al. (2009), Yang et al. (2009), and Qi et al. (2008). George et al. (2003) used cyclone separators as pre-separation stage to reduce the size of electrostatic precipitator for fly ash removal.

Solid particles can generally be classified according to the particle size into coarse, medium, and fine particles. Many workshops and factories have the three particle size categories at different locations of the working area. The proposed separator is designed to collect wide range of solid particles at high separation efficiency and an acceptable operating pressure drop. Therefore, two pre-separation stages, a settling chamber and a cyclone, are located before a bag filter stage to form a three-stage gas–solid separator. It is intended that each stage separates certain solid particles category. The separator is designed to be compact and mobile to enable its use at different locations of a working zone. Optimizing the separator operating pressure drop also optimizes the separator energy consumption. This is achieved mainly by reducing the bag filter pressure drop due to cake formation. Moreover, the proposed design enables that any stage could be by-passed if it does not match the particles to be collected.

2. Separator overview

The proposed separator consists of three stages arranged in series, Fig. 1. The minimum particle size to be completely collected is defined by the bag filter cloth. It is generally intended to collect particles down to particle diameter 1 μm at solid loading 20 g/m^3 and an air volume flow rate of 0.05 m^3/s. It should be noted that, during the experimental investigation, the hood is replaced by a solid particles feeder with the fan located before it.

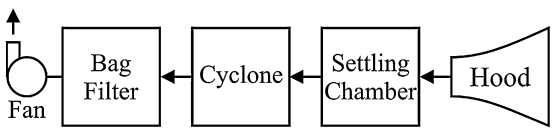

Fig. 1 – Schematic diagram of the separator.

The first stage is a settling chamber which collects coarse particles ($d_p \geq 100$ μm) to reduce solid loading and prevent abrasion in the next stages. The second stage is a cyclone separator where medium to fine particles ($d_p \geq 15$ μm) are to be collected before entering the bag filter. Particles escaping the cyclone separator are to be collected in the bag filter ($d_p \geq 1$ μm).

If the settling chamber and/or the cyclone separator collect 95% (for example) of the particles before entering the bag filter then the operating bag filter pressure drop will be 95% less according to Eq. (1). Furthermore, the frequent need to clean the bag filter will be clearly reduced. Adding pre-separation stages although reduces the bag filter operating pressure drop and its size, it introduces pressure losses due to the new stages. Therefore, to achieve net reduction of the separator pressure drop and hence a save in energy consumption, it is important to keep the pressure loss due to the two pre-stages lower than that due to cake filtration.

3. Separator design

A separator conceptual design is performed first based on well-known design procedures for each type given in literature. Each stage of the separator is designed separately. In order to refine the design, an aerodynamic study using CFD will be performed on each stage. Probable interaction between stages is not taken into consider during conceptual design stage whereas it will be considered in the CFD modeling of the separator.

3.1. Settling chamber design

Proper design of the settling chamber requires that the gas retention time equals or greater than the settling time of the particles to be completely separated (Sutherland, 2008). For a rectangular chamber Rousseau (1987) showed that

$$L_{set} W_{set} = \frac{Q}{v_o} \quad (2)$$

where Q is the gas volume flow, v_o is the terminal settling velocity, L_{set} and W_{set} are the settling chamber length, and width, respectively. Perry et al. (1997) and Yang (2003) present correlations for estimating the particles settling velocity according to their density. A settling velocity of 0.3 m/s corresponding to spherical dry sand particles of 85 μm diameter is selected for the conceptual design of the settling chamber. The settling time of these particles in a 0.5 m height is 1.67 s. For a design air volume flow rate of 0.05 m^3/s, the settling chamber volume V_{set} that ensures a gas retention time of 1.67 sec under uniform steady state condition is 0.083 m^3. Assuming a length to width ratio of 1.2, it follows, from Eq. (2), that the rectangular settling chamber length is $L_{set} = 0.46$ m, width is $W_{set} = 0.38$ m for a height H_{set} of 0.5 m. The air velocity at settling chamber inlet according to continuity equation is 0.26 m/s. It is recommended that the air velocity in the settling chamber must not exceed the pickup velocity to avoid re-entrainment of the settled particles. According to Lee and Lin (2007) this value is far from the pick-up velocity for most common materials.

However, the hood may require a typical hood face velocity of 10 m/s for proper contaminant pickup (Wendes, 1994). Typical air velocity required to convey the particles from the hood to the separator can also be as high as 10–12 m/s for fine