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Enhancement of solid particle separation efficiency in gas cyclones using electro-hydrodynamic method

W.I. Mazyan [a], A. Ahmadi [b], H. Ahmed [c], M. Hoorfar [a,*]

[a] University of British Columbia, School of Engineering, Canada
[b] University of Prince Edward Island, School of Sustainable Design Engineering, Canada
[c] American University of Sharjah, School of Engineering, United Arab Emirates

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A B S T R A C T

This paper investigates the feasibility of using electro-hydrodynamic forces to enhance the efficiency of solid-gas separation in cyclone separators. Electro-hydrodynamic forces are applied using electrostatic coating of particles on which the lateral forces are increased in the presence of a radial static charge. It is shown that these additional forces are larger than the centrifugal force. The experimental and theoretical results show that the proposed method enhances the efficiency by 33% for the particle sizes of 4 μm, and hence can be used as an enhancement to the conventional cyclone designs.

1. Introduction

Natural gas has become one of the most desired energy sources due to its efficient combustion and low carbon dioxide emissions. Dependency on natural gas is increasing rapidly [1] to avoid potential risks associated with alternative energy sources produced by entities such as nuclear and electrical power generation plants. To meet this increasing demand, there have been advances in different parts of natural gas processing steps including gas extraction, treatment, preparation to transport and transportation to the desired destination. The treatment process involves filtration (the removal of solid particles and liquid droplets [2]) and the removal of sour gases (such as H_2S and CO_2) [3]. Filtration is a vital process in natural gas treatment as it prevents pitting of the downstream mechanical equipment.

There are many technologies available for filtration of solid particles and liquid droplets [2,4,5]. Among these techniques, Cyclone scrubbers have been used widely, as they can handle high temperatures and corrosive liquids, and also offer low capital cost and ease of operation as they do not possess moving parts. A typical design of cyclone separators is shown in Fig. 1. As the particulate gas enters the chamber tangentially, the particles follow a helical path and experience centrifugal forces. Since the solid particles are denser than the gas particles, they are pushed towards the cyclone walls by the centrifugal force and are collected at the bottom of the cyclone. The filtered gas is then collected at the gas outlet vent located at the top of the cyclone.

Since the introduction of cyclones, modeling the particle-separation efficiency has been a topic of interest to reduce the optimization cost [6]. For example, Zhao [7] developed a time-of-flight model to predict the particle separation efficiency, and compared their model efficiency with the experimental results of [8] as well as other numerical models presented by Leith and Licht [9] and Barth [10]. Zhao's model was in agreement with the experimental results with a maximum error of 10%. In another study, Qian and Zhang [11] added the effect of the straight tube and dustbin on the separation efficiency. The straight tube effect was included in their model by modifying the particle residence time so that the entire cyclone geometry would be utilized. Their findings indicated a maximum error of 7% compared to the experimental data procured by Hoffmann et al. [12] and Qian et al. [13].

The main drawback of the cyclone filters is their low efficiency in solid particle removal. Based on the current designs of cyclones, the efficiency of solid removal increases at higher inlet velocities. However, a higher velocity causes a greater pressure drop (due to the increased turbulence), and hence, an increase in the operating cost. In recent years, many researchers have focused on increasing the efficiency of cyclones while maintaining the pressure drop and reducing the operating cost [6]. While most of the industrial cyclones use a certain optimum velocity (of 18.3 m/s)

* Corresponding author at: School of Engineering, University of British Columbia, Canada.
E-mail address: mina.hoorfar@ubc.ca (M. Hoorfar).

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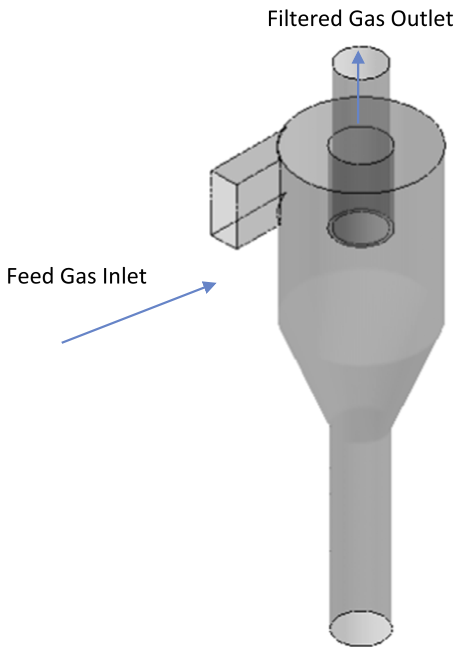

Fig. 1. Schematic of cyclone separator.

for the highest efficiency, several researchers have focused on exploring alternative designs to enhance the cyclone performance. For instance, to further reduce the pressure drop, Xiong et al. [6] proposed the use of vortex finders at the inlet of the cyclone; the vortex finders, which are plates/cavities with straight or helical profiles, were able to reduce the overall pressure drop by generating a vortex. Compared to cyclone separators possessing a basic vortex finder, the helical design reduced the pressure drop by 73% and improved the overall separation efficiency by 9%. As a result, an efficiency of 99% was obtained for removal of particles bigger than 10 μm, and 40% was obtained for removal of 2-μm particles. Xiong et al. [14] also compared the efficiency of a single cyclone with that of a multi-cyclone setup. Their multi-cyclone system consisted of 15 single cyclone separators positioned in parallel with the same inlet. Their findings indicated that the collection efficiency of the multi-cyclone separator is 2–10% less than that obtained from the single cyclone separator. This efficiency reduction is suggested to be due to the non-uniform distribution of the intake flow at each of the cyclones, resulting in different separation performance [14].

In recent years, wet cyclone scrubbers, which are based on spraying mist to the particulate gas, have been proposed to increase the centrifugal force acting on the solid particles. For instance, Yang and Yoshida [15] investigated the injection of pure mist (water at varying rates from 0 to 2.4 L/h) **within particulate natural gas and the subsequent effects on the separation efficiency. Their results showed a maximum of 20% efficiency improvement in particle capture at the 0.042 L/m^3 mist to gas flowrate ratio. Despite the general success of the wet cyclone scrubbers in enhancing the separation efficiency, they have limitations due to the additional centrifugal force provided by these systems. In essence, the additional centrifugal force requires an increase in the size of the mist, which will ultimately add to the operating cost of the cyclone.

The use of electro-hydrodynamic and magnetic forces to increase the efficiency of the cyclones has also been proposed. Yoshida et al. [16] studied the effect of the conical length on separating negatively charged silica particles from water in electro-hydro cyclones. In this particular study, sodium hydroxide was added to the water-silica mixture to increase the pH of the mixture, and thus increase the negative charge on the silica particles. Their findings indicated that the 50% cut-size (i.e., the particle size for which the separation efficiency of the cyclone is at 50%) decreased as the electrical potential increased. Despite the potential of their design, it cannot be applied to pure gas applications. In another study, Svoboda et al. [17] investigated the effects of applying a radial magnetic field to control the density difference of the ferro-coated silicon particles between the overflow and underflow of the dense medium cyclone. Since the particles at the inlet have different ferrous-silicon compositions, a reduction in the density difference between the overflow and underflow is required to reduce the wide range of densities available inside the cyclone. Their study showed that by increasing the magnetic flux density from 0 to 70 G, the density difference between the overflow and underflow outlets reduced from 0.45 g/cm^3 to 0.25 g/cm^3 at a ferro-silicon feed of 2.35 g/cm^3. This design is only applicable when the silica particles are 'naturally' mixed with the ferrous particles.

This paper investigates the feasibility of using electro-hydrodynamic (EH) forces to enhance the overall efficiency of the solid-gas separation in the cyclone scrubbers in pure gas operations. The proposed design alterations include spraying electro-coat to further increase the lateral forces on the particles. The theoretical and experimental results show that the use of an additional EH forces increases the separation efficiency compared to the conventional cyclone designs. Moreover, a cost analysis is presented to compare the operational cost of both the conventional and proposed designs.

2. Methodology

The EH forces are introduced by creating a static charge on the particles coated by electro-coat. In this method, solid particles in the gas are electro-sprayed by a charged fluid in an insulated chamber. The electro-spray process consists of a nozzle in which a high voltage is applied across its orifice while the coating liquid passes through the nozzle. The ferrous powder coat becomes charged as shown in Fig. 2 [18,19]. The electro-coating is an adhesive powder, and hence, attaches to the dust particles. These charged particles move in a spiral path as they enter the cyclone. Therefore, in the presence of a radial static charge (see Fig. 3), the charged particles experience an additional force in the direction of the centrifugal force (radial). These electrostatic fields can be created using a grounded metallic sheet on the walls of the cyclone.

In this study, a cyclone with a radius of 190 mm was analyzed. The inlet velocity of the gas-dust mixture was assumed to be 20 m/s, where the analysis of the sample particle was modeled at the average width of the inlet (40 mm). In the analytical calculation, the surface charge of the solid particle was approximated to be

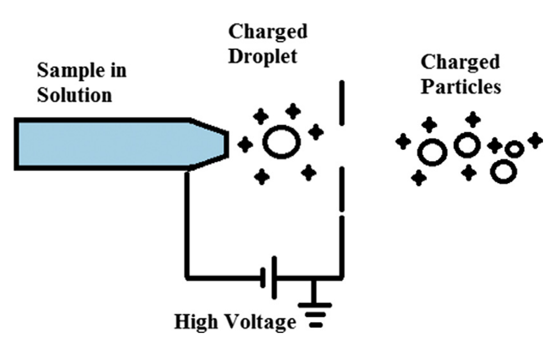

Fig. 2. Electro-coating apparatus.