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Novel cyclone empirical pressure drop and emissions with heterogeneous particulate

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ABSTRACT

With low capital cost and no moving parts cyclones are ideal emissions control devices for particulate laden gases. Their operating cost is almost entirely the financial and environmental cost of the fan energy required to overcome their pressure drop. A novel cyclone design discovered through modeling was reported to have a lower pressure drop than the standard cyclone. Empirical tests were conducted with 30.5 cm diameter cyclones comparing this novel design to the current standard cyclone design at inlet air velocities from 8 to 18 m s^{-1} using a heterogeneous test material at inlet concentrations from 3 to 75 g m^{-3}. Cyclone exhaust was passed through filters. Laser diffraction particle size distribution analysis of filter catch was used to estimate $PM_{2.5}$ emissions. Response surface models were used to compare the emissions and cyclone pressure losses of the two designs. While emissions were essentially identical among the cyclone designs, pressure losses were 30% less for the novel cyclone when compared to a standard cyclone of equal diameter and volumetric flow rate. This represents a substantial potential savings in energy.

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1. Introduction

Many industrial and agricultural air emissions are controlled with cyclones (also called dust, reverse-flow, or axial-flow cyclones; air cyclones; or cyclonic separators). Cyclones have no moving parts and a relatively low initial cost. Their operating costs are primarily due to the electrical energy required for fans to overcome the pressure drop (friction losses) in the cyclone and connected ducts. Since generating electricity results in emissions at the power plant, reducing the energy required to operate cyclones could potentially reduce power plant emissions (Funk, 2010). Therefore cyclone performance may be improved by reducing pressure drop, and thus energy consumption, as well as by increasing collection efficiency.

1.1. Motivations

Recent cyclone performance research was motivated in part by increasing energy costs. The other motivation was regulatory. The Clean Air Act of the United States requires states to develop a general plan to attain and maintain the National Ambient Air Quality Standards (NAAQS) in all areas and a specific plan to attain the standards for each area,

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typically a county or parish, designated nonattainment for a NAAQS. These plans, known as State Implementation Plans or SIPs, are developed by state and local air quality management agencies and submitted to the U.S. Environmental Protection Agency (EPA) for approval. EPA NAAQS for particles less than 2.5 μm in aerodynamic equivalent diameter ($PM_{2.5}$) were lowered to 15 μg m^3 (CFR, 2006) and the 2009 final designations of non-attainment were released in 2012 (EPA, 2012). On December 14, 2012 the NAAQS for annual average $PM_{2.5}$ were lowered again, to 12 μg m^3 (CFR, 2013). As SIP authors may try to comply with EPA regulations through controlling anthropogenic sources of $PM_{2.5}$, more stringent permit qualifications may arise. Ignoring the environmental cost of generating the energy used by abatement devices would be counter-productive to the goal of improving regional air quality.

1.2. Cyclone performance and the influence of inlet concentration

Publications analyzing cyclone performance historically have reported performance as a collection efficiency – the collected percent of mass entering, or as a cut point – that particle size for which the collection efficiency is 50 percent (Faulkner et al., 2007, 2008). Particulate matter emitted is quantified by isokinetically sampling a portion of the exhaust following standards such as EPA Method 201A (CFR, 2010), or by passing all of the cyclone exhaust through a filter weighed before and after the test under standard conditions (as with this study). The mass emitted is compared to the sum of the mass captured by the cyclone and emitted, or to the weight metered into the air stream (as in these tests), or the exhaust concentration is compared to results from isokinetically sampling the inflow. In all cases, whether sampling a portion of the gas flow or filtering all of it, whether reporting overall collection efficiency or cut point, results have also varied with the mass flow (loading) and particle size distribution of material entering the cyclone (Hoffmann et al., 1992). Agricultural processing cyclone research publications have reported a wide range of inlet concentration (airflow particulate loading rate), from 1 g m^{-3} (Wang et al., 2003; Faulkner & Shaw, 2006) to 240 g m^{-3} (Whitelock & Buser, 2007), with other ranges in between: 2 to 16 g m^{-3} (Baker et al., 2004); 8 to 10 g m^{-3} (Funk et al., 2000); 8 to 16 g m^{-3} (Funk et al., 2001); 7 to 15 g m^{-3} (Hughs & Baker, 1998); and 75 g m^{-3} (Baker & Hughs, 1998, 1997).

1.3. The standard cyclone

A cyclone design enjoying wide use today is called the 'enhanced' (or modified) 1D3D. The 1D3D cyclone was first introduced by Texas A&M University (Avant et al., 1976; Parnell & Davis, 1979; Parnell, 1980). The 1D3D cyclone has a cylinder that is one diameter in length and a cone that is three diameters in length, for a total length of four diameters, with a design inlet velocity of 16.3 m s^{-1}. Collection efficiency improvements brought about by innovative modifications (a shorter, wider inlet, a larger solids outlet at the bottom, and a product receiver or expansion chamber) were confirmed through USDA tests (Baker & Hughs, 1998, 1999). The enhanced 1D3D design, shown in Fig. 1b is now widely used in the U.S. The predominance of this design has continued increasing as older abatement devices and older cyclone designs are replaced through repairs or new construction. Collection efficiencies are typically 99% with heterogeneous particulate.

1.4. The novel cyclone

Elsayed & Lacor (2010) used response surface methodology to find optimal values for each of seven geometric dimensions of a cyclone design. They used the Muschelknautz & Kambrock (1970) mathematical equations to estimate pressure drop and cut point during optimization. Then they tested the novel design suggested by the optimization study using computational fluid dynamics (CFD) simulations. This research was expanded by using artificial neural network methodology (Elsayed & Lacor, 2011) and genetic algorithms (Elsayed & Lacor, 2012, 2013) to explore the response surface or desirability function, and confirmed in each case by CFD modeling. With each of these approaches to finding the optimal value for seven key dimensions the general size and shape of the resulting cyclone design was similar (Table 1). Table 1 also presents the dimensions of the cyclone fabricated for use in these empirical trials. Though it was not to exact specifications, it was in the same design family.

The resulting novel designs were predicted to have a collection efficiency equal to the Stairmand (1949) cyclone, but with approximately half the pressure drop. The enhanced 1D3D design, used by many agricultural processing facilities in the United States, is similar to the Stairmand design, so the potential for energy savings represented by this novel family of designs aroused considerable interest. The version of Elsayed and Lacor's novel cyclone design constructed for this experiment, Fig. 1a, had a cylinder 1.61 diameters in length and a cone 2.62 diameters in length, with a design inlet velocity of 13.1 m s^{-1}. It also had a larger inlet and a larger outlet (vortex finder) than the enhanced 1D3D cyclone, Fig. 1b.

1.5. Objectives

The object of this study was to empirically verify the results of Elsayed and Lacor's simulations by comparing the performance (pressure drop and emissions) of their novel cyclone design to the standard enhanced 1D3D cyclone design over a range of inlet velocities using heterogeneous particulate matter over a range of inlet concentrations. Emissions performance was focused on fine particulate ($PM_{2.5}$) emissions because that has been the focus of recent regulations.