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A model analysis on the pulse-jet cleaning performance of electrostatically stimulated fabric filtration

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ABSTRACT

Evaluation of the pulse-jet cleaning performance of electrostatically stimulated fabric filtration (ESFF) collectors incorporated with conventional fabric filtration (FF) and additional electrostatic stimulation is a major challenge. This paper proposes a method in which as many fundamental variables of a fabric filter with ESFF as possible are held constant during comparison of its operation to that of a fabric filter without ESFF. In various testing conditions for a novel ESFF collector, each of the specific drag coefficients, k_2, with ESFF was found to be approximately one-third of those without ESFF, which demonstrates that ESFF offers performance at a lower pressure drop than FF. In addition, the ratio of k_2 with ESFF to k_2 without ESFF was on average a constant (0.34 ± 0.05[1]) throughout the testing; thus, it is called the pressure drop reduction factor (PRF). PRF compares the conventional fabric filter operation to ESFF operation and is used to develop a [PRF] model that defines the relation between pressure variations across the conductive filter bags and the cleaning cycle. In this discussion, the pressure variations are a result of pressure drop, filtration velocity, residual static pressure, and pulse pressure. Therefore, the model cannot only simplify the establishment of the cleaning cycle with ESFF, but also avoid complex evaluations of the cleaning performance involving enormous amounts of data. A comparison between model simulations and experimental results confirms the availability of the model. The pressure drops after the cleaning cycles determined from the model revert closely to their initial levels, indicating that the expected cleaning operations have thus been achieved.

1. Introduction

Electrostatically stimulated fabric filtration (ESFF) technology can enhance the collection efficiency of fine particles [1]. The depth-filtration performance of an ESFF system benefits most from a combination of conventional fabric filtration with agglomeration of electrostatically-charged micron particles.

A combination fabric filter/electrostatic precipitator (ESP) hybrid which was introduced by the U.S. Electric Power Research Institute (EPRI), also called the Compact Hybrid Particulate Collector (COHPAC), has been successfully tested in pilot facilities at utility boilers [2–4]. Further, in a similar configuration to COHPAC, an EPA-developed (EPA, U.S. Environmental Protection Agency) innovation replaces the last section of the ESP with pulse-jet ESFF and maintains a high-voltage charging and collection field with the existing ESP power supply. This innovation leads to emissions approximately one order of magnitude lower than that for an uncharged fabric filter. One type of ESFF employs discharge electrodes (wires) placed axially inside reverse air filter bags with conductive fibers woven into the bags. The conductive fibers generate an electrostatic field between the electrodes and the surface of the bag [5]. A novel type of ESFF uses external placement of discharge wires within an array of conductive filter bags. This wire-bag electrodes structure suspended in the baghouse constitutes an ESFF operation field. The ESFF has the advantages of both ESP and fabric filter: advantages due to an ESP collector in which the particulate matter (PM) loading to the fabric filter is sufficiently low to allow the fabric filter to operate at a very high *A/C* (3–5.5 m/min) without excessive pressure drop or penetration and the collection efficiency of fabric filtration is enhanced because the PM is charged from the ESP. Further, the fabric filter section of the ESFF is less sensitive to changes in fuel composition and collects PM better than an ESP alone [6]. Initial research from 1998 to 2003 was supported by the EPA in collaboration with the Southern Research Institute (SRI) and resulted in a pilot-scale ESFF baghouse in the SRI Combustion Research Facility. The SRI testing demonstrated that ESFF not only is economically competitive with ESP and conventional fabric filter collectors, but also has an advantage in mass collection efficiency, which can be expected to be as high as 99.99% if more demanding emissions standards must be met [7]. However, ESFF technology is now at a standstill, mainly because few appropriate substitutes for the conventional filter bags have yet been developed with qualified collector electrodes, the features of which are enduring conductivity and anti-oxidation in the

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[1] Standard deviation.

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presence of high permeability and applicable mechanical strength. Furthermore, no data on cleaning operations are available for full-scale applications.

Recently, with the assistance of the Chinese government, our team has been conducting research on conductive fabric fibers and the pulse-jet cleaning performance of ESFF. The pulse-jet cleaning procedure is in brief as follows [8,9]: The flow of dusty gas does not have to stop during cleaning because other bags continue to filter at the same time, which causes a repeated duty because the bags are being cleaned and continually refilled by the ensuing dusty gas. This leads to a cleaning cycle that is more intense and has a greater frequency than the other fabric filter cleaning methods. However, the cleaning mechanism of ESFF still has problems associated with pressure variations: problems from unbalanced static pressure distribution on the surface of filter bags [10], from pressure fluctuations in the alternate period between fabric filtration and cake filtration during on-line and off-line operations of the pulse-jet cleaning [11], from fluctuations in filtration velocity influenced by particle penetration across filter bags at a high transitory velocity in a cleaning sequence, and from the irregular dustcake reorganization and downstream particle emission after cleaning [12,13]. Further, an additional electrostatic field that adds a second group of variables, including operating voltage and current, and electrical properties of the collected particles, influences pressure variations on cake porosity and particle adhesion to fabrics [14]. Therefore, this set of variables can influence pressure variations and also complicate evaluation of the cleaning performance of ESFF.

Using the Kozeny–Carman (KC) equation [15,16], the most well-known permeability–porosity relation used in the field of seepage flow in porous media, Cooper et al. [17] and Denis et al. [18] analyzed and described a pulse-jet filter drag model which evaluates the formation of filter drag in terms of gas volumetric flow rate, particulate loading, filter area, and filtration properties of the particulate as it forms a dustcake on the filter bag surface. The model establishes that the slope k_2 of the drag versus weight curve is a characteristic of a particular dust, gas, fabric, and dustcake structure. Two characteristics of k_2 effectively demonstrate fabric filter performance in terms of pressure drop and indicate this performance between fabric filter operation and ESFF operation. However, the y-intercept, S_E, in the linear portion is rarely determined from laboratory measurements and the irregularity of k_2 under various conditions of the operation do not fully clarify the trend of pressure variations in an ESFF field. Although total mass emissions with ESFF were about one-fifth of that for FF and pressure drop increased about one-third as fast compared with FF [7,9], evaluation of the pulse-jet cleaning performance of ESFF has still not advanced. Further, according to the Koehler and Leith model [19],

$$\Delta P = \frac{1}{2}\left[P_S + k_1 v_f - \sqrt{(P_S - k_1 v_f)^2 - 4W\frac{k_2}{k_3}}\right] + k_v v_f^2,$$

the clean fabric resistant k_1, bag cleaning efficiency coefficient k_3, and loss coefficient for the venturi at the inlet to the bag k_v must be determined from laboratory measurements through trial and error. Our team formulated a novel [PRF] model of ESFF in terms of the performance on pressure variations that considers parameters such as pressure drop, filtration velocity, residual static pressure, and pulse pressure. With the [PRF] model developed, we can compare model simulations with experimental results to establish the cleaning cycle.

2. Materials and methods

2.1. Experimental setup

A bench-scale ESFF collector consisting of three major sections, particle generator instruments, an ESFF baghouse, and a pulse-jet cleaning system (Fig. 1), was used in our experiments.

Dusty airflow (35 m^3/h, the maximum) was controlled with a vacuum pump at the end of the collector. Test particles (silicon micropowder, 1.6 μm < mass diameter < 10 μm) generated by a particle feeder were ejected from a compressed air PM atomiser and then transported with inlet airflow to the baghouse. A conductive filter bag was suspended in the centre of the baghouse, surrounded by an array of four corona electrodes in an axially parallel style. The majority of charged micron particles were agglomerated into the larger particles and moved on the surface of the bag within the ESFF operation field. The dimensions of the bag (Fig. 2) were Φ133 × 500 mm (filtration area, 0.2 m^2) and the filter cloth comprised nonwoven polyphenylene sulfide (PPS) fabrics filmed with conductive carbon fibers. The test filtration velocity ranged from 1.04 to 1.45 m/min. Corona voltage and current were measured with a DC power supply.

The cleaning system section comprised a compressed air reservoir, an oil–water separator (pressure reduction valve), an automatic pressure controller (CQ-B-DC, ISO), and an electromagnetic valve (DCF-Z-25 type with diameter 1″). The pressure drop across the bag can get as high as 2500 Pa or more and was recorded using two pressure probes (PT2330-M20, ISO) fixed before and after the filter. These probes transmitted the data recorded to the automatic pressure controller. Once a pressure drop was achieved at the cleaning startup, the pulse airflow from the compressed air injection nozzle (with a standard diameter of 10 mm) was controlled by the electromagnetic valve, which produced a short burst (pulse width 0.1–0.99 s) of high-pressure compressed air (reduced to 0.3 MPa by the pressure reduction valve) in each cleaning process. Thus, periodical cleaning work was achieved until the pressure drop decreased to the initial range.

A well-designed conductive fiber (with conductivity no less than $10^{-7}\ \Omega^{-1}\cdot cm^{-1}$) was key for the ESFF filter bag. The carbon fiber became the qualified ESFF filter material, standing out from some varieties of aramid fiber, graphite fiber, aluminium fiber, and ordinary fabric fiber (with electrical resistance higher than $5 \times 10^6\ \Omega$). The electrical characteristics obtained from testing carbon fibers demonstrated that, compared with a control group of stainless steel fibers that outperformed in terms of conductivity (surface resistance: 0 Ω), one kind of carbon fibers made via the film dipping technique (highlight shown in Table 1) had a similar onset corona voltage and surface accumulated charge but lower breakdown voltage and output power. Although two other types of carbon fibers also featured competent electrical performance, it was utilized as the target conductive fiber of the ESFF filter bag owing to its more feasible mechanical design and layout.

2.2. Experimental methods

On the basis of the working form of the KC equation for a pulse-jet filter drag model, SRI states that, given a sufficiently specific area in the ESFF baghouse, the filter drag across the bag caused by the dust load can be assumed to be a linear function:

$$S = S_E + k_2 W, \tag{1}$$

where S is the filter drag (quotient of ΔP and A/C), S_E is the effective residual drag or after-cleaning drag, W is the areal density of the dustcake deposited during a filtering cycle, and k_2 is the specific drag coefficient.

The above equation can be further facilitated by the assumption of constant inlet mass loading c, so that ck_2 becomes the slope of the equation when drag is plotted versus the cumulative volume $\int \frac{Q}{A_f} dt$ across the filter. W is described by the following equation, where c is given in grams per cubic meter, Q is the volumetric flow rate in cubic meter per minute at baghouse temperature and pressure, and A_f is the surface area of the filter in square meters:

$$W = \int c\frac{Q}{A_f} dt \ (\mathrm{g/m^2}) \tag{2}$$