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The influence of design parameters on the occurrence of shielding in multi-electrode ESPs and its effect on performance

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ABSTRACT

A numerical model in which OpenFOAM® is used to model the electrostatic field resulting from corona discharge in single-channel wire-plate electrostatic precipitators (ESPs) was applied to systematically study the shielding effect that can arise between adjacent discharge electrodes. It is shown that the OpenFOAM model is capable of accurately quantifying the extent of shielding, and that the degree of shielding is predicted to increase as the spacing between the cylindrical discharge electrodes is decreased. This increase in the degree of shielding consequently resulted in a reduction of the discharge current. The numerical model was also used to quantify the effect of various other ESP parameters on the degree of shielding by studying the space charge density and current density distributions, and the plate-to-plate spacing was found to be the most influential parameter. By incorporating the electrostatic field obtained from the OpenFOAM model in a CFD model based in Star-CCM+®, it is further shown that a decrease in particle collection efficiency is predicted to occur when the shielding intensity increases. Such a systematic study to quantify the extent of shielding and its effect on ESP performance in terms of particle collection efficiency has not received much attention in the literature to date. Predicting the incidence and extent of shielding as a function of geometric ESP parameters are also invaluable to avoid laboratory or pilot scale results that are biased because of the occurrence of shielding.

1. Introduction

Electrostatic precipitators (ESPs) are still widely used for the removal of particulate matter (PM) from industrial gas streams since these units offers advantages such as long service life, low maintenance requirements, excellent reliability, and relatively flexible operation compared to fabric filter units [1]. Increasingly stringent environmental legislation that governs point-source gaseous and PM emissions from industrial stacks necessitates regular upgrading and improvement of the design and operation of emissions abatement units, and particularly that of ESPs. This is specifically significant in developing countries such as India and South Africa, where the costly retrofit of existing ESPs to fabric filter units is undesirable [1]. Since optimally designed and operated ESPs can deliver PM collection efficiencies that are comparable to that which is routinely obtained using fabric filter units, improving existing ESP performance by the implementation of design and process control modifications are more financially attractive. Detailed three-dimensional numerical modeling combined with CFD modeling can be an invaluable tool in this regard, i.e. to study ESP processes and to formulate scalable process models and improvement strategies. Although such numerical models need to be extensively validated against measurements, it can also be applied to gain deeper insight into the underlying principles that govern ESP performance, which is not easily feasible with an empirical approach. Consequently, numerical modeling of ESP processes have gained significant attention during the last few years [2].

To date, numerical modeling studies of ESP processes have mainly focused on the solution of the governing equations involving the complex corona discharge for small laboratory-scale ESPs using methods such as the finite element (FEM)-method of characteristics (MoC) [3,4], the FEM-boundary element method (BEM)-MoC [5], the FEM-charge simulation method (CSM) [6], the FEM-donor cell method (DCM) [7], and the finite difference method (FDM)-MoC [8]. Other CFD studies have focused on modeling the gas flow through multi-plate industrial-scale ESPs to analyze and improve the gas flow distributions through the ESP while neglecting the electrostatic field and particle dynamics [9,10]. Modeling of the electrostatic field along with fluid and particle dynamics has also been performed, but due to the complexity of describing the three interacting fields, such models are typically applied only to single-channel, single discharge electrode ESP systems [11,12],

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or single-channel multi-electrode ESP systems [13]. Additionally, simple cylindrical discharge electrodes (wires) were modeled in the majority of studies, while only a few studies have reported on modeling of the corona discharge produced by more sophisticated discharge electrodes such as simple spike-electrodes [14–16]. Modeling of the particle collection efficiency in single-channel wire-plate ESP systems as a function of parameters such as the discharge electrode voltage, the number of discharge electrodes, and the collection plate spacing have subsequently also been reported along with comparisons between the model predictions [16,17] and the experimental results [17–21].

One way of increasing the particle charging rate and therefore the particle collection efficiency is by increasing the discharge (corona) current (I) achieved under a specific applied discharge electrode voltage (V). This may be accomplished by changing the discharge electrode design [16], or by increasing the number of discharge electrodes per ESP channel. However, when studying the effect of the number of discharge electrodes on particle collection efficiency, Kasdi [21], who reported on the V-I characteristics of single channel, multi-wire electrode ESP systems both experimentally and numerically, found that the discharge current from adjacent discharge wires are suppressed by each another under certain conditions. More specifically, it was found that the current density at the collecting plate surface opposite to the inner discharge wire-electrodes were lower compared to the current density on the collecting plate surface opposite to the outer discharge electrodes [21–23]. The cumulative effect of this phenomenon was a reduction in the total corona current when decreasing the electrode-to-electrode spacing beyond a certain threshold. Al Hamouz et al. [24], and Abdel-Salam and Eid [25] also reported such a loss in the corona current when studying the performance of small-scale wire-plate ESPs as a function of the discharge electrode-to-electrode spacing for wire-electrodes, the wire-electrode radii, and electrode-to-plate spacing using experimental measurements and numerical modeling techniques. Similar to the results of Kasdi [21], the reduction in the current density at the collecting plate surface corresponding to the position of the inner wire-electrode relative to that of the two outer wire-electrodes in the various three-electrode, single channel ESPs studied by Al Hamouz et al. [24], and Abdel-Salam and Eid [25] was also noted. This phenomenon of reduction of the corona discharge current of the inner electrodes in a multi-electrode ESP is colloquially referred to as shielding, and its influence has usually been neglected in most numerical modeling studies. Also, the potential effect that shielding can have on the particle collection efficiency has not yet been described to date.

This paper is aimed at addressing this shortcoming, and therefore a previously validated 3-D numerical model [16] was used to further study the shielding effect that can arise between adjacent electrodes in multi-electrode ESP systems. The ability of the previously published numerical model [16] to accurately describe the current loss under shielding conditions was verified by comparison with the experimental results of Kasdi [21], Long and Yao [13], and Lawless [26]. Consequently, the shielding of adjacent cylindrical wire-electrodes is systematically studied by analyzing the space charge density profiles, the current density profiles, and the V-I characteristics under a varying number of discharge electrodes, varying electrode-electrode spacing, varying plate-to-plate spacing, and varying discharge electrode voltage in a single-channel multi-electrode ESP system. By coupling the results of the electrostatic OpenFOAM® model with a CFD model based in Star-CCM+®, the effect of shielding on the particle trajectories and particle collection efficiency is also analyzed. Although all simulations were performed using 3-D models, only the two-dimensional analyses (at $z = 0$) of the space charge density and current density profiles are presented in this paper, as the profiles did not vary considerably along the length of the wire-electrodes.

2. Numerical modeling and solution methods

The open source code, OpenFOAM® [27], was used to solve the governing equations for the electrostatic field arising due to corona discharge, and the output was imported in the form of user-defined field functions into to the commercial CFD software package STAR-CCM+® [28] that was used to solve the transport equations for the continuous phase, and dispersed phase. Particle charging was also modeled using user-defined functions in Star-CCM+.

The governing equations used for modeling the electrostatic field, the continuous phase fluid dynamics, the particle dynamics, and particle charging as well as boundary conditions are summarized in Table A-1 and Table A-2 of the appendix. A detailed description of the composite model may be found in a previously published paper [16]. To simulate the independent corona discharge of each individual discharge electrode, and thus to describe the shielding effect, the boundary conditions for the electric field and the space charge density were defined for each individual electrode independently. Each discharge electrode was thus defined as an individual boundary. The differentiation between the discharge characteristics of each individual wire-electrode was further achieved by adopting Kaptzov's hypothesis and iteratively adjusting the surface space charge density of each wire-electrode, followed by calculation of the electric field magnitude at each electrode's surface until the values converged (tolerance was set at 0.5%) with the value calculated using Peek's formula (Table A-1). The surface space charge density of each wire-electrode was further assumed to be constant over the wire-electrode surface, which was further subject to the charge conservation criteria.

2.1. Simulated ESP geometries

2.1.1. Validation of numerical model using literature data

The corona current and current density distributions at the collector plate were validated against the published experimental measurement results of Kasdi [21], in which a simple wire-plate ESP system with three cylindrical discharge wire-electrodes was used. In the work of Kasdi [21], the current density distributions at the collecting plate was measured and reported while no gas flow was present, and was used in this paper for comparison with the numerical modeling results. The model results for current density at the collecting plates were further validated against the experimental measurement results of Lawless [26], which also consisted of a wire-plate ESP system without gas flow. Additionally, the numerical modeling results for corona current per unit wire length were also compared with modeling results reported by Long and Yao [13]. In the experimental results reported by Kasdi [21], shielding was shown to be present and was also accounted for in the subsequent numerical modeling, while no mention was made of shielding in the experimental results of Lawless [26], nor in the numerical modeling results presented by Long and Yao [13]. In modeling of the latter two cases in this paper for comparative purposes, shielding was also not taken into consideration. Based on the results reported in this paper regarding the relationship between the degree of shielding and the electrode-to-electrode and plate-to-plate spacing, it is likely that shielding would have been negligible in these two cases. Therefore, for validation of the current model's ability to describe the shielding effect, the results of Kasdi [21] was used, while the results of Lawless [26] and Long and Yao [13] was used to first validate the current model w.r.t. describing the V-I characteristics of multi-electrode ESPs The characteristics of the ESP systems used for these validations and comparisons are summarized in Table 1.

2.1.2. Computational model used for evaluation of shielding

Following the validation of the numerical model using the case studies from literature (Table 1), the effect of various dimensional parameters on the degree of shielding, the current density profiles, and the space charge density profiles were studied using a single-channel