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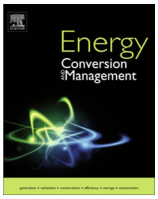

Numerical and experimental evaluation of fly ash collection efficiency in electrostatic precipitators

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ABSTRACT

This paper evaluates experimentally and numerically the influence of different geometrical and operating parameters of a single stage wire-duct electrostatic precipitators (WDEP) on its fly ash collection efficiency. The governing equations are solved under dust loading conditions using the finite element method (FEM) and a modified method of characteristics (MMC). In addition, a proto-type design that represents a WDEP was successfully designed and fabricated at the research institute of KFUPM (RI-KFUPM). The experiments were carried out under laboratory conditions where the WDEP was made of Plexiglas with a length of 2 m, height of 1 m, wire-to-collecting plate spacing of 0.2–0.3 m, and an inter-electrode (wire-to-wire) spacing of 0.16–0.21 m. Smoke of fired coal was used as a source of seed particles of PM10 category (with 75–80% of particles lying below 10 μm). An indication of the effectiveness of the numerical approach was carried out through a comparison of computed results as well as presently and previously obtained experimental data.

1. Introduction

Due to the vast industrial and urban development, which affected positively the standard of life of human beings, enormous types of wastes with tremendous quantities were generated as a side effect of this development. Particulate emissions are definitely among the industrial waste that needs control. Particulate matter is described as dispersed airborne solid and liquid particles that can be distinguished not only on the basis of chemical composition but also with respect to size. It can alone or combined with other pollutants pose serious health hazards. Several systems and processes have been used for the control of particulate emissions. Those include settling chambers, cyclones, filters, wet scrubbers, and electrostatic precipitators (ESPs). All systems share high collection efficiency. Electrostatic precipitators are one of the most promising ways of controlling air pollution caused by industrial plants (smoke, fumes, and dust) [1–5].

The basic principles governing the operation of electrostatic precipitators are relatively straightforward, and hence are well described in the literature and can be found in Robinson [6] and Rose [7]. The most common geometry for an electrostatic precipitator is the wire-duct or wire-plate electrostatic precipitator (WDEP). A wide range of factors determine the performance of electrostatic precipitators. For optimum design of electrostatic precipitators, it is essential to determine the electric field, current density and hence the corona power loss and, finally, the collection efficiency. Theoretical as well as experimental analysis in WDEP has received the attention of several investigators. Many of the models reported depend on numerically solving the main system of equations describing the precipitator geometry with a certain choice of boundary conditions. Many investigators solved the governing equations with no dust loading conditions [8]. For example, Butler et al. [9] interfaced the finite element method and the method of characteristics for solving the electric field and charge density values. Cooperman [10] presents a closed form analytic formula for predicting the current–voltage characteristics. For predicting the electric field and charge density under no dust loading conditions, Davis and Hoburg [11] combined the finite element method and the method of characteristics. On the other hand, Levin and Hoburg [12] used the finite element method and a donor cell method. Elmoursi and Castle [13] used the charge simulation method to model the electrical characteristics of wire-tube electrostatic precipitators. Their study involved the evaluation of the electric field, voltage and charge density distributions in the presence of mild corona quenching. Adamiak [14] predicted the characteristics of a WDEP by combining the method of characteristics and the boundary element method (BEM). Upwind (or downwind) finite difference scheme has been proposed by Lei et al. [15] for the calculation of the three-dimensional distributions of the electric potential and the space charge in a wire-plate electrostatic precipitator. Numerical calculations based on the finite difference method and experimental investigations of gas-particle flows

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involving an electrical field, as they are found in the electrostatic precipitation process, has been reported by Böttner [16]. Under these dust free conditions, simultaneous solution for the governing Poisson's and current continuity equations of WDEP has been made by Rajanikanth and Thirumaran [17] using a combined Boundary Element and Finite Difference Method over a one-quarter section of the precipitator. Anagnostopoulos and Bergeles [18] presented a numerical simulation methodology for the calculation of the electric field in wire-duct precipitation systems using finite differencing in orthogonal curvilinear coordinates to solve the potential equation. Neimarlija et al. [19] used the finite volume discretization of the solution domain as a numerical method for calculating the coupled electric and space-charge density fields in WDEP. An unstructured cell-centered second order finite volume method has been proposed for the computation of the electrical conditions by Long et al. [20]. Khaled and Edein [21] used the finite difference method to simulate electrical conditions of wire plate precipitators under clean air. Rajanikanth and Sarma [22] proposed a model to determine the electrical characteristics of wire plate precipitators. The model has been solved by the finite difference method and the variational principle. Their work tried to optimize the geometric parameters such as shape of corona wires as well as collection plates. Al-Hamouz [23] used a combined FEM and a modified method of characteristics (MMC) to determine the corona current in wire duct ESP without considering the fly ash particles in the governing equations. On the other hand, under dust loading conditions, the equations governing the electrical conditions of cylindrical and wire duct precipitators have been solved using different numerical techniques. Elmorsi and Castle [24] succeeded in the use of the charge simulation method to model the electrical characteristics of cylindrical type electrostatic precipitators in the presence of dust loading. Abdel-Satar and Singer [25] presented a charge simulation numerical method for solving Poisson's equation, the current density equation and the current continuity equation in WDEP considering the effect of particle charge density and taking into account the effect of the variation of ion mobility with the ion position in space. Cristina and Feliziani [26] proposed a procedure for the numerical computation of the electric field and current density distributions in a "dc" electrostatic precipitator in the presence of dust, taking into account the particle-size distribution. Talaie [27] proposed a finite difference model for the prediction of electric field strength distribution and voltage–current characteristic for high-voltage wire-plate configuration. For particle of the size (0.1–0.1 μm), Ohyama et al. [28] proposed a finite difference numerical model for calculation the WDEP efficiency. For a cylinder wire plate electrode configuration, Dumitran et al. [29] estimated the electric field strength and ionic space charge density. Talaie et al. [30] proposed a finite difference procedure to evaluate the voltage current characteristics in WDEP under positive and negative applied voltages. The model took the effect of particle charge into consideration and makes it possible to evaluate the rate of corona sheath radius augmentation as a result of increasing the applied voltage. Long et al. [31] used the unstructured finite volume method to compute the three dimensional distributions of electric field and space charge density. In computing the ionic space charge and electric field of WDEP, Beux et al. [32] proposed a semianalytical procedure, based on the Karhunen–Loeve (KL) decomposition to parameterize the current density field.

A group of experimental studies have been carried out under dust loading conditions. For example, Jedrusik et al. [33] investigated the influence of the physicochemical properties (chemical composition, particle size distribution and resistivity) of the fly ash on the collection efficiency. For this purpose, three electrodes with a difference in design were tested. Miller et al. [34] investigated the impact of different electrode configurations on the WDEP efficiency. Zhuang et al. [35] presented experimental and theoretical studies for the performance of a cylindrical precipitator for the collection of ultra fine particles (0.05–0.5 μm). Recently, Al-Hamouz and El-Hamouz [36] investigated the effect of different operating conditions on the corona current and current density profiles of a WDEP. The collection efficiency was not investigated. Some other researchers used either pulsed energized ESP or included the effect of electrohydrodynamics in their calculations. For example, Buccella [37] determined the electric field, current and charge densities in a pulsed energized ESP. The governing equations were solved using the implicit–explicit finite difference time domain method. On the other hand, Xing et al. [38] had studied the effect of electrohydrodynamic secondary flow on the particle collection of ESP.

All work reported in the abovementioned literature solved the governing equations either under no dust loading conditions and hence the collection efficiency was not considered or with dust loading but with different numerical techniques other than the finite element method. As such, in this paper the performance of a developed finite element based algorithm for the prediction of fly ash collection efficiency of a WDEP is investigated under dust loading conditions while excluding the effect of electrohydrodynamics. In addition, a prototype WDEP which has been fabricated and tested at the RI-KFUPM is also used to validate the proposed algorithm.

2. Mathematical formulation, assumptions and boundary conditions

2.1. Mathematical formulation

Fig. 1 shows a schematic and top view of a wire-duct electrostatic precipitator configuration. When the applied voltage is raised, the gas near the more sharply curved wire electrodes breaks down at a voltage above what is called the onset value and less than the spark breakdown value. This incomplete dielectric breakdown, which is called a monopolar corona, appears in air as a highly active region of glow. The monopolar corona within duct-type precipitators includes only positive or negative ions (the back corona is neglected), the polarity of the ions being the same as the polarity of the high voltage wires in the corona. In these figures, R is the wire (electrode) radius, S is the wire-to-plate spacing, D is the wire to wire spacing and H is the precipitator length.

For this configuration of WDEP, the following system of equations describes the monopolar corona:

$$\nabla \cdot \vec{E} = \rho/\varepsilon_0 \tag{1}$$

$$\nabla \cdot \vec{J} = 0 \tag{2}$$

$$\vec{E} = -\nabla\varphi \tag{3}$$

$$\vec{J} = \vec{J}_{io} + \vec{J}_p \tag{4}$$

$$\vec{J}_{io} = k_{io}\rho_{io}\vec{E} \tag{5}$$

$$\vec{J}_p = k_p\rho_p\vec{E} \tag{6}$$

where $\vec{E}$ is the electric field intensity vector, ρ is the total space charge density (summation of the ion charge density ρ_{io} and particle charge density ρ_p, i.e. $\rho = \rho_{io} + \rho_p$), $\vec{J}$ is the total current density vector, φ is the potential, ε_0 is the permittivity of free space, and k_{io} and k_p are the mobilities for ions and particles, respectively. Eqs. (1)–(6) represent Poisson's equation, the current continuity