Drift velocity of particulates in an electrostatic precipitator: comparison of modelling with experiments

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Abstract

The evaluation of drift velocity of charged particulates in a laboratory scale electrostatic precipitator (ESP) will be discussed. The collection efficiency of an ESP depends on a large number of electrohydrodynamic parameters. The main mass transfer parameter in an ESP is the drift velocity of particulate which is determined by gravitational force, Coulomb force, drag force, inertial force of added mass, and lift force. The calculated migration velocity, using the fundamental motion equations of particles in an electrohydrodynamic field, differs very much from the effective drift velocity obtained experimentally.

In the paper we develop a new concept of drift velocity calculation using the theory of dimensional analysis and the experimental data of collection efficiency in a laboratory scale ESP. As a result we obtained a universal relationship between drift velocity and a proposed ESP similarity number.

Introduction

The electrostatic precipitator (ESP) is a very complex device the performance of which depends on the interaction between a high-strength electric field, a turbulent gas flow field, and the motion of particulates.

The values of the drift velocity of the particulates are very much influenced by the turbulence intensity of the gas flow, especially by the corona-generated turbulence production and generation of secondary flows in the ESP. Studies of ESP performance in industrial conditions show that the drift velocity, which is one of the main factors influencing ESP efficiency, depends essentially on:
What we have enumerated above is not, however, a complete list of the parameters that influence drift velocity.

Up to now several approaches have been attempted for the numerical prediction of drift velocity by means of Monte Carlo simulations of particle motion coupled with CFD prediction of the turbulent electrohydrodynamic flow within the ESP. But the crucial problem of CFD simulations based on Navier-Stokes equations of turbulent flow is that these equations are not closed, which means that the number of unknown parameters is higher than the number of equations. To close the system of equations, additional hypotheses are used which allow some approximation expressions to be formed that relate the averaged and fluctuation velocity fields.

Another possibility for the evaluation of drift velocity is the experimental one. For this reason we performed a large number of ESP tests, varying, among others, the field strength at the edge of the corona, electric current, gas velocity, shape of tube cross section, size of the tube sides, and number of energization edges.

The high-voltage electrodes consisted of round rods fitted with equispaced discharge stars with several ionizing sharp edges. The discharge electrodes are spaced in the center of the test tube with different shapes: round, square and hexagonal, and different geometrical sizes of the tube's cross section, from 6 to 8 inches. The average diameter of the particulates was 0.5 micron.

**Universal Relationship of Drift Velocity in a Tubular ESP**

The analytical technique for the determination of the drift velocity in the ESP tubes is based on the well known theory of dimensional analysis and similarity.

This theory describes the method for reducing the number and complexity of experimental variables which affect the collection phenomenon of charged particles in a high voltage electrical field, using a type of compacting technique. In our case, we have four different dimensions called primary or fundamental dimensions, which govern the collection phenomenon in the ESP:

- Mass, M
- Time, T
- Length, L
- Current, I
The most important benefit of using the theory of dimensional analysis is that we determine the scaling laws which can convert our experimental data from an inexpensive, small ESP model into design information for an expensive, large ESP unit. The validation of the scaling law means that between the model and the real ESP there exists a condition of similarity.

Another benefit of dimensional analysis is that it helps our thinking and planning for a successful experiment or effective theory. It suggests the direction for obtaining important relationships before we waste money on computer time to determine the solution of the problem. We will also obtain insight into the form of physical relationship we are trying to investigate.

The main objective is to replace the number of dimensional variables which describe the drift velocity in ESP performance by one dimensionless parameter.

The method that we used was proposed in 1914 by Buckingham and is now called the Buckingham Pi Theorem.

To find these numbers of similarity we have to form a $\pi$ group as a power product of $n$ variables plus one additional variable which is assigned any convenient nonzero exponent.

We will assume that the ESP performance depends on the following most important dimensional variables:

1. Electrical field strength $E \left( \frac{v}{m} \right) \left[ LMT^{-3} I^{-1} \right]$
2. Current $I(A) \left[ I \right]$
3. Gas velocity $U \left( \frac{m}{s} \right) \left[ LT^{-1} \right]$
4. Gas viscosity $\mu \left( \frac{kg}{m \cdot s} \right) \left[ ML^{-1} T^{-1} \right]$

From these four variables we selected the following three variables with independent dimensions: electrical field strength, current and gas velocity.

According to the Pi Theorem we obtain the nondimensional ESP similarity number

$$N_{ESP} = \frac{EI}{\mu U^2}$$

On the basis of the law of similarity we can affirm that the nondimensional drift velocity $W/U$ for two ESP's with different field strength, currents, sizes, gas velocity, etc. is equal to:

$$(\frac{W}{U}) \text{ is equal to } \left( \frac{W}{U} \right)_{2}$$

when
In the Figure the experimental values of the drift velocity have been plotted against the ESP similarity number \( N_{ESP} = \frac{EI}{\mu U^2} \). All the data was obtained under different test conditions, i.e., varying the field strength at the edge of the corona, the electric current, gas velocity, number of energization sharp edges, the shape and size of the collection tube cross section and the discharge electrode.

It can be seen in Figure 1 that a unique relationship exists between the relative drift velocity of particulates and the discovered ESP similarity number. This unique relationship can be described by the following mathematical expressions:

\[
0 < N \leq 1.6 \times 10^7: \quad \frac{W}{U} = 0.05 \exp (0.91 \log N - 6.15) \quad (4)
\]

\[
N > 1.6 \times 10^7: \quad \frac{W}{U} = 0.122 \log N - 0.804 \quad (5)
\]

Figure 1: Drift velocity versus ESP similarity number.