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Research paper

Numerical simulation of temperature effect on particles behavior via electrostatic precipitators

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HIGHLIGHTS

- Electro-hydrodynamics in wire-plate electrostatic precipitator is modeled with CFD method.
- High temperature weakens the particle charging.
- Increasing temperature will decrease the Coulomb, Saffman lift and Brownian forces and increase the drag force.
- High temperature enhances the interaction between particles and fluid.
- It becomes more difficult to collect particles when temperature increases.

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ABSTRACT

A comprehensive numerical model is developed and applied to study the effect of temperature on the behavior of charged particles in a wire-plate electrostatic precipitator (ESP). In this model, the complex interactions in different temperature conditions between the electric field, fluid dynamics and the particulate flow are taken into account. The finite volume method is used to solve the electric field and Euler-Lagrange model is used to describe particle-laden flows. From the present simulation, the effect of temperature on electro-hydrodynamics (EHD) characteristics and particle charging and tracing are investigated. The numerical results show that high temperature thickens the boundary layer along the plate and strengthens turbulence. The corona onset electric field intensity and mean field intensity both decrease as temperature increases. Considering space charging and diffusion charging, high temperature weakens the particle charging. With the increase of temperature, the Coulomb, Saffman lift and Brownian forces go down while the drag force goes up. The Coulomb force and the drag force are the key forces acting on particles in the ESP for 10 μm particle. The variation of the two forces along with particles trajectories indicates that high temperature enhances the interaction between particles and fluid. Finally, it becomes more difficult to collect particles when temperature increases.

1. Introduction

Particle removal at high temperatures is a technology extensively applied in many processes, such as combined cycle pressurized fluidized combustion (PFBC) and integrated gasification combined cycle (IGCC). High-temperature electrostatic precipitator (ESP) is one of the major industrial devices for gas cleaning to meet the environmental requirements, which is of particular significance in China. Therefore, it's quite necessary to study the effect of temperature on electro-hydrodynamics (EHD) characteristics and particles behavior.

The electrostatic precipitation involves several complicated and interrelated physical mechanisms: creation of a non-uniform electric field and ionic current in a corona discharge, diffusion and field charging of particles moving in combined electro-hydrodynamic fields, and turbulent transport of charged particles to a collection plate [1].

There have been many experimental and numerical studies for classical ESPs at room temperature in past years. But for particle removal at high temperatures with an ESP, the latest experimental data date from the mid-1980s [2,3]. According to the results obtained by Rinard [2], Tassicker [3], Brown and Walker [4] and Audrey [5], it is possible to use an ESP at temperatures up to 1273 K.

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The temperature effect on the ESP's electrical behavior is: when the temperature increases, the ESP working zone decreases. Besides, Naoki and Hisao [6] studied the influence of temperature from 363 K to 623 K on performance of an ESP. They found that collection efficiency decreases with an increase in gas temperature.

Although a large number of numerical analysis studies have been reported in this field, most of the studies operated at room temperature [7–13]. They developed electric field model, gas-particle flow model and particle charging model. In addition, a modified finite element method (FEM) was developed to investigate the vibrations of collecting electrodes by Nowak et al. [14]. Lancereau et al. [15] identified five dimensionless numbers to analysis wire-cylinder electrostatic precipitator under laminar flow conditions. Nouri al [16] studied the effect of the pressure on positive and negative corona discharge behavior in wire-to-plane electrostatic precipitator. Guo et al. [17] developed a full scale ESP model to describe the wire-plate electrostatic precipitator, while discrete element method (DEM) was used to model the cake formation process considering detailed particle-wall and particle–particle interactions.

However, most of the above studies are limited to room temperature or mediate temperature, and the particle behaviors are not clear under high temperature conditions. Thus, the main objective of the current work is to develop a comprehensive model to investigate the effects of wide operating temperature from 293 K to 1273 K on the electro-hydrodynamic characteristics and particles behavior in a wire-plate ESP.

2. Mathematical model

In this work, the description of ESP operation at different temperatures is based upon a theoretical analysis focused on the gas flow, electric field, particle dynamics and particle charging, and each sub-process is separately described by their respective governing equations. The integrated model takes into consideration all the processes involved inside an industrial ESP.

2.1. Gas phase hydrodynamics

Due to the limit of computer capacity, the most effective way for practical computation is to use time-averaged Navier–Stokes equations. For a steady-state turbulent flow, the govern equations can be written as

Conservation of mass:

$$\frac{\partial}{\partial x_k}(\rho u_k) = 0 \tag{1}$$

Conservation of momentum:

$$\frac{\partial}{\partial x_k}\left[\rho u_i u_k - (\mu + \mu_t)\frac{\partial u_i}{\partial x_k}\right] = -\frac{\partial P}{\partial x_i} + f_{Di} + \rho_{ion}E_i \tag{2}$$

Conservation of energy:

$$\frac{\partial}{\partial x_k}(\rho u_k C_p T) = \frac{\partial}{\partial x_k}\left(\lambda_t \frac{\partial T}{\partial x_k}\right) + q_V \tag{3}$$

$$q_v = \frac{\sum_{k=1}^{N_j} \frac{\dot{m}_p^k}{m_p^k} Q_V^k \Delta\tau}{V_c} \tag{4}$$

In the above equations, u_k is the gas velocity component in the x_k direction, μ_t is turbulent dynamic viscosity, f_{Di} is drag force per unit volume. ρ_{ion} is the ion charge density, E_i is the electric strength component. The term $\rho_{ion}E_i$ expresses the ionic wind effect on the gas flow. P and T are the pressure and temperature, respectively. C_p is the specific heat, λ_t is the thermal conductivity. q_v is the volumetric heat source caused by particles. Q_V is the interphase exchange of heat between particle and gas. N_j is the number of particles visiting the control volume, k is the index of particle, $\Delta\tau$ is the particle residence time in the cell, m_p^k is the mass flow rate and V_c is the cell volume.

The gas physical parameters are influenced by temperature. Sub-models are implemented to represent the variation of them with temperature. The density is calculated by the equation of state of ideal gas, while the viscosity is a function of temperature according to Sutherland's three-coefficient law. The ratio of thermal conductivity and specific heat is described as [18]:

$$\frac{\lambda_t}{C_p} = 2.58 \times 10^{-5}\left(\frac{T}{298\ \mathrm{K}}\right)^{0.69}\ \mathrm{kg\ m^{-1}s^{-1}} \tag{5}$$

The specific heat of gas is calculated by CHEMKIN and then the thermal conductivity is available.

2.2. Electric field

In the wire-plate electrostatic precipitators, the electrostatic field and the ion charge density are highly non-uniform and can be described by the following equations.

Poisson equation:

$$\frac{\partial^2 \varphi}{\partial x_k^2} = -\frac{\rho_{ion}}{\varepsilon_0} \tag{6}$$

Current continuity equation:

$$\frac{\partial}{\partial x_k}\left[\rho_{ion}(k_{ion}E_k + u_k) - D_e\frac{\partial \rho_{ion}}{\partial x_k}\right] = 0 \tag{7}$$

$$k_{ion} = 2.1 \times 10^{-4} \Big/ \delta \tag{8}$$

$$\delta = \frac{T_0}{T}\frac{P}{P_0} \tag{9}$$

where φ is the electric potential, ε_0 is the permittivity of free space, k_{ion} is the mobility of ions, E_k is the electric strength in the x_k direction and D_e is the effective diffusivity of ions. δ is the relative density of gas with respect to the normal conditions. $T_0 = 273.15$ K, $P_0 = 101325$ Pa.

The electric field intensity E_i can be defined by a simple relation:

$$E_i = -\frac{\partial \varphi}{\partial x_i} \tag{10}$$

The description of the electric filed and the ion density are implemented by solving scalar transport equations using the finite volume method. The convective flux, diffusion coefficient and source term can be respectively simplified as Table 1, where Φ_k is the scalar of interest, F_i is the convective flux, Γ_k is diffusion coefficient, and S_{Φ_k} is the source terms.

Table 1
Terms of the scalar transport equations.

Equation	Φ_k	F_i	Γ_k	S_{Φ_k}
Electric potential	Φ	0	ε_0	ρ_{ion}
Charge density	ρ_{ion}	u_k	$\varepsilon_0\ D_e$	$-k_{ion}(\varepsilon_0 E_k \partial\rho_{ion}/\partial x_k + \rho_{ion}^2)$