Fuel Processing Technology 143 (2016) 86–99

Contents lists available at ScienceDirect

Fuel Processing Technology

journal homepage: www.elsevier.com/locate/fuproc

Research article

Three-dimensional model of electrostatic precipitators for the estimation of their particle collection efficiency

Jacobo Porteiro *, Rubén Martín, Enrique Granada, David Patiño

E.T.S. Ingenieros Industriales, University of Vigo, Campus Lagoas-Marcosende, 36310 Vigo, Spain

ARTICLE INFO

Article history:
Received 16 June 2015
Received in revised form 15 November 2015
Accepted 17 November 2015
Available online 28 November 2015

Keywords:
CFD
Electrostatic precipitators
Collection efficiency

ABSTRACT

In this work, a computational model for the simulation of electrostatic precipitators' (ESPs) operation was developed. Special attention has been paid to several parameters that greatly influence the voltage–intensity curve, namely: ion mobility, ion diffusion coefficient and roughness of the electrode. Specifically, a reliable value for ion diffusion coefficient is given. The model proposed takes into account the coupling between gas, electric fields, and particle motion. The model is applied to a 3D geometry and validated against the experimental data reported in the literature. The comparison is made through the V–I characteristic, showing that the computed results reproduce quite faithfully those reported experimentally. Once the model is validated, the theoretical distributions of velocity, electric potential and ionic density are obtained; in addition, the theoretical collection efficiency is obtained as a function of particle diameter. The proposed methodology allows for the complete modeling of ESP and the estimation of their performance and may be a very helpful tool in the development of this type of equipment.

Nomenclature

a	Lassen constant = 3 [–]
$\vec{a}$	particle acceleration [m·s^{-2}]
b_{ion}	ion mobility [m^2·V^{-1}·s^{-1}]
$\vec{B}$	magnetic field [T]
C_c	Cunningham correction factor [–]
D_e	ion effective diffusivity/ion diffusion coefficient [m^2·s^{-1}]
D_p	particle diameter [m]
e	electron charge = 1.60217657·10^{-19} [C]
$\vec{E}$	electric field [V·m^{-1}]
E_{Peek}	Peek saturation field value [V·m^{-1}]
f	roughness coefficient [–]
f_h	humidity correction factor [–]
$\vec{F}$	generic term of the forces acting on the fluid [N·m^{-3}]
$\overrightarrow{F_e}$	electric force [N]
$\overrightarrow{F_d}$	drag force [N]
h	enthalpy [J·kg^{-1}]
h_a	absolute humidity [g·m^{-3}]
H	relative humidity [%]
i	Cartesian direction index [–]
$\vec{J}$	current density [A·m^{-2}]
k	Boltzmann constant = 1.3806488 · 10^{-23} [J·K^{-1}]
Kn	Knudsen number [–]
m	particle mass [kg]
$\dot{m}$	particle flux [kg·s^{-1}]
n	particle index [–]
N	number of particles [–]
P	fluid pressure [Pa]
P_0	reference pressure = 101,325 [Pa]
P_w	pressure of the saturated water vapor [Pa]
q	particle charge [C]
q_s	field charging saturation value [C]
q_{fc}	particle charge due to the field charging mechanism [C]
q_{dc}	particle charge due to the diffusion charging mechanism [C]
r_w	wire radius [m]
R	ESP radius [m]
R_g	specific gas constant [J·kg^{-1}·K^{-1}]
S	Sutherland constant [K]
S_h	source term of energy [W·m^{-3}]
t	time [s]
Δt	time increment [s]
T	temperature [K]
T_0	reference temperature = 293 [K]
T_s	reference temperature = 273 [K]
$\vec{u}$	particle velocity [m·s^{-1}]
$\vec{v}$	fluid velocity [m·s^{-1}]
$\overrightarrow{v_{cell}}$	Eulerian velocity of the particles [m·s^{-1}]
v_d	ion drift velocity [m·s^{-1}]
V	electric potential, voltage [V]
V_c	cell volume [m^3]
V_{in}	corona inception voltage [V]

---

* Corresponding author.
E-mail address: porteiro@uvigo.es (J. Porteiro).

http://dx.doi.org/10.1016/j.fuproc.2015.11.010
0378-3820/

Greek symbols

α	alpha coefficient in the Cunningham correction factor [–]
β	beta coefficient in the Cunningham correction factor [–]
γ	gamma coefficient in the Cunningham correction factor [–]
δ	density correction factor [–]
ε_0	permittivity of free space [$\mathrm{F \cdot m^{-1}}$]
ε_r	relative permittivity [–]
η	collection efficiency [%]
μ	fluid viscosity [$\mathrm{kg \cdot m^{-1} \cdot s^{-1}}$]
μ_r	reference fluid viscosity [$\mathrm{kg \cdot m^{-1} \cdot s^{-1}}$]
μ_0	permeability of free space [$\mathrm{N \cdot A^{-2}}$]
ρ	fluid density [$\mathrm{kg \cdot m^{-3}}$]
ρ_c	charge density [$\mathrm{C \cdot m^{-3}}$]
ρ_{ion}	ionic density [$\mathrm{C \cdot m^{-3}}$]
ρ_p	particle charge density [$\mathrm{C \cdot m^{-3}}$]
$\overline{\overline{\tau}}$	stress tensor [$\mathrm{kg \cdot m^{-1} \cdot s^{-2}}$]
ω	under-relaxation factor [–]

1. Introduction

Electrostatic precipitators (ESPs) have been widely used in different industries for a long time. Most of these applications correspond to large-scale designs, such as those found in thermal power plants and other industrial processes. However, recently, small-scale designs are becoming more popular with the increasing knowledge and awareness of particulate matter pollution as well as the implementation of stricter regulations. Thus, many studies are being performed in this field, not only experimentally but also theoretically to adapt the existing models or to develop new ones to accurately simulate these devices.

The simulation of ESPs to predict their collection efficiency generally has two different approaches. On one hand, the simplest approaches are one-dimensional studies based on the Deutsch–Anderson equation or its derivatives [1,2], using a simplified Lagrangian approach for the particles that usually neglects field saturation phenomenon or the presence of current. On the other hand, CFD simulations are more accurate and reliable as an ESP is a device in which several physic phenomena occur; therefore, the coupling between gas, particles and electric magnitudes can be considered as well as the three-dimensional geometry of a real problem [3–7].

As noted by Guo et al. [8], a multi-scale ESP prediction tool that accounts for all of the key phenomena is not available; therefore, ESP design and optimization remain at an empirical level due to insufficient knowledge about the effect and interactions of the different parameters implied in the ESP operation. In this way, engineers still rely on the Deutsch–Anderson equation in ESP design, probably because (despite the fact that some ESP research using CFD simulation has been developed recently) the geometries presented in the literature are still quite simple in concept and can hardly represent a real and industrial geometry.

Different ESP CFD models have been proposed; however, most of them do not account for all the crucial details involved in an ESP operation, and some important parameters used for its modeling are not always given.

Dastoori et al. [3] simulated a 2.5 [m] wire–cylinder ESP, in which some grounded baffles were introduced to study its influence in the collection efficiency, resulting in a positive effect. However, the model proposed does not take into account the effect of pressure and temperature in the gas flow parameters. This incomplete accounting of all parameters' variation is also the case of Skodras et al. [4], who performed a 2D simulation of a small-scale wire–plate ESP with several electrodes, in which special attention was paid to the coupling between particle dynamics and electric field, obtaining satisfying results. Nevertheless, this model does not consider the roughness of the electrode through a coefficient to accurately predict the corona inception point. Following the same line, the roughness was not considered by Moody [5], who simulated several configurations of a small-scale wire–cylinder ESP, in which the ESP collection efficiency as a function of particle diameter was studied. However, the model proposed does not take into account the voltage polarity when applying Peek's formula.

In addition, Farnoosh [6] performed different small-scale wire–plate ESP simulations with several discharge electrode geometries, verifying the reliability of the numerical model with the existing experimental data. Nevertheless, the model proposed does not account for the humidity effect, which is usually neglected when obtaining the saturation field value [4,5].

Besides the physical differences in the different CFD models proposed with regard to the gas flow properties and Peek's formula, the algorithm used for the adjustment of the saturation field on the electrode surface is similar in almost all of the references found. Choi and Fletcher [7] performed a simulation of a wire–plate ESP, in which an iterative process was proposed as a function of electric fields ratio affected by an exponent, which is the current ratio from the preceding two steps. Farnoosh [6] proposed a model using the same electric fields ratio approach, but using a unity exponent in this case.

The ion mobility value to be used is an issue still unresolved or at least under discussion. A fixed value is usually used neglecting the effect of temperature and humidity [9] despite knowing its dependence on these parameters [10]; in fact both temperature and humidity influence has been considered by Guo et al. [11].Moreover, the sign of the charge of the ion is not usually taken into account [3,4,6]. The situation is similar for the ion effective diffusivity. The value of the ion effective diffusivity is not universally agreed upon and is normally not even declared. In some cases, the formula predicted by the kinetic theory [12] is used. However, some references use a reference value based on the argument that turbulence amplifies diffusivity in such a way that kinetic theory predictions are not true and the value proposed for ion diffusivity is several orders of magnitude higher [4].

In this work, special attention has been paid to the precise derivation of the model equations, the selection of the aforementioned parameters and its implementation in a commercial CFD code (ANSYS-Fluent). Different Peek's formulas were used depending on the corona sign, also taking into account the effect of humidity in the saturation field. Additionally, a roughness coefficient was included to account for the fact that real inception voltage values are lower than those predicted in theory. In addition, the influence of temperature in ion mobility is included, and a value of effective ion diffusivity is given. The value is obtained from a simple tuning through a V–I characteristic experimentally obtained, which can be used in the simulation of any geometry, and thus it is supposed to be one of the major contributions of this work. In addition, a methodology is presented to calculate the roughness coefficient through a straightforward test to obtain the corona inception point. The model is checked against the experimental data given in the literature. In summary, a CFD model that accounts for all fundamental nuances of ESP operation was developed; the model is demonstrated to provide reliable results, as shown by comparison with the experimental results.

2. Description of ESP design

The ESP used to test our model was presented by Poskas et al. [13]. As reported, the ESP has three pairs of stainless steel pipes with a diameter of 120 [mm] (each) and a length of 1000 [mm], arranged as shown in Fig. 1, and installed between two holding planes. A nichrome wire of 0.2 [mm] diameter is stretched along the axis of each pipe, separated by 160 [mm] between them. The flue gas is introduced to the ESP by the upper part, and the outlet is located in the lower part in the opposite side. Both the inlet and the outlet have the same diameter of 180 [mm]. The pipes are connected at the top and the bottom with a manifold that links the pipes with the inlet and outlet, respectively.

The ESP was applied to the filtration of particles emitted from a biomass boiler at a flow rate of flue gases of 177 [$\mathrm{m^3}$ N/h], which leads to an average inlet velocity of 1.93 [m/s]. The measured temperature of