A dusty gas approach for electrostatic precipitation of monodisperse aerosols using One-Dimensional Turbulence

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The objective of this work is to present an economical alternative for the simulation of turbulent flows in electrostatic precipitators (ESPs), which does not rely on classical sub-grid scale turbulence models.

Key modeling insights

Unlike in Reynolds-Averaged Navier-Stokes (RANS) or Large Eddy Simulations (LESs), the One-Dimensional Turbulence (ODT) does not require any kind of wall-modeling or sub-grid scale modeling [1]. The model resolves all relevant length scales in a 1-D domain, while modeling the 3-D aspects of the turbulent velocity transport and turbulent pressure transport. The application of ODT in this work considers a monodisperse aerosol with one representative particle modal diameter d_p. Although we do not employ any charging model, we reckon the role of the charge state in the particle mobility coefficient β_p. Thus, we consider some representative particle charge q for the calculation of β_p,

$$\beta_p = \frac{qD_p}{k_B T}. \qquad (1)$$

Here, k_B is the Boltzmann constant, and T is the temperature. The particle diffusion coefficient D_p is obtained by the Stokes-Einstein relation. Air and aerosol are the carrier and disperse phases of densities ρ_g and ρ_p, with velocity fields $\vec{V}_g$ and $\vec{V}_p$, respectively. We use a dusty gas approach [2] with mass averaged velocity $\rho\vec{V} = \rho_g\vec{V}_g + \rho_p\vec{V}_p$, and total density $\rho = \rho_g + \rho_p$. The disperse phase density can be solved by consideration of a convective flux for ρ_p, an electrical drift, and a Fickian mass diffusive flux, simplified for low mass loading and small D_p,

$$\frac{\partial\rho_p}{\partial t} + \nabla\cdot\left(\rho_p\vec{V} + \rho_p\beta_p\vec{E} - D_p\nabla\rho_p\right) = 0. \qquad (2)$$

Air also transports ionic charge due to the effect of a corona discharge in the ESP. The $\rho_{f,i}$ ionic charge density equation, in that sense, is also similar to Eq. (2). However, it is entirely dominated by the drift term. An additional equation for the particle charge density $\rho_{f,p}$ can also be solved, although this is not strictly necessary. In such case,

$\rho_f = \rho_{f,i} + \rho_{f,p}$, and $\rho_{f,p}$ can influence the electric field. We solve a 1-D version of Eq. (2) without the convective flux, together with 1-D equations for momentum and enthalpy (in the form of temperature), using a finite volume method and a Lagrangian ODT formulation. The ODT formulation observes the effect of the electrohydrodynamic (EHD) body force on turbulent transport, see [3].

Results

Figure 1 shows the results for mass-related penetration obtained by the simulations (relative to the bulk particle density $\rho_{p,b}$). The framework successfully represents the drift of the disperse phase, and shows that particle diffusion is negligible, i.e., penetration is negligible at zero EHD body force. Results are shown for two arbitrary values of q, namely, q_e and $8q_e$ (q_e is the elementary charge), which lie below the saturation charge value [4]. It is clear that q greatly influences the penetration.

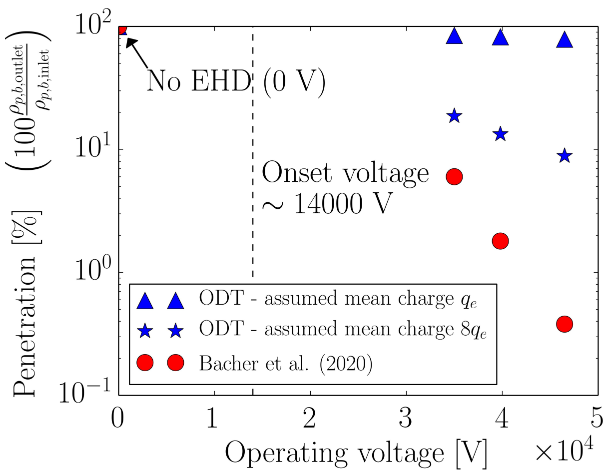

Figure 1: Mass-related penetration results. Experimental results from [5] are shown for comparison

Conclusions

The proposed modeling framework is an appealing 1-D method for the simulation of ESPs which has the potential to yield consistent physical results, given the representation of (turbulent) advective, electrical drift and diffusive fluxes within ODT. Future work should incorporate a charging model, e.g., [4,6], in order to reduce the empiricism associated to the value of β_p in the simulations.

References

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