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# Combined effect of thermophoretic and Coulombic forces on particle deposition in a turbulent flow

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ABSTRACT

In order to further improve the previous results of Chiou et al. [Int. J. Thermal Sci. 50 (2011) 1867–1877] and Chiou et al. [Int. J. Thermal Sci. 49 (2010) 290–301] as provided individually in [1] and [2], especially for the particles with high values of the particle relaxation time $\tau_p^+$, the formulating method proposed previously by Chiou et al. [2] has been modified by introducing the interactions between turbulent transport mechanisms and the persistence of turbulent structures into the present analysis. The close agreement with experimental measurements of the neutral deposition in an isothermal turbulent tube flows over a wide range of particle sizes may be regarded as a supporting evidence for the adequacy of the present formulation. The same method has also been extended to further study the significant role of coupling between thermophoretic and turbophoretic interactions, with particular emphasis on the superposition of external applied electric field onto the nonisothermal turbulent flows. The effects of the Coulombic force on the particle mass flux across the viscous sublayer are specified by the number of charges acquired by diffusion, field and combined charging mechanisms of particles at the saturation charge level. The resulting deviations from the curves calculated under isothermal condition become significant with increased thermal intensity gradient and Prandtl number, even when the external electric field is present. The observed trends of the mean deposition velocity $\overline{v}_d^+$ is useful in stressing that when both the Coulombic and thermophoretic forces operate together, the total is not the sum of these drift mechanisms considered in isolation, and confirming that the particles with high inertia have sufficient wallward momentum to coast across the boundary layer without being influenced strongly by the thermophoretic or Coulombic force.



## 1. Introduction

One particular area concerns accumulation of particles from gaseous suspensions onto cooled or heated solid objects, examples being the pigments, the chemical coating of metals, the removal of particles from a gas stream, the fouling heat exchanger and boiler tubes, and the erosion turbine equipments. There can be distinct advantages in exploiting deposition mechanisms to improve efficiency. In contrast there is an equal number of circumstances where suppression of particle deposition is necessary if the surface is to remain clean. The effects caused by thermal gradient are that gas molecules possess high kinetic energy gained from the region of higher temperature strike the particles and that the molecular bombardment of particles is more energetic on the hot side than on the cold side. Therefore, when a cluster of particles is suspended in a turbulent fluid with non-uniform distribution of temperature, the thermal gradient induces a force to accelerate particles toward the colder region of a fluid, and the force is called thermophoresis. Available evidences have experimentally shown that thermophoresis plays an important role in the migration of small particles for $d_p < 1.0\mu m$ [3–7]. In performing measurements of the thermophoretic effect on particle transfer processes by fluorimetric technique [8], the experimental work was conducted in an annular turbulent flow with fully developed boundary layer. The total mass of monodispersed spherical particles deposited on the inner rod surfaces and collected on the pipe centerline filter is adapted to provide the wall mass flux and the mainstream particle concentration, respectively. The measured deposition velocity is defined as the ratio of the wall mass flux to the pipe centerline concentration. Because of the uranium particles ($d_p = 0.05\mu m$ and $d_p = 0.25\mu m$ in diameter) on the heated surfaces appeared to be reduced by 10%–15% of the corresponding value for unheated surfaces, it was

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**Nomenclature**

| | |
|---|---|
| $c$ | instantaneous particle concentration |
| $C$ | mean particle concentration |
| $c'$ | fluctuating particle concentration |
| $C_c$ | Cunningham slip correction factor |
| $C_m$ | momentum exchange coefficient |
| $C_s$ | thermal slip coefficient |
| $C_t$ | temperature jump coefficient |
| $D_b$ | Brownian diffusion |
| $d_p$ | particle diameter |
| $D_p$ | particle diffusion coefficient |
| $e$ | electronic unit charge |
| $E$ | electric field intensity |
| $e_p$ | dielectric constant |
| $f$ | friction factor |
| $F$ | Coulombic force |
| $F_{th}$ | thermophoretic force |
| $N$ | particle deposition flux |
| $K_e$ | Boltzmann constant |
| $K_g$ | fluid thermal conductivity |
| $K_n$ | Knudsen number |
| $K_p$ | particle thermal conductivity |
| $K_{th}$ | thermophoretic coefficient |
| $N_i$ | ion concentration |
| $n_p$ | maximum saturation charge number |
| $P$ | pressure |
| Pr | Prandtl number |
| $p_\tau$ | statistic distribution for $\tau$ |
| $q$ | total electric charge |
| $r$ | tube radius |
| $r_p$ | particle radius |
| Re | Reynolds number |
| $T$ | mean temperature |
| $u_*$ | friction velocity |
| $v'_f$ | fluctuating fluid velocity in radial direction |
| $v_d$ | particle deposition velocity |
| $V_e$ | electric drift velocity |
| $V_p$ | mean particle velocity |
| $v'_p$ | fluctuating particle velocity |
| $V_{pc}$ | particle convection velocity |
| $v_r$ | particle drift velocity |
| $V_{th}$ | thermophoretic velocity |
| $y$ | distance from wall |

*Greek letters*

| | |
|---|---|
| $\alpha$ | thermal diffusivity |
| $\rho_g$ | fluid density |
| $\rho_p$ | particle density |
| $\nu$ | kinematic viscosity |
| $\mu$ | dynamical viscosity |
| $\sigma$ | shear stress |
| $\varepsilon_t$ | turbulent eddy viscosity |
| $\varepsilon_m$ | turbulent eddy diffusivity |
| $\varepsilon_p$ | particle eddy diffusivity |
| $\lambda$ | mean free path |
| $\tau$ | sublayer growth period |
| $\tau_g$ | integral time scale |
| $\tau_p$ | particle relaxation time |

*Superscripts*

| | |
|---|---|
| $+$ | Dimensionless parameters |
| $\bar{}$ | average with respect to statistic distributions |

*Subscripts*

| | |
|---|---|
| $\infty$ | bulk stream conditions |
| $w$ | wall conditions |

proposed that heating one or two rows of the fixed blades in the last stages of the steam turbine may provide partial solutions to the erosion damage caused by the droplets. A plate-to-plate thermal precipitation system has been adapted to investigate the deposition of agglomerating submicron particles for diesel engine exhaust gas treatment [9]. The measured results revealed that the deposition efficiencies are nearly independent of Knudsen number $K_n$ for particle size range of $34-300nm$, and that a constant thermophoresis coefficient $K_{th}=0.55$ for the free molecular regime ($K_n>>1$) can also be applied for agglomerate soot particles in the transition regime ($K_n\approx 1$).

Goren [10] was the first one to theoretically demonstrate the solid particle deposition onto a cold solid wall in the presence of thermophoretic effect. This was later followed by similarity solutions of two-dimensional boundary layers and stagnation point flows [11,12], and laminar flow in tubes [13,14]. These investigations demonstrated that, when thermal gradients exist close to a surface, the deposition caused by Brownian diffusion can be significantly enhanced or suppressed, depending on the direction of temperature gradient. As can be seen from modeling clusters deposition in the thermal plasma flash evaporation process [15], the concentration boundary layer was found to be significantly suppressed by the thermophoretic force. It was also showed that the thermophoresis will give rise to a uniform deposition efficiency for different cluster sizes ($1-10\ nm$). From a numerical investigation of thermophoretic efficiency at the entrance region of a circular tube [16], it has been found that the deposition efficiency is higher at the entrance region than that of fully developed flow. In a Lagrangian simulation [17], the particle tracking code has been modified to predict the particle deposition in a turbulent boundary layer and extended to include the effect of thermophoresis, while the particle tracking facility in the CFD code uses the eddy lifetime model to simulate turbulent particle dispersion. Furthermore, a Lagrangian stochastic model has been formulated to simulate the dispersion and deposition of submicron particles in nonisothermal turbulent flows [18]. It was concluded that thermophoresis can be considered to arise naturally from the modeling of molecular diffusivity without the need to model explicitly the thermophoretic force, and that the model can be generalized to the prediction of deposition in the presence of large temperature gradients by incorporating the effects of convective turbulent motions. A hybrid Eulerian–Lagrangian procedure was invoked to evaluate the air flow and temperature distribution as well as particles dispersion and deposition [19]. Depending upon temperature gradient, varied degrees of thermophoresis and Brownian diffusion may contribute on the particle deposition, and the relative role of thermophoresis enhances as temperature gradient increases. As a consequence, thermophoresis has the potential to cause enhanced deposition rates for the intermediate sized soot particles that cannot be effectively reached by inertial or Brownian effects.

In an isothermal turbulence flow with fully developed boundary layer, one of the experimental data obtained by Liu and Agarwal [20] is accepted as a most dependable data set. In general, the measured deposition velocities are characterized as the curves of