International Journal of Thermal Sciences 50 (2011) 1867–1877

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

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

Particle deposition with thermal and electrical effects in turbulent flows

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ARTICLE INFO

Article history:
Received 10 March 2010
Received in revised form
30 November 2010
Accepted 20 March 2011
Available online 17 June 2011

Keywords:
Random surface renewal model
Eddy impaction
Particle inertia
Thermophoresis
Analytical equation
Deposition velocity

ABSTRACT

Development of relationships for the particle concentration and convection velocity profile has been obtained by the adaptation of the surface renewal model to the particle continuity and momentum equations of the turbulence boundary-layer flow in the presence of thermal field [1]. The predictions obtained on the basis of this model for nonisothermal deposition velocity of particles have been found to be in good agreement with the experimental measurements for fully-developed turbulence tube flow conditions. The aim of this work is to extend the previous model for an applied electric field, with the inclusion of the effect of Coulombic force in addition to the Brownian and turbulent diffusion, the eddy impaction, the turbophoresis, and the thermophoresis. The calculations show an interaction between thermophoresis and turbophoresis in the presence of an applied electric field. The effect of electric force in nonisothermal flows can have a dramatic effect on thermophoretic deposition for $\tau_p^+ < 0.02$, where turbophoretic effect has ceased. The effect of axial pressure gradient is also included.

1. Introduction

The free-flight model was one of the most used calculation methods for the observed large increase in deposition velocities [2–5]. The fundamental difference between different calculation methods of this model lies in prescribing the initial velocity that the particles possess at the distance where they effectively breaks away from the containing eddies and embarks on a free flight toward the wall. This model yielded reasonable agreement with deposition rate measurements for intermediate relaxation times, but poor agreement at high values. The measured deposition velocities, which are generally accepted as one of most dependable data set, have been found to be changed fairly to a slowly falling value with increasing the particle relaxation time τ_p^+ [6]. The previous paper [7] gave an alternative approach to formulate the thermophoretic velocity and the particle concentration profiles in a nonisothermal turbulence flow with fully-developed boundary layer. The characteristic features of this approach model were based on the consideration that a net particle flux J arises mainly from the Brownian diffusion D_b and thermophoretic force suspended in a flowing fluid,

$$J = -D_b \frac{\partial C}{\partial y} + \upsilon_{th} C, \tag{1}$$

where y is the wall-normal distance and $\partial C/\partial y$ is the wall-normal gradient of mean particle concentration C. The mean thermophoresis velocity υ_{th} depends on the wall-normal gradient in mean fluid temperature. Incorporating the Cunningham correction as shown by Hinds [8]

$$C_c = 1 + \frac{1}{Pd_p}\left[15.6 + 7.0\exp(-0.059Pd_p)\right], \tag{2}$$

the Brownian diffusion D_b for a rarefied gas effect can be calculated by

$$D_b = C_c \frac{K_b T}{3\pi\mu d_p}, \tag{3}$$

where P is the absolute pressure in kPa, d_p the particle diameter in μm, μ the dynamical viscosity, T the absolute temperature, and Boltzmann's constant $K_b = 1.38 \times 10^{-23}$ J/K.

The proposed relationships for the particle concentration distribution and transport coefficient within the average sublayer growth period $\bar{\tau}$ was obtained by adaptation of the surface rejuvenation model [9,10] to the particle continuity equation,

$$\frac{\partial C}{\partial \tau} = \frac{\partial}{\partial y}\left[D_b \frac{\partial C}{\partial y} - C\upsilon_{th}\right], \tag{4}$$

where τ is the residence time between two successive eddies. The calculations of particle transport coefficient $\bar{\upsilon}_d \overline{H}/D_b$ within the average sublayer growth period $\bar{\tau}$ were presented for various values

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1290-0729/$ – see front matter
doi:10.1016/j.ijthermalsci.2011.03.013

Nomenclature

c	mean thermal speed
C	mean particle concentration
C_c	Cunningham slip correction factor
d	tube diameter
D_b	Brownian diffusion
d_p	particle diameter
D_p	particle diffusion coefficient
e	electronic unit charge
E	electric field intensity
e_p	relative permittivity or dielectric constant
f	friction factor
υ'_f	fluctuation fluid velocity in radial direction
υ_d	particle deposition velocity
υ_e	electric drift velocity
υ_p	mean particle velocity
υ'_p	fluctuating particle velocity
υ_{pc}	particle convection velocity
υ_r	particle drift velocity
υ_{th}	thermophoretic velocity
x	distance along wall
y	distance from wall
F	Coulombic force
H	sublayer layer growth thickness
J	particle mass flux
K_b	Boltzmann constant
K_e	proportional constant
K_{th}	thermophoretic coefficient
N_i	ion concentration
n_p	maximum saturation charge number
P	pressure
Pr	Prandtl number
p_τ	statistic distribution for τ
q	total electric charge
r	tube radius
r_p	particle radius
Re	Reynolds number
$\Re_{Lf}(\tau)$	Lagrangian correlation coefficient
t	time
T	mean temperature
u_*	friction velocity

Greek letters

α	thermal diffusivity
ρ_g	fluid density
ρ_p	particle density
ν	kinematic viscosity
μ	dynamical viscosity
ε_t	turbulent eddy viscosity
ε_m	turbulent eddy diffusivity
ε_p	particle eddy diffusivity
λ_p	mean free path
τ	sublayer growth period
τ_g	integral time scale
τ_p	particle relaxation time

Superscripts

$+$	dimensionless parameters
$\_$	average with respect to statistic distributions

Subscripts

∞	bulk stream conditions
w	wall conditions

of $\overline{H}/\sqrt{D_b\overline{\tau}}$ on the basis of the previous analyses by Refs. [11,12]. The behavior of thermophoretic depositions within the average sublayer growth period obtained on the basis of this model is useful in stressing the importance of thermophoretic effect on the deposition processes. The small particles have been found to benefit most from this effect because with their low inertia they tend to follow the flow more closely. The predicted trend of average particle deposition velocities in an isothermal turbulence flow has been found to be in good agreement with both the Harriott technique [11] and the formulation proposed by Ref. [12]. However, because the order of Bessel function has to be a positive integer, the expression of analytical equations obtained by this formulation scheme is limited to the determination of average transport properties in accordance with specified transport parameters. Further, as compared to the measured deposition velocities [6], the validity of this calculation scheme seems to be restricted in an intermediate range of particle relaxation time.

A simple stochastic theory was developed and used in the quantitative predictions for the deposition velocity of higher inertia particles [13]. The calculations of particle motion were based on the free-flight model [15] in which the fluid motion was determined by direct numerical simulation of the Navier–Stokes equations. The Eulerian computational methods of deposition [14,16–19] have been developed by solving both the particle continuity and momentum equations. It was represented a considerable progress in the physical understanding of deposition processes. When the particles with certain range of inertia move against the wall-normal gradient in turbulent fluctuation intensity, they would get trapped into the low turbulence energy regions. The wall-normal component of particle Reynolds stresses in the regions was assumed to play an important role in particle deposition processes. Therefore, the absence of the use of the particle momentum equation in the previous paper [7] is considered to be its major weakness, and so does the free-flight model. Recently, the work of Ref. [1] presented another alternative approach for calculating the deposition velocities in connection with the random surface renewal model [20–24]. Both the particle continuity and momentum equations in a simulate turbulence fluid field were written as

$$\frac{\partial C}{\partial \tau} = -\frac{\partial}{\partial y}(C\upsilon_p) + \frac{\partial}{\partial y}\left(\varepsilon_p \frac{\partial C}{\partial y}\right), \tag{5}$$

$$\frac{\partial \upsilon_p}{\partial \tau} = -\frac{\partial \overline{\upsilon_p'^2}}{\partial y} - \frac{\upsilon_p}{\tau_p} - \frac{D_b}{\tau_p C}\frac{\partial C}{\partial y} + \frac{\upsilon_{th}}{\tau_p}, \tag{6}$$

where υ_p is the mean particle velocity, υ'_p the particle fluctuation velocity, ε_p the particle turbulence diffusivity, and τ_p the particle relaxation time. The key to this analytical approach is that the mean particle velocity υ_p can be simplified as the sum of a diffusive and a convective part, in the manner suggested by Refs. [16,17]. With this simplification, the net particle flux can thus be separated into the diffusive and convective components by defining

$$J = -\left[(D_b + \varepsilon_p)\frac{\partial C}{\partial y} - C\upsilon_{th}\right] + C\upsilon_{pc}. \tag{7}$$

Consequently, the concentration dependent terms of the external forces imposed by the surrounding fluid are shifted from the momentum equation into the mass conservation equation. The unsteady equation for the mass balance of particles in an individual turbulence element approaching to the wall becomes