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Original Research Paper

Thermophoretic deposition of aerosol particles in laminar mixed-convection flow in a channel with two heated built-in square cylinders

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ABSTRACT

The thermophoretic deposition of aerosol particles in laminar mixed-convection flow in a channel with two heated built-in square cylinders was studied numerically. The objective of this research was to study the effect of free convection and the distance between cylinders, on deposition of particles. Continuity, momentum and energy equations were solved to determine the velocity and temperature profiles in the channel. The particle trajectories were evaluated by solving the Lagrangian equation of motion that included the drag, Brownian diffusion and thermophoresis forces. It was found that the temperature gradient near the channel wall, in mixed flow regime, is higher than the temperature gradient in forced convection regime. Increasing the temperature gradient increased the effect of thermophoresis on deposition of particles. It was observed that the deposition was increased with the Richardson number. The distance between cylinders is a parameter that influences the deposition of particles. Temperature gradient decreases with increasing the cylinders' distance; on the other hand, the length of the high temperature gradient zone, which is located in the region between the cylinders where the most deposition occurs, will be increased. These two opposite phenomena cause the fact that at a distance which is four times longer than the cylinders' length, a maximum cumulative deposition fraction occurs. It was eventually concluded that the thermophoresis and the inertial impaction are dominant deposition mechanisms of particles on the channel wall.

1. Introduction

In many engineering applications, deposition of particles from flowing content of aerosol to adjoining surfaces is important. The results of studies on deposition of aerosol onto surfaces have been applied in many engineering fields. Thermophoresis is the main mechanism of particle deposition in a number of systems of practical interest where highly non-isothermal environment exists. Thermophoresis is the term used to explain the phenomenon that causes suspended particles to migrate in the direction of decreasing temperature, when subjected to a temperature gradient in the fluid [1–3]. Examples of this phenomenon include submicron and micron particle depositions onto wafers in the clean room, tobacco smoke or bioaerosol deposits in lungs, and painting or other works of art solid by dust and ash.

In the field of viscous fluids there is a large body of papers dealing with the effect of thermophoresis on particle deposition. We limited ourselves to a short description of the state of the art in the effect of free convection on the particle deposition. Epstein et al. [4] discussed the thermophoresis transport of small particle through a free convection boundary layer adjacent to cold, vertical deposition surface in a viscous and incompressible fluid. Chiou [5] has considered the particle deposition from natural convection boundary layer flow onto an isothermal vertical cylinder. The paper by Jayaraj et al. [6] dealt with thermophoresis in natural convection with variable properties for a laminar flow of a viscous fluid over a cold vertical flat plate. Selim et al. [7] analyzed the effect of surface mass flux on a mixed-convection flow past a heated vertical flat permeable plat with thermophoresis, by considering a nonuniform surface mass flux through the surface. Lin et al. [8] presented a three-dimensional analysis of particle deposition for the modified chemical vapor-deposition (MCVD) process. The results of Line et al. indicate that free convection has a noticeable effect on the overall deposition in the tube. Walsh et al. [9] studied thermophoretic deposition of aerosol particle in laminar tube flow with mixed convection. Their results indicate that more particles deposit at shorter axial distance in downward flow through a vertical pipe than in upward flow.

It is concluded that free convection has important effect on particle deposition. Generally, the combined effects of free and force

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Nomenclature

C_c	Stokes–Cunningham correction factor
C_m, C_s, C_t	constant coefficient
D	distance between cylinders
d	channel width
d_p	diameter of the aerosol particles
F_{th}	thermophoresis force
G_I	Gaussian random number with zero-mean, unit variance
L	length of channel
L_1	distance from inlet to upper cylinder
K	thermophoresis
Kn	Knudsen number
k_f	thermal conductivity of fluid
k_p	thermal conductivity of the particle
$n_i(t)$	Brownian force
Re	Reynolds number
Ri	Richardson number
S	relative density ($\frac{\rho^p}{\rho}$)
T	temperature of fluid
T_{in}	temperature of the hot cylinder
T_∞	reference temperature
T_b	temperature of square cylinders
T_w	wall temperature
u_i	velocity vector of the fluid flow
u_i^p	velocity vector of the aerosol particles
u	x-component of fluid velocity
v	y-component of fluid velocity
W	height of square cylinders

Greek symbols

α	thermal diffusivity
β	coefficient of thermal expansion
σ	Boltzmann constant
λ	mean free path of fluid
μ	dynamic viscosity of fluid
ρ	density of fluid
ρ_p	density of the particle
τ_p	Stokes relaxation time of the particle

convection must be considered when Ri ~1 in which the Richardson number (Ri = Gr/Re^2) is the ratio of the free convection to force convection.

In this study, a two-dimensional mathematical model has been developed to predict the particle deposition from a laminar mixed convection downward flow in a channel with two heated built-in square cylinders. The square cylinders were symmetrically placed in the channel axis to increase temperature gradient for better demonstration of thermophoretic effect on deposition of particles. The objective of this work is to consider the effects of free convection and the distance between cylinders on the cumulative deposition fraction of aerosol particles in downward laminar mixed convection channel flow. Richardson number was assumed to be 5 for a better demonstration of free convection effect. The temperature profile at two specified axial positions in the channel was compared with theoretical work of Habachi and Acharya [10], to evaluate the validity of numerical results. The effects of some major parameters such as distance between cylinders and Richardson number on deposition of particles have been studied.

2. System configuration

Fig. 1 shows the schematic of the computational domain, used in this study. The domain is a duct with length L and width d, containing two square cylinders of width and length W. L_1 and D are the length from inlet to the upper cylinder and the distance between the two cylinders, respectively. Computations were carried out for the flow as well as particle dispersion and deposition around the cylinders. Air flowed with uniform velocity (V_{in}) and temperature (T_{in}) through the channel.

3. Governing equations and solution procedure

The numerical model relies on a typical Eulerian gas flow and Lagrangian particle dispersion formulation. The governing equations of the fluid are those that express the conservation of mass, momentum and energy. The flow is assumed to be steady, laminar and two-dimensional. Radiation has been neglected and therefore the results are applicable for moderate temperature differences. The fluid is assumed to satisfy the Boussineq approximation which relates the temperature to the density by the following equations:

Mass:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \quad (1)$$

X-momentum:

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho}\frac{\partial P}{\partial x}+\nu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) \quad (2)$$

Y-momentum:

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-\frac{1}{\rho}\frac{\partial P}{\partial y}+\nu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+g\beta(T-T_\infty) \quad (3)$$

Energy:

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right) \quad (4)$$

where u and v are the x- and y-component of velocity, ρ is fluid density, p is pressure, ν is the kinematic viscosity of the fluid, β is the coefficient of the thermal expansion for the fluid ($\beta = T_\infty^{-1}$ for ideal gas), T is fluid temperature, T_∞ is the reference fluid temperature, g is the gravitational acceleration vector, and α is thermal diffusivity of the fluid. The boundary conditions are as follows.

$$\begin{cases} 1.\ u(0,y)=u(d,y)=v(0,y)=v(d,y)=u(x,L)=0 \\ 2.\ u(x,0)=0 \\ 3.\ v(x,0)=V_{in} \\ 4.\ \frac{\partial v}{\partial y}(x,L)=0 \\ 5.\ T(0,y)=T(d,y)=T_W \\ 6.\ T(x,0)=T_{in} \\ 7.\ \frac{\partial T}{\partial y}(x,L)=0 \end{cases}$$

The equation of particle dispersion for small heavy rigid spheres with a diameter d_p is given below [11]: