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Eulerian–Lagrangian analysis of solid particle distribution in an internally heated and cooled air-filled cavity

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ABSTRACT

A parametric study has been conducted to investigate particle deposition on solid surfaces during free convection flow in an internally heated and cooled square cavity filled with air. The cavity walls are insulated while several pairs of heaters and coolers (HACs) inside the cavity lead to free convection flow. The HACs are assumed to be isothermal heat source and sinks with temperatures T_h and T_c ($T_h > T_c$). The problem is numerically investigated using the Eulerian–Lagrangian method. Two-dimensional Navier–Stokes and energy equations are solved using finite volume discretization method. Applying the Lagrangian approach, 5000 particles, distributed randomly in the enclosure, were tracked for 150 s. Effects of drag, lift, gravity, buoyancy, pressure gradient, shear stress terms, thermophoresis and Brownian forces on particles movements are considered. Furthermore, effects of various design parameters on the heat transfer rate and deposition of particles such as Rayleigh number ($10^4 \leqslant Ra \leqslant 10^7$) as well as orientation and number of the HACs are investigated. Our simulations indicate that thermophoretic force can significantly affect the distribution of particles of $d_p = 1\ \mu m$ diameter. It is also found that at low Rayleigh numbers the particle distribution is strongly non-uniform. Moreover, it was observed that by increasing number of the HACs and changing orientation of the HACs from vertical to horizontal, deposition rate of the solid particles increases significantly.

1. Introduction

Natural convection fluid flow and heat transfer in enclosed spaces with a heater and/or cooler inside are encountered in a number of industrial applications such as indoor ventilation with radiators, cooling of electrical components, and heat exchangers [1]. From energy saving point of view, improvement of heat transfer in any application of natural convection is a primary and crucial topic. Thus, several investigations can be found concentrating on natural convection [2–7]. Deng [2] studied laminar natural convection in a two dimensional square enclosure with two and three source–sink pairs on the vertical side walls. Park et al. [3] investigated and reported natural convection in a square cavity with two hot inner circular cylinders at different vertical locations. They highlighted that heat transfer rate has a direct relationship with Rayleigh number. Saravanan et al. [6] performed a numerical study of natural convection in a differentially heated square

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Nomenclature

A	dimensionless surface area per depth $A = 2(L + W)$, m
C_c	Cunningham's factor
C_D	drag coefficient
C_m	constant in Eq. (17) (=1.14)
C_p	specific heat, J kg^{-1} K^{-1}
C_s	constant in Eq. (17) (=1.17)
C_t	constant in Eq. (17) (=2.18)
d_p	diameter of the nanoparticle, m
d_{ij}	deformation tensor $= (u_{i,j} + u_{j,i})/2$
$F_{L,i}$	lift force per unit mass in the i direction, ms^{-2}
$F_{Th,i}$	thermophoretic force per unit mass in the i direction, ms^{-2}
F_B	Brownian force per unit mass in the i direction, ms^{-2}
$F_{P,i}$	pressure gradient force per unit mass in the i direction, ms^{-2}
$F_{\mu,i}$	shear stress per unit mass in the i direction, ms^{-2}
g	gravity acceleration, ms^{-2}
G_i	Gaussian random numbers
H	enclosure height, m
L	dimensional height of the heater and cooler, m
K	constant in Eq. (14) (=2.594)
k_B	Boltzmann constant (=1.38 $\times$ 10^{-23})
k	fluid thermal conductivity, Wm^{-1} K^{-1}
k_p	particle thermal conductivity, Wm^{-1} K^{-1}
Kn	Knudsen number (=$2\lambda/d$)
N	number of particles or pairs of the HACs
$\overline{Nu}_i$	average Nusselt number on the walls of ith heater
p	fluid pressure, (Pa), N m^{-2}
Pr	Prandtl number $(= \nu_f/\alpha_f)$
R	universal gas constant, J K^{-1} mol^{-1}
Ra	Rayleigh number $= g\beta_f(T_h - T_c)H^3/\alpha_f\nu_f$
Re_p	relative Reynolds number (=$\rho d_p\lvert u_p - u\rvert/\mu$)
S	relative density (=ρ_p/ρ)
St	Stokes number
T	fluid temperature, K
T_0	reference temperature (=$(T_h + T_c)/2$), K
t	time, s
u, v	dimensional velocity components, ms^{-1}
u_i	fluid velocity in the i direction, ms^{-1}
$u_{p,i}$	particle velocity in the i direction, ms^{-1}
x, y	dimensional Cartesian coordinates, m
X, Y	dimensionless Cartesian coordinates, m

Greek symbols

ρ	density, kg m^{-3}
β	thermal expansion coefficient, K^{-1}
θ	dimensionless temperature
μ	dynamic viscosity, kg m^{-1} s^{-1}
ν	kinematic viscosity, m^{2}s^{-1}
τ	particle relaxation time (Eq. (10)), s
α	thermal diffusivity, m^{2}s
∇	gradient
Δ	delta

Subscripts

c	cold or cooler
f	base fluid
h	hot or heater
i	vector axis indicators
L	lift
p	particle
Th	thermophoresis
B	Brownian