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Particle transport in a small square enclosure in laminar natural convection

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The transport of particles with diameters in the range of 50 nm to 1 μm in laminar free convection of air in square enclosures was numerically investigated by an Eulerian–Lagrangian method. Two-dimensional square enclosures with widths from 2.5 mm to 5 cm, with two adiabatic surfaces and 100 and 200 °C temperature difference between the other two surfaces, were considered. The Rayleigh numbers varied from 100 to 8×10^5. The air flow was simulated in Eulerian frame using a commercial CFD software, whose predictions were compared with published benchmark results. Lagrangian particle transport calculations were carried out by tracking 1000 particles that were initially randomly distributed in the flow field, and assuming one-way coupling between the particles and the carrier gas. Particle motion mechanisms considered included gravity, drag, lift force, thermophoresis and Brownian dispersion.
The results showed that at Rayleigh numbers lower than about 10 000 the entire flow field was dominated by a single recirculation pattern. For these low Rayleigh number cases most of the particles disperse towards the walls, while a fraction of particles were trapped in a quasi-steady recirculation zone. Inside this recirculation zone the particles were at quasi-equilibrium with respect to the hydrodynamic and dispersive forces that acted on them, and left the zone due to Brownian dispersion only at a very low rate. This quasi-equilibrium zone was not observed at the higher Rayleigh numbers where a single recirculation pattern no longer governed the entire flow field. The results also confirmed the important role of thermophoresis and Brownian dispersion, in particular for submicron size particles.

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1. Introduction

The transport of solid particles and liquid droplets in a fluid has long been a subject of great interest. Understanding, measuring, and quantifying the deposition of aerosol on walls is important in various sectors of science and technology. Some examples are the deposition of drugs and harmful substances in the nasal and respiratory tracts in medical science and engineering; deposition of particles and droplets in gas and steam turbines in power plant engineering; the atmospheric dispersal of pollutants and the determination of indoor air quality in environmental science; the transport and sedimentation of various substances in rivers in civil engineering; fouling of process and heat transfer equipments in process industries; and the transport of chemical aerosols in chemical process engineering.

Natural convection heat transfer is importance in many engineering applications, such as solar collectors, environmental engineering and electronic packaging. Considerable attention has been given to the study of natural convection in enclosures that are heated either externally or by internal energy sources. Natural convection induced by external heating is of importance in the

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Nomenclature

A	Constant used in Eq. (12)
B	Constant used in Eq. (13)
C	Cunningham's factor
C_T	thermophoretic coefficient
f	Stokes–Cunningham drag coefficient
F_B	Brownian force (N)
F_{TP}	thermophoresis force (N)
g	gravity m/s^2
G_i	Gaussian random numbers
K	Boltzmann constant (J/K)
K_f	fluid thermal conductivity (W/m K)
K_p	particle thermal conductivity (W/m K)
Kn	Knudsen number
L	shear induced lift force (N)
L_c	characteristic length of enclosure (m)—width is used here
M_G	molecular mass of gas (kg Kmol)
R	universal gas constant (J Kmol K)
Ra	Rayleigh number ($=g\beta(T_h-T_c)W^3/(\nu\alpha)$)
St	Stokes number ($=(\rho_P C d_P^2 U_0)/(18\mu L_c)$)
T	fluid temperature (K)
u_g	local gas velocity (m/s)
u_P	velocity of particle (m/s)
$\vec{U}_P$	particle velocity (m/s)
$\vec{U}_G$	gas velocity at particle's location (m/s)
$\vec{U}_0$	gas velocity far away from the wall (m/s)
V	volume (m^3)
x	position of particle

Greek symbols

β	thermal expansion coefficient (1/K)
Δ	gradient
μ	dynamic viscosity (kg/m s)
ν	kinematic viscosity (m^2/s)
ρ_G	gas density (kg/m^3)
ρ_P	particle density (kg/m^3)

Subscripts

B	Brownian
c	cold
G	gas
h	hot
i	vector axis indicators
P	particle
TP	thermophoresis
x, y	axis indicators

Superscripts

$t+\Delta t$	time step

estimation of heat loss from solar collectors (Buchberg, Catton, & Edwards, 1976) and across double-paned windows (Korpela, Lee, & Drummond, 1982), in the design of energy efficient buildings, and in many other applications. Natural convection driven by volumetric energy sources is of importance for post-accidental heat removal in nuclear reactors (Baker, Faw, & Kulacki, 1976), and geophysical problems associated with the underground storage of nuclear water (Mckenzie, Roberts, & Weiss, 1974).

A comprehensive review of numerical methods for natural convection in rectangular cavities was presented by de Vahl Davis (1986). His results are used as the bench-mark solutions for natural convection in externally heated enclosures. Among more recent investigations, Wang, Mujumdar, and Yap (2006) numerically studied free convective heat transfer for three different nanofluids contained in horizontal and vertical cavities. Their results indicate that considerable heat transfer enhancement is possible with nanofluids. Nanofluids, due to enhanced heat transfer capacity as compared to traditional fluids, provide