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Large Eddy simulations of particulate flows inside a square differentially heated cavity at Rayleigh numbers up to 10^{11}

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ABSTRACT

The Differentially Heated Cavity (DHC) has often served as a suitable geometric model for naturally driven particulate flows inside closed volumes. While providing deep insights of the flow dynamics, 3D DNS or 3D LES simulations of DHC flows are very time-consuming and their potential extension to higher Rayleigh (*Ra*) numbers typical of room dimensions is problematic. In this study, therefore, a 2D-LES Euler-Lagrange approach is used to predict turbulent particle transport in a DHC.
We first validate our predictions against a 2D DNS database at *Ra* 10^9 and 10^{10} with particles having diameters greater than 15 μm. We show that our LES results are in very agreement with the DNS data. In a second step, we extend our simulations to a fully turbulent Ra number 10^{11} and particle diameters between 0.5 and 10 m. Details are provided on the particle deposition locations and airborne concentration decay rate with time. We show in particular that as the flow becomes more turbulent, the particle settling rates approach those predicted by the simple stirred settling model.

1. Introduction

Particle dispersion in turbulent flows is a central issue in many industrial, chemical and environment applications. In the particular case of indoor air quality, the concentration of allergens and pollutant particles is a major concern for a healthy environment. Indoor particles are usually entrained by turbulent naturally driven flows that are caused by heated and cold surfaces [1–10]. How turbulence affects particle deposition rates is of great importance because aerosol depletion limits airborne concentrations.

The natural circulation gas speeds in indoor spaces are several orders of magnitude greater than the settling velocities of typical aerosols (1–10 μm), and therefore the aerosol particles will tend to be entrained by the mean flow, albeit not perfectly. Hence, a rigorous methodology to determine particle-turbulence interactions is needed to get a precise description of the mechanisms driving particles removal.

When particles are entrained in a turbulent naturally driven flow within a cavity, several particle transport mechanisms are competing. While the mean flow will strive to entrain the particles with it, at least two other mechanisms will also be active: on the one hand, gravity will drive particles downward towards horizontal bottom floors, and on the other hand, turbulence will drive particles by turbophoresis to low-turbulence regions, e.g. laminar sublayer regions near the vertical walls. It is therefore not clear whether turbulence will enhance or retard particle deposition.

A typical indoor flow is the naturally driven circulation pattern in a square or cubical cavity in which a differential in temperature is imposed on two opposing vertical walls while other walls are held adiabatic. This flow configuration is known as the Differentially Heated Cavity (DHC) and has been the subject of a great many investigations in recent years, both analytical and experimental. Particle motion in DHC flows has however only been addressed in a few studies.

Le Quéré [11] first presented accurate solutions for 2D laminar DHC flows for Rayleigh (*Ra*) numbers up to 10^8 employing a pseudo-spectral Chebyshev collocation method to solve the Navier–Stokes and energy transport subject to the Boussinesq approximation. Later, *Le* Quéré and Behnia [12] conducted 2D Direct Numerical Simulations (DNS) around the transitional regime up to $Ra = 10^{10}$. They identified the critical Rayleigh number to be at $Ra = 1.8 \times 10^8$.

With the availability of more powerful computer resources, investigators ventured into 3D DHC simulations at ever higher *Ra* numbers. Hence in the recent past, analytical efforts in DHC studies have involved three dimensional DNS [2, 4, 13] and Large Eddy Simulations (LES) [14]. An exhaustive review of free convection in enclosures is provided by [15].

In contrast to flow field simulations, particle transport in DHC flows, especially at high Ra number, has received little attention despite its importance. Akbar et al. [1] have studied particle transport in a small square DHC where the flow was laminar and highlighted the

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Nomenclature

Latin symbols

C	Particles concentration
C_D	Drag coefficient
C_P	Specific heat capacity, J/kg.K
d_P	Particles diameter, m
g	Gravity acceleration, m/s^2
H	Height of cavity, m
k	Turbulent kinetic energy, m^2/s^2
N_P	Number of airborne particles
P	Pressure, Pa
Ra	Rayleigh number
Re_P	Particles Reynolds number
t	Time, s
t^*	Dimensionless time
T	Temperature, K
T_{ref}	Reference temperature, K
u	Vector velocity of fluid, m/s
u_P	Vector velocity of particle, m/s
U_{ts}	Terminal velocity, m/s
U_1, U_2	Dimensional velocity components, m/s
U_1^*, U_2^*	Dimensionless velocity components
V_{ref}	Reference velocity, m/s
x, y	Cartesian coordinates, m
X, Y	Dimensionless Cartesian coordinates

Greeks symbols

α	Thermal diffusivity, m^2/s
β	Thermal expansion, 1/K
κ_P	Particle thermal conductivity, W/mK
μ	Dynamic viscosity, Pa.s
μ_t	SGS turbulent viscosity, Pa.s
ρ_{ref}	Reference density, kg/m^3
ρ	Fluid density, kg/m^3
ρ_P	Particle density, kg/m^3
τ	Reference time, s
τ_P	Particles relaxation time, s
ν	Kinematic viscosity, m^2/s

Notation

LES	Large Eddy Simulation
$(.)_P$	Variable of particles
$\bar{(.)}$	Filtered variable

importance of thermophoresis and Brownian diffusion in the submicron particle range. Recently, Bagheri et al. [5] have considered solid particle transport inside DHC in laminar flows up to Ra of 10^8. The particles had diameters ranging from 10 nm up to 10 μm. The authors described the dependency of particle deposition on the particle diameter as well as the Ra number and evaluated the importance of the various forces in different conditions.

In turbulent flows, Puragliesi et al. [4] have performed 2D DNS with Lagrangian particle tracking inside a square DHC at Ra 10^9 and 10^{10}. In their numerical investigations, they took into account drag, gravity, buoyancy, lift and thermophoresis forces on the particles trajectory. Puragliesi et al. [4] showed that the large inertia particles (15–35 μm) tend to deposit essentially on the bottom wall due to gravitational settling, but a strong recirculating zone, which lifts off and segregates the particles, contributes to decrease the settling rate. The influence of the lift and thermophoretic forces was found to be negligible.

A similar Euler-Lagrange work using the LES methodology was conducted by Bosshard et al. [14]. In both of the above-mentioned investigations, only particles with aerodynamic diameters larger than 10 μm were considered, which is rather restrictive as indoor particles are typically in the micrometer range. Most recently, Dehbi et al. [10] have conducted LES of particulate flows in a realistic 3D DHC at Rayleigh number of 109 and showed very good agreement with the experimental removal rates [9] of particles in the micrometer range. The authors concluded that small particles in the DHC are removed much more rapidly than predicted by the simple stirred settling model [16].

A parametric Euler/Lagrange CFD study has been performed by Garoosi et al. [8] to determine solid particle distribution inside an insulated cavity containing several pairs of heaters and coolers at different positions, orientations and sizes. Their studies indicate that particle distribution and deposition depend strongly on the Rayleigh number.

While providing deep insights of the particulate flow dynamics, 3D simulations are very time-consuming and their potential extension to higher Ra numbers is severely limited by current CPU resources.

In this study, we therefore employ 2D Large Eddy Simulation (LES) to study particle removal using an Euler-Lagrange procedure up to Ra 10^{11}. As a first step, we validate the methodology by comparing results against the 2D DNS database [4] at Ra 10^9 and 10^{10}.

The rationale for using the 2D approach is that previous DNS studies [2] have shown that 2D and 3D treatments of the flows inside the DHC give essentially the same predictions for the mean flow in the center plane, although there are slight differences in the Reynolds stresses near the cavity corners. Thus, particle dynamics results of the 2D simulations are expected to give reasonably accurate predictions of particle depletion in 3D at a fraction of the computational expense.

2. LES modeling of the turbulent flow in a square cavity

2.1. Computational problem set-up

The conceptual 2D square DHC is shown Fig. 1. In this set-up, the two opposite vertical walls are kept isothermal at different temperatures while other walls are adiabatic. A no-slip boundary condition is imposed on all cavity walls. The working fluid is air and it is assumed incompressible and Newtonian with constant properties computed at a reference temperature. The temperature difference ΔT is small enough to allow the use of the Boussinesq approximation [17]. In the Boussinesq

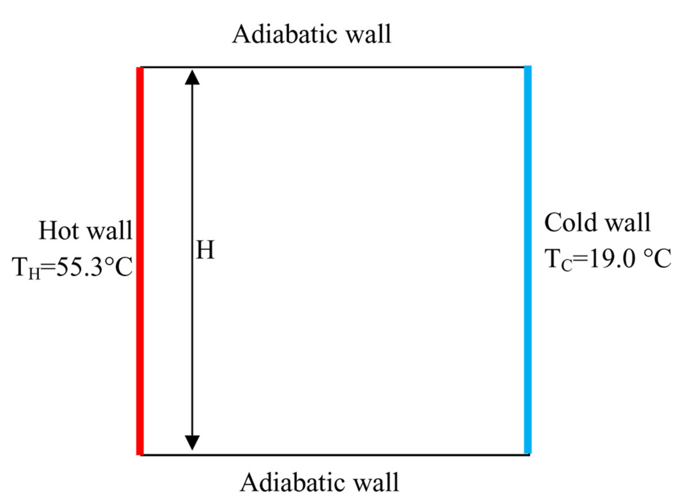

Fig. 1. Schematic of the differentially heated square cavity.