Turbulent Thermal Convection Driven by Heat-Releasing Particles

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Abstract. Thermal convection driven by heat-releasing particles in a quasi-3D cavity has been investigated through four-way coupled Euler-Lagrange direct numerical simulations. To examine the effects of thermal buoyancy and particle inertia, the Rayleigh-Robert number and density ratio are chosen in the range of $4.97 \times 10^5 \leq Rr \leq 4.97 \times 10^8$ and $1 \leq \rho_p/\rho_f \leq 250$, respectively, and the Prandtl number $Pr = 1$. Compared to the convection driven by uniform internal heating, it is found that the particles of small inertia ($\rho_p/\rho_f = 1$) have a weak effect on enhancing convective heat transfer as Rr increases. The ensemble-averaged temperature is highly dependent on the spatial distribution of particles. For higher inertia ($\rho_p/\rho_f \geq 10$), the particles are expelled away from the vortex core by the centrifugal force originating in the particle-vortex interaction. It results in the preferential accumulation of particles commonly at the vortex edges and, consequently, a highly non-uniform distribution of heat sources. Of interest, the occurrence of preferential accumulation may suppress or promote the heat escaping through the walls, namely, redistributing the heat flux on the top and bottom walls.

Keywords: particle-laden flow · Heat-releasing particles · thermal convection

1 Introduction

Particle-laden thermal flow can be commonly encountered in various natural and engineering applications, such as volcanic ash clouds spreading into the atmosphere [1] and solar receivers that utilize particle-laden molten salt as a medium to absorb solar heat [2], etc. A distinctive feature of these flow systems is the coupling of momentum and heat between the carrier phase and the dispersed phase, which spans multiple scales. In addition, the fluid motions are affected by the heat sources from particles, which brings a flurry of interesting phenomena and daunting challenges.

The physical model that buoyancy convection driven by the radiative heating of particles has gradually gained attention in recent years [3–7]. In this model, the fluid motions are driven by the heat sources from particles, so the temperature fields around particles are completely different from the isothermal particles in thermal flow. Zamansky [8,9] numerically studied turbulent thermal convection driven by particle heat

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release in a three-period square cavity and analyzed the dependence of velocity and temperature on Stokes Number (St). Pan [3] and Yang [5,6,10] investigated the Rayleigh-Bérnard convection (RBC) with heat-releasing particles and they focused on the effect of different particle sizes on the boundary layer thickness and Nusselt number (Nu). The most recent work of Du [4] conducted the wall-bounded thermal turbulent convection driven by heat-releasing inertial particles with two-way thermal coupling and one-way momentum coupling. The mechanism of particle concentration at the wall is discovered and scaled.

The work mentioned above is mainly conducted by two-way or even one-way coupling, which is valid for dilute ($10^{-6} \leq \Phi_v \leq 10^{-3}$) or dusty ($\Phi_v \leq 10^{-6}$) flow, where Φ_v is the volume fraction of particles. However, the two-way coupled simulation of particle-laden flow initially lying in the dilute dispersion regime is likely to fail due to the extreme local accumulation of particles. When the dispersed phase is dense as $\Phi_v \geq 10^{-3}$, the interaction between particles, including collision, heat conduction, agglomeration, and breakup, is important, and only four-way coupling can characterize these flows properly.

In this work, thermal convection driven by heat-releasing particles in a quasi-3D cavity has been investigated through four-way coupled Euler-Lagrangian direct numerical simulations. It is found that flow motions and heat transfer processes are highly dependent on the spatial distribution of particles. Moreover, the centrifugal force originating in the inertia and particle-vortex interaction results in the preferential accumulation of particles and, consequently, a highly non-uniform distribution of heat sources.

2 Problem Set-Up and Governing Equations

As Fig. 1 illustrates, a square cavity with a height of H and width of W is placed vertically, in which a layer of particle-laden fluid is filled. The width of the square cavity is small compared to the height and large compared to the particle diameter, namely $d \ll W \ll H$, where d is the particle diameter. In this model, we assume that the velocity of fluid in z-direction is small so that can be neglected. The flow characteristic tends to be 2D and the particle feature is still 3D.

No-slip and no-penetration boundary conditions are adopted for all four walls. The side walls are thermal insulation, while the top and bottom walls keep a constant temperature T_0. In the initial state, the temperature of the particles and fluid is T_0, and particles are randomly distributed in the square cavity. Particles raise their temperature by absorbing external radiation. With the Oberbeck-Boussinesq approximation, the fluid density is simply assumed to be linearly dependent on temperature, namely $\rho = \rho_f[1-\beta(T-T_0)]$, where ρ_f and β are the fluid density and thermal expansion coefficient at reference temperature T_0, respectively. The particle diameter is assumed to be smaller than the Kolmogorov scale. The dimensionless governing equations can be readily obtained as

$$\nabla \cdot \boldsymbol{u} = 0 \tag{1a}$$

$$\partial_t \boldsymbol{u} + \nabla \cdot (\boldsymbol{u}\boldsymbol{u}) + \nabla p = Pr^{1/2} Rr^{-1/2} \nabla \cdot (\nabla \boldsymbol{u}) + T\boldsymbol{e}_y + \boldsymbol{F}_p \tag{1b}$$

$$\partial_t T + \nabla(\boldsymbol{u}T) = Pr^{-1/2} Rr^{-1/2} \nabla \cdot (\nabla T) + Q_p + Q_f^o \tag{1c}$$

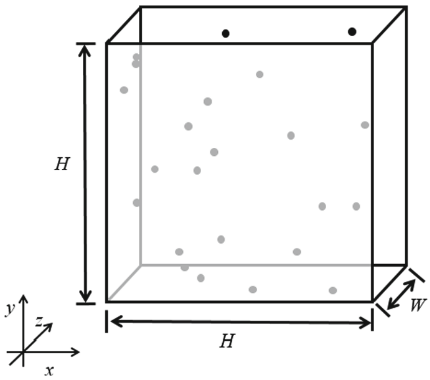

Fig. 1. The configuration of the convection driven by heat-releasing particles.

$$\frac{\mathrm{d}\boldsymbol{v}_i}{\mathrm{d}t} = \sum_j \boldsymbol{F}_{ij}^c + \frac{C_d Re_p}{St_p}(\boldsymbol{u}_i - \boldsymbol{v}_i) \tag{1d}$$

$$\frac{\mathrm{d}T_i}{\mathrm{d}t} = \sum_j Q_{ij}^c + \frac{Nu_p}{St_\theta}(T_{fi} - T_i) + Q_i^o \tag{1e}$$

which are nondimensionalized by the characteristic scales

$$T_{ref}^* = \frac{H^{*2} Q_f^{o*}}{8\kappa\rho_0 C_{pf}^*} \tag{2a}$$

$$\boldsymbol{u}_{ref}^* = \sqrt{g^* \beta T_{ref}^* H^*} \tag{2b}$$

$$\tau_{ref}^* = \frac{H^*}{\sqrt{g^* \beta T_{ref}^* H^*}} \tag{2c}$$

$$H_{ref}^* = H^* \tag{2d}$$

Superscript $(\cdot)^*$ emphasize that the physical quantities and operators are dimensional. $\boldsymbol{u}$, p, T, ν, κ are the velocity vector, pressure, temperature, kinematic viscosity, and thermal diffusivity of the carrier phase, respectively. $\boldsymbol{g}$ is the gravitational acceleration vector that points in the negative direction of the y-axis. $\boldsymbol{F}_p$ and Q_p represent the momentum and heat exchange rate between fluid and particles. Q_f^o is the heat flux that the fluid absorbs from external sources. $\boldsymbol{v}_i$, and T_i are the velocity vector and temperature of the i-th particle, $\boldsymbol{F}_{ij}^c$ and Q_{ij}^c are the contact force and heat conduction flux between the i-th and j-th particle or j-th particle and wall when they come into contact. Q_i^o is the power of external energy absorbed by the i-th particle. For simplification, we assume that all particles have the same physical properties, including Q_i^o. The particle Reynolds number Re_p is defined as $Re_p = \rho_f d_p |\boldsymbol{u}_i - \boldsymbol{v}_i| / \mu_f$.

The key parameters include the Prandtl number Pr, the Rayleigh-Robert number Rr, the momentum Stokes number St_p, the thermal Stokes number St_θ, which are defined respectively as

$$Pr = \frac{\nu}{\kappa}, \quad Rr = \frac{g\beta T_r ef H^3}{\nu\kappa}, \quad St_p = \frac{\tau_p}{\tau_f}, \quad St_\theta = \frac{\tau_\theta}{\tau_f}, \quad n_p = \frac{NH}{W} \tag{3}$$

where $\tau_p = \rho_p d^2/18\rho_0\nu$ is the momentum relaxation time and $\tau_\theta = d^2\rho_p C_{pp}/\kappa\rho_0 C_{pf}$ the thermal relaxation time. St_p and St_θ are the ratio of particle momentum and thermal relaxation time to flow characteristic time $\tau_f = \tau^*_{ref}$, respectively. Due to the influence of particles on τ_f, here we use density ratio ρ_p/ρ_f to represent the strength of inertial effect of particle. n_p indicates the number of particles per unit volume. The definition of Rr has the same form as that in RBC, and represents the strength of buoyancy.

The discrete element method (DEM) is adopted to calculate the motion and temperature of each individual particle separately. The soft-particle approach is adopted here to model the complex interactions between particles, namely $\boldsymbol{F}^c_{ij}$ and Q^c_{ij} [11]. In such an approach, the particles are permitted to suffer minute deformations, and the elastic, plastic, and frictional forces, as well as the heat flux between particles, can be modeled. The drag coefficient C_d and Nusselt number Nu_p are calculated by semi-theoretical and semi-empirical model [12, 13].

The CFD-DEM method we adopted, as well as the consideration of four-way coupling between particles and fluid, is able to guarantee the accuracy of numerical results at higher particle volume fractions ($\Phi_v \leq 0.1$). Therefore, it is more reliable for the simulation of particle-laden flows with high local aggregation.

3 Results Discussion

The parameters covered by the present simulations are shown in Fig. 2, the Prandtl number is fixed at $Pr = 0.7$, and the thermal Stokes number is $St_\theta \ll 1$. All the above simulations have reached the statistically steady state, and the flow duration exceeds $1260\tau_f$ and increase to approximately $9960\tau_f$ as Rr increase.

According to the study of Wang [14], the $\langle T \rangle$ exhibit a $-1/5$ power relationship to Rr, where $\langle \cdot \rangle$ is the ensemble average, namely the temporal and spatial average. Figure 3(a) show the effect of n_p and Rr on $\langle T \rangle$ under the same density ratio $\rho_p/\rho_f = 1$. And $n_p = 0$ represents the reference case that convection is driven by uniform internal

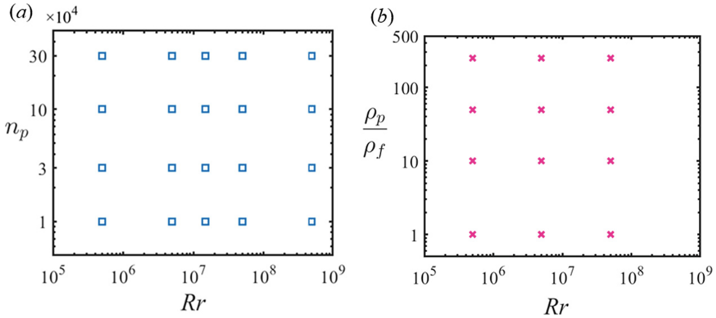

Fig. 2. The parameter space in the $Rr - n_p$ plane (a) and $Rr - \rho_p/\rho_f$ plane (b).

heating that heat sources are from the fluid directly. It is found that the power relationship does not change in particle-driven thermal convection, which indicates the inherent unity between these flows. The particles with small inertia ($\rho_p/\rho_f = 1$) have a weak effect on the global average temperature $\langle T\rangle$. However, as the inertia of particles increases, the average temperature $\langle T\rangle$ decrease and the decrease becomes more significant at higher Rr.

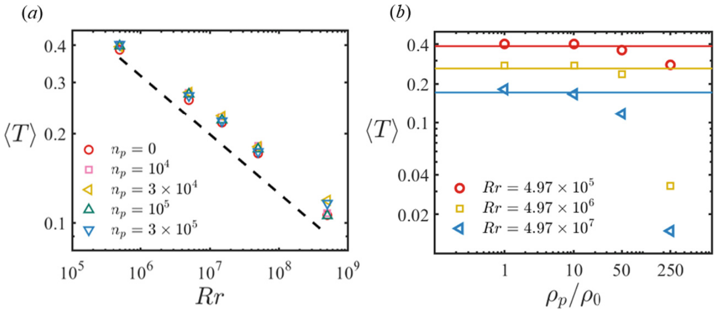

Fig. 3. The global average temperature with $\rho_p/\rho_f = 1$, different (n_p, Rr) (a) and with $n_p = 10^4$, different $(\rho_p/\rho_f, Rr)$ (b). The dashed line has a slope of $-1/5$, and the solid line represents the value of internal heating convection at the corresponding Rr. The internal heating convection can be regarded as convection induced by a large number of heat-releasing particles that are uniformly distributed and have no momentum coupling with the fluid

For the current particle-laden flow, the heat generated by the particles will eventually escape through the top and bottom walls. To separate the contributions of different mechanisms to heat transfer, we take a temporal and spatial average of the Eq. (1c) at the statistically steady state, and then we have

$$\langle wT\rangle = -Pr^{-1/2}Rr^{1/2}\frac{\mathrm{d}\overline{T}}{\mathrm{d}z}\bigg|_{z=0} + \int_0^1\int_0^z \overline{Q_p}dz'dz \tag{4}$$

It can be considered that the heat transport due to convection $q_{conv} = \langle wT\rangle$ and the nonuniform distribution of particles $q_{part} = 1 - \int_0^1\int_0^z \overline{Q_p}dz'dz$ determines the heat flux $q_b = Pr^{-1/2}Rr^{1/2}\frac{\mathrm{d}\overline{T}}{\mathrm{d}z}\Big|_{z=0}$ on the bottom wall. So we can rewrite the Eq. (4) as $q_b = 1 - q_{part} - q_{conv}$. Note that $q_{part} = 1/2$ when particles are uniformly distributed in the cavity, and local accumulation of particles may cause q_b to deviate from this equilibrium value $1/2$. Thus q_{part} can reflect the spatial distribution tendency of particles.

As Fig. 4(a) illustrates, the particles of small inertia ($\rho_p/\rho_f = 1$) enhance convective heat transfer as Rr increases, which is consistent with the findings of Kuerten [15], while the enhancement becomes weaker as n_p increases. This enhancement originates from the temperature gradient around the heat-releasing particles, which effectively promotes the mixing of heat. The number density n_p may play a key role in the transfer of the particles, which consequently affects heat source distribution. As shown in Fig. 4(b),

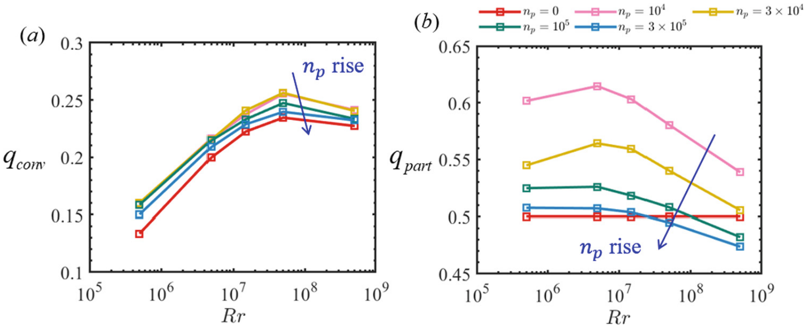

Fig. 4. The variations of the q_{conv} (a) and q_{part} (b) with increasing Rr, n_p for fixed $\rho_p/\rho_f = 1$

when the Rr increases, q_{part} drops more slowly at higher n_p. q_{part} decreases to less than $1/2$ implying that the region where particles tend to stay is shifted from $z > 1/2$ to $z > 1/2$.

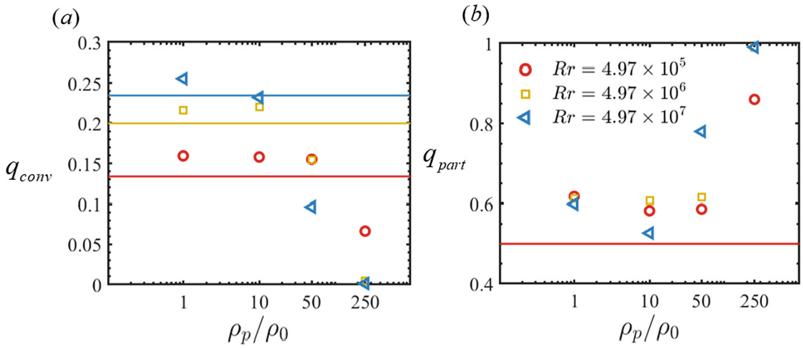

Fig. 5. The variations of the q_{conv} (a) and q_{part} (b) with increasing Rr, ρ_p/ρ_f for fixed $n_p = 10^4$. The solid line represents the value of single-phase internal heating convection at the corresponding Rr

However, as the density ratio ρ_p/ρ_f increases, q_{conv} decreases rapidly until it approaches 0, q_{part} increases dramatically and closes to 1 at $\rho_p/\rho_f = 250$ as Fig. 5(a) and (b) shows. It can be seen that the inertia of the particles plays a crucial role in the current particle-laden flow. The fundamental causes lie in the coupling of momentum and heat between the two phases. Thus, the spatial distribution characteristics of the particles have a drastic effect on the flow. The inertia of the particle, meanwhile, dominates the particle transfer process. As Fig. 6 illustrates, the particles with a small density have no significant preference to be distributed in the square cavity. However, as the density ratio increases, the particles are expelled away from the vortex core by the centrifugal force originating in the particle-vortex interaction, which leads to almost all particles accumulating near the wall. Once most of the heat is released near the walls, it is difficult for the heat-releasing particles to drive convection.

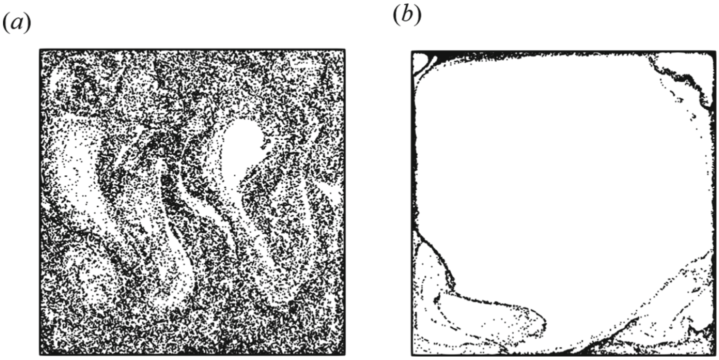

Fig. 6. Instantaneous distribution of particles after reaching a statistically steady state with $Rr = 4.97 \times 10^8$, $n_p = 10^5$ and $(a) : \rho_p/\rho_f = 1$, $(b) : \rho_p/\rho_f = 250$

4 Conclusion

In this paper, four-way coupled Euler-Lagrange direct numerical simulations have been conducted for thermal convection driven by heat-releasing particles in a quasi-3D cavity. The effects of density ratio ρ_p/ρ_f and number density n_p on the heat transfer process at different Rr are focused on. The results show that the heat-releasing particle-driven convection is highly similar to the uniform internal heating convection at small density ratios $\rho_p/\rho_f = 1$, and particles enhance convective heat transfer to a certain extent. However, at high-density ratios $\rho_p/\rho_f = 250$, the flow motion is critically dependent on the distribution properties of the particles. As a result of the inertial mechanism, the heavy particles will concentrate near the wall, eventually leading to extremely weak or even no convection.

References

1. Lube, G., Breard, E.C., Esposti-Ongaro, T., Dufek, J., Brand, B.: Multiphase flow behaviour and hazard prediction of pyroclastic density currents. Nat. Rev. Earth Environ. **1**(7), 348–365 (2020)
2. Pouransari, H., Mani, A.: Effects of preferential concentration on heat transfer in particle-based solar receivers. J. Solar Energy Eng. **139**(2) (2017)
3. Pan, M., Dong, Y., Zhou, Q., Shen, L.: Flow modulation and heat transport of radiatively heated particles settling in Rayleigh-bénard convection. Comput. Fluids **241**, 105454 (2022)
4. Du, Y., Yang, Y.: Wall-bounded thermal turbulent convection driven by heat-releasing point particles. J. Fluid Mech. **953**, A41 (2022)
5. Yang, W., Zhang, Y.-Z., Wang, B.-F., Dong, Y., Zhou, Q.: Dynamic coupling between carrier and dispersed phases in Rayleigh-bénard convection laden with inertial isothermal particles. J. Fluid Mech. **930**, A24 (2022)
6. Yang, W., Wan, Z.-H., Zhou, Q., Dong, Y.: On the energy transport and heat transfer efficiency in radiatively heated particle-laden Rayleigh-bénard convection. J. Fluid Mech. **953**, A35 (2022)

7. Rahmani, M., Geraci, G., Iaccarino, G., Mani, A.: Effects of particle polydispersity on radiative heat transfer in particle-laden turbulent flows. Int. J. Multiph. Flow **104**, 42–59 (2018)
8. Zamansky, R., Coletti, F., Massot, M., Mani, A.: Radiation induces turbulence in particle-laden fluids. Phys. Fluids **26**(7), 071701 (2014)
9. Zamansky, R., Coletti, F., Massot, M., Mani, A.: Turbulent thermal convection driven by heated inertial particles. J. Fluid Mech. **809**, 390–437 (2016)
10. Yang, W., Wang, B.-F., Tang, S., Zhou, Q., Dong, Y.: Transport modes of inertial particles and their effects on flow structures and heat transfer in Rayleigh-bénard convection. Phys. Fluids **34**(4), 043309 (2022)
11. Di Renzo, A., Di Maio, F.P.: Comparison of contact-force models for the simulation of collisions in DEM-based granular flow codes. Chem. Eng. Sci. **59**(3), 525–541 (2004)
12. Li, J., Mason, D.: A computational investigation of transient heat transfer in pneumatic transport of granular particles. Powder Technol. **112**(3), 273–282 (2000)
13. Zhu, H., Zhou, Z.Y., Yang, R., Yu, A.: Discrete particle simulation of particulate systems: theoretical developments. Chem. Eng. Sci. **62**(13), 3378–3396 (2007)
14. Wang, Q., Lohse, D., Shishkina, O.: Scaling in internally heated convection: a unifying theory. Geophys. Res. Lett. **48**(4), e2020GL091198 (2021)
15. Kuerten, J.G., Van der Geld, C., Geurts, B.J.: Turbulence modification and heat transfer enhancement by inertial particles in turbulent channel flow. Phys. Fluids **23**(12), 123301 (2011)