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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 $(10^4 \le Ra \le 10^7)$ 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 $d_n = 1 \mu m$ 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.

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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

$\begin{array}{llllllllllllllllllllllllllllllllllll$	Α	dimensionless surface area per depth $A = 2(L + W)$, m	
	C_c	Cunningham's factor	
$\begin{array}{llllllllllllllllllllllllllllllllllll$	C_D	drag coefficient	
	C_m	constant in Eq. (17) (=1.14)	
C _s constant in Eq. (17) (=1.17) C _t constant in Eq. (17) (=2.18) d _p diameter of the nanoparticle, m d _{jj} deformation tensor = (u _{ij} + u _{jj})/2 F _{Li} lift force per unit mass in the <i>i</i> direction, ms ⁻² F _B Brownian force per unit mass in the <i>i</i> direction, ms ⁻² F _B Brownian force per unit mass in the <i>i</i> direction, ms ⁻² F _B Brownian force per unit mass in the <i>i</i> direction, ms ⁻² F _{ji} shear stress per unit mass in the <i>i</i> direction, ms ⁻² G aussian 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 × 10 ⁻²³) k fluid thermal conductivity, Wm ⁻¹ K ⁻¹ kn Knudsen number (=2 λ/d) N number of particles or pairs of the HACs Nu _i average Nusselt number on the walls of <i>i</i> th heater p fluid pressure, (Pa), N m ⁻² Pr Prandtl number (= ν_f/α_f) R universal gas constant, J K ⁻¹ mol ⁻¹ Ra Rayleigh number = $g\beta_f(T_h - T_c)H^3/\alpha_f v_f$ Re _p relative Reynolds number (= $n_p/a_{\mu_j} - u_{\parallel/\mu}$) S tokes 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 _j fluid velocity in the <i>i</i> direction, ms ⁻¹ x, y dimensional cartesian coordinates, m X, Y dimensional cartesian coordinates, m X, Y dimensional cartesian coordinates, m Greek symbols ρ density, kg m ⁻³ β thermal diffusivity, m ² s ⁻¹ Y kinematic viscosity, kg m ⁻¹ s ⁻¹ Y kinematic viscosity, m ² s ⁻¹ Y dimensional diffusivity, m ² s ∇ gradient A delta Subscripts c cold or cooler f base fluid h hot or heater <i>i</i> vector axis indicators L lift p particle Th thermophoresis B movnian	C_p	specific heat, J kg ⁻¹ K ⁻¹	
C _c constant in Eq. (17) (=2.18) d _p diameter of the nanoparticle, m d _{ij} deformation tensor = (u _{ij} + u _{ji})/2 F _{i,i} lift force per unit mass in the <i>i</i> direction, ms ⁻² F _{<i>m</i>,i} thermophoretic force per unit mass in the <i>i</i> direction, ms ⁻² F _{<i>p</i>,i} pressure gradient force per unit mass in the <i>i</i> direction, 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 × 10 ⁻²³) k fluid thermal conductivity, Wm ⁻¹ K ⁻¹ k _n constant in Eq. (14) (=2.594) 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 (= $2\lambda/d$) 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 (= y/x_f) R universal gas constant, J K ⁻¹ mol ⁻¹ Ra Rayleigh number $= g\beta_f(T_h - T_c)H^3/\alpha_f v_f$ Rep relative Reynolds number ($=pd_p u_p - u /\mu$) S relative density ($=\rho_p \rho$) 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 _{p,i} particle velocity in the <i>i</i> direction, ms ⁻¹ u _{p,i} particle velocity in the <i>i</i> direction, ms ⁻¹ W, dimensionaless Cartesian coordinates, m X, Y dimensionless temperature μ dynamic viscosity, kg m ⁻³ β thermal expansion coefficient, K ⁻¹ θ dimensionless temperature μ dynamic viscosity, m ² s ⁻¹ \forall kinematic viscosity, m ² s ⁻¹ \forall kinematic viscosity, m ² s ⁻¹ \forall gradient Δ delta Subscripts c cold or cooler f base fluid h hot or heater <i>i</i> vector axis indicators L lift p particle Th thermophoresis B Brownian	C_s	constant in Eq. (17) (=1.17)	
$\begin{array}{ll} d_p & \text{diameter of the nanoparticle, m} \\ d_i & \text{deformation tensor } = (u_{ij} + u_{ji})/2 \\ F_{1,i} & \text{lift force per unit mass in the i direction, ms^{-2} \\ F_{n,i} & \text{thermophoretic force per unit mass in the i direction, ms^{-2} \\ F_p & \text{Brownian force per unit mass in the i direction, ms^{-2} \\ f_{\mu,i} & \text{shear stress per unit mass in the i direction, ms^{-2} \\ g & \text{gravity acceleration, ms^{-2} \\ G & \text{Gaussian random numbers} \\ H & \text{enclosure height, m} \\ L & \text{dimensional height of the heater and cooler, m} \\ K & \text{constant in Eq. (14) (=2.594)} \\ k_g & \text{Boltzmann constant (=1.38 \times 10^{-23})} \\ k & \text{fluid thermal conductivity, Wm^{-1} K^{-1} \\ k_p & \text{particle thermal conductivity, Wm^{-1} K^{-1} \\ k_n & \text{Knudsen number (=2\lambda/d)} \\ N & \text{number of particles or pairs of the HACs} \\ \overline{Nu}_i & \text{average Nusselt number on the walls of ith heater } \\ p & \text{fluid pressure, } (Pa), N m^{-2} \\ Pr & \text{Pradutl number (= y_i/x_i) \\ R & universal gas constant, K^{-1} \text{mol}^{-1} \\ Ra & Rayleigh number = g\beta_i (T_h - T_c)H^3/\alpha_j v_f \\ \text{Re}_p & \text{relative Reynolds number (=\rho_d \rho_p \mu_p - u / \mu) \\ St & Stokes number \\ T & fluid temperature, K \\ T_0 & reference temperature (=(T_h + T_c)/2), K \\ t & time, s \\ u, v & \text{dimensional velocity components, ms}^{-1} \\ u_{\mu i} & \text{fluid velocity in the i direction, ms}^{-1} \\ u_{\mu j} & \text{particle velocity in the i direction, ms}^{-1} \\ \pi & \text{dimensionelss Cartesian coordinates, m \\ X, Y & \text{dimensionelss Cartesian coordinates, m } \\ X, Y & \text{dimensionelss targenature} (=(L_1, +L_2)/2), K \\ t & \text{time, s} \\ u, v & \text{dimensionelss targenature} (=L_1, +L_2)/2, K \\ t & \text{time, s} \\ u, v & \text{dimensionelss Cartesian coordinates, m } \\ X, Y & \text{dimensionelss targenature} \\ \beta & \text{thermal expansion coefficient, K}^{-1} \\ \theta & \text{dimensionelss targenature} \\ \beta & \text{thermal diffusivity, m}^2 s^{-1} \\ \tau & \text{particle relaxation time (Eq. (10)), s} \\ \alpha & \text{thermal diffusivity, m}^2 s^{-1} \\ \tau & \text{particle relaxation time (Eq. (10)), s} \\ \alpha & thermal di$	C_t	constant in Eq. (17) (=2.18)	
digi deformation tensor = $(u_{ij} + u_{jj})/2$ F_{Li} illif force per unit mass in the <i>i</i> direction, ms ⁻² F_{B} Brownian force per unit mass in the <i>i</i> direction, ms ⁻² F_{Pi} shear stress per unit mass in the <i>i</i> direction, ms ⁻² F_{pi} shear stress per unit mass in the <i>i</i> direction, ms ⁻² F_{pi} shear stress per unit mass in the <i>i</i> direction, ms ⁻² F_{pi} shear stress per unit mass in the <i>i</i> direction, ms ⁻² F_{pi} shear stress per unit mass in the <i>i</i> direction, ms ⁻² F_{pi} shear stress per unit mass in the <i>i</i> direction, ms ⁻² F_{pi} shear stress per unit mass in the <i>i</i> direction, ms ⁻² F_{pi} shear stress per unit mass in the <i>i</i> direction, ms ⁻² F_{pi} shear stress per unit mass in the <i>i</i> direction, ms ⁻² F_{pi} dimensional height of the heater and cooler, m K constant in Eq. (14) (=2.594) K_{B} Boltzmann constant (=1.38 × 10 ⁻²³) K fluid thermal conductivity, Wm ⁻¹ K ⁻¹ K_{p} particle thermal conductivity, Wm ⁻¹ K ⁻¹ K_{p} particle thermal conductivity, Wm ⁻¹ K ⁻¹ K_{n} Knudsen number (=2 <i>i</i> / <i>d</i>) N number of particles or pairs of the HACS \overline{Nu}_{i} average Nusselt number on the walls of ith heater p fluid pressure, (<i>Pa</i>), N m ⁻² P Prandtl number (= v_{f}/x_{f}) R universal gas constant, J K ⁻¹ mol ⁻¹ R Rayleigh number = $gF_{f}(T_{n} - T_{c})H^{2}/x_{f}V_{f}$ Re _p relative density (= ρ_{p}/ρ) St Stokes number T fluid temperature, K T_{0} reference temperature (= $(T_{h} + T_{c})/2$), K t time, si u, v dimensional velocity components, ms ⁻¹ u_{pi} particle velocity in the <i>i</i> direction, ms ⁻¹ x, y dimensional cartesian coordinates, m X, Y dimensionless temperature μ dynamic viscosity, $m^{2}s^{-1}$ τ particle relaxation time (Eq. (10)), s α thermal diffusivity, m ² s ⁻¹ τ particle relaxation time (Eq. (10)), s α thermal diffusivity, m ² s ⁻¹ τ particle relaxation time (Eq. (10)), s α thermal diffusivity, m ² s ⁻¹ T particle Th thermophoresis B B	d_p	diameter of the nanoparticle, m	
	a _{ij}	deformation tensor = $(u_{i,j} + u_{j,i})/2$	
	F _{L,i}	lift force per unit mass in the <i>i</i> direction, ms $\frac{1}{2}$	
r_{P_i} biownian note per unit mass in the i direction, ms ⁻² $F_{P_i,i}$ 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 × 10 ⁻²³) k fluid thermal conductivity, Wm ⁻¹ K ⁻¹ k_p particle thermal conductivity, Wm ⁻¹ K ⁻¹ K_n number of particles or pairs of the HACs Nu_i average Nusselt number on the walls of ith heater p fluid pressure. (P_0 , N m ⁻² Pr Prandtl number (= $2\lambda/d$) R universal gas constant, J K ⁻¹ mol ⁻¹ Ra Rayleigh number ($pd_p u_p - u /\mu$) S relative density (= ρ_p/ρ) St Stokes number T fluid thermeature, 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>i</i> direction, ms ⁻¹ u_i fluid velocity in the <i>i</i> direction, ms ⁻¹ u_j particle velocity in the <i>i</i> direction, ms ⁻¹ u_i fluid velocity in the <i>i</i> direction, ms ⁻¹ u_i fluid velocity in the <i>i</i> direction, ms ⁻¹ u_i fluid velocity in the <i>i</i> direction, ms ⁻¹ u_i fluid velocity in the <i>i</i> direction, ms ⁻¹ u_i fluid velocity in the <i>i</i> direction, ms ⁻¹ v_i	Г _{Th,i} Б	Brownian force per unit mass in the <i>i</i> direction, ms^{-2}	
$\begin{array}{rcl} P_{\mu i} & \text{pressure gravity for the form that is a first relation, ms^{-2} \\ g & \text{gravity acceleration, ms}^{-2} \\ G_i & \text{Gaussian random numbers} \\ H & \text{enclosure height, m} \\ L & \text{dimensional height of the heater and cooler, m} \\ K & \text{constant in Eq. (14) (=2.594)} \\ k_B & \text{Boltzmann constant (=1.38 \times 10^{-23})} \\ k & \text{fluid thermal conductivity, Wm}^{-1}K^{-1} \\ k_p & \text{particle thermal conductivity, Wm}^{-1}K^{-1} \\ k_p & \text{particle thermal conductivity, Wm}^{-1}K^{-1} \\ Kn & \text{Knudsen number (=2\lambda/d)} \\ N & \text{number of particles or pairs of the HACs} \\ \hline Nn & \text{number of particles or pairs of the HACs} \\ \hline Nn & \text{number of particles or pairs of the HACs} \\ \hline Nn & \text{nuiversal gas constant, J}K^{-1} \text{mol}^{-1} \\ Ra & Rayleigh number (=v_f/\alpha_f) \\ R & \text{universal gas constant, J}K^{-1} \text{mol}^{-1} \\ Ra & Rayleigh number = g\beta_f(T_h - T_c)H^3/\alpha_f v_f \\ \text{Re}_p & \text{relative Reynolds number (=}(-pd_p)u_p - u /\mu) \\ \text{S} & \text{relative density (=}\rho_p/\rho) \\ \text{St} & \text{Stokes number} \\ T & \text{fluid temperature, K} \\ T_0 & \text{reference temperature (=}(T_h + T_c)/2), K \\ t & \text{time, s} \\ u, v & \text{dimensional velocity components, ms}^{-1} \\ u_{p,i} & \text{particle velocity in the i direction, ms}^{-1} \\ u_{p,i} & \text{particle velocity in the i direction, ms}^{-1} \\ M_{infusional Cartesian coordinates, m \\ \hline \\ Greek symbols \\ \rho & \text{density, kg m}^{-3} \\ \beta & \text{thermal expansion coefficient, K}^{-1} \\ \theta & \text{dimensionaless temperature} \\ \mu & \text{dynamic viscosity, m}^2 \text{s}^{-1} \\ \tau & \text{particle relaxation time (Eq. (10)), s} \\ \alpha & \text{thermal diffusivity, m}^2 \text{s} \\ \nabla & \text{gradient} \\ \Delta & \text{delta} \\ \hline \\ \text{b hot or heater} \\ i & \text{vector axis indicators} \\ L & \text{lift} \\ p & \text{particle} \\ \text{Th thermophoresis} \\ B & \text{Brownian} \\ \hline \end{array}$	F _B	pressure gradient force per unit mass in the <i>i</i> direction, ms^{-2}	
$ \begin{array}{ll} f_{\mu,j} & \text{gravity acceleration, ms^{-2}} \\ \hline g_{i} & \text{Gaussian random numbers} \\ H & \text{enclosure height, m} \\ L & \text{dimensional height of the heater and cooler, m} \\ K & \text{constant in Eq. (14) (=2.594)} \\ k_{g} & \text{Boltzmann constant (=1.38 \times 10^{-23})} \\ k & \text{fluid thermal conductivity, Wm^{-1} K^{-1} \\ k_{p} & \text{particle thermal conductivity, Wm^{-1} K^{-1} \\ Kn & \text{Knudsen number (=2\lambda/d)} \\ N & \text{number of particles or pairs of the HACs} \\ \overline{Nu_{i}} & \text{average Nusselt number on the walls of ith heater} \\ p & \text{fluid pressure, (P0, N m^{-2} \\ Pr & \text{Prandtl number (=} v_{f}/\alpha_{f}) \\ R & \text{universal gas constant, J K^{-1} mol^{-1} \\ Ra & Rayleigh number = g\beta_{f}(T_{h} - T_{c})H^{3}/\alpha_{f}v_{f} \\ \text{Re}_{p} & \text{relative Reynolds number (=} (-dp_{l}u_{p} - ul/\mu) \\ S & \text{relative Reynolds number (=} (-dp_{l}u_{p} - ul/\mu) \\ S & \text{relative Reynolds number (=} (T_{h} + T_{c})/2), K \\ t & \text{time, s} \\ u, v & \text{dimensional velocity components, ms^{-1} \\ u_{i} & \text{fluid velocity in the i direction, ms^{-1} \\ u_{p,i} & \text{particle velocity in the i direction, ms^{-1} \\ u_{p,i} & \text{particle velocity in the i direction, ms^{-1} \\ x, y & \text{dimensionless Cartesian coordinates, m} \\ \hline \\ Greek symbols \\ \rho & \text{density, kg m^{-3}} \\ \beta & \text{thermal expansion coefficient, K^{-1} \\ \theta & \text{dimensionless temperature} \\ \mu & \text{dynamic viscosity, kg m^{-1} s^{-1} \\ v & \text{kinematic viscosity, m^{2} s^{-1} \\ \tau & \text{particle relaxation time (Eq. (10)), s} \\ \alpha & \text{thermal diffusivity, m^{2} s} \\ \nabla & \text{gradient} \\ \Delta & \text{delta} \\ \\ Subscripts \\ c & \text{cold or cooler} \\ f & \text{base fluid} \\ h & \text{hot or heater} \\ i & \text{vector axis indicators} \\ L & \text{lift} \\ p & \text{particle} \\ Th & \text{thermophoresis} \\ B & \text{Brownian} \\ \end{array}$	$F_{i,i}$	shear stress per unit mass in the <i>i</i> direction ms^{-2}	
<i>G</i> _i Gaussian random numbers <i>H</i> enclosure height, m <i>L</i> dimensional height of the heater and cooler, m <i>K</i> constant in Eq. (14) (=2.594) <i>k</i> _B Boltzmann constant (=1.38 × 10 ⁻²³) <i>k</i> fluid thermal conductivity, Wm ⁻¹ K ⁻¹ <i>k</i> _p particle thermal conductivity, Wm ⁻¹ K ⁻¹ <i>k</i> _p particle thermal conductivity, Wm ⁻¹ K ⁻¹ <i>k</i> _n Knudsen number (=2.//d) <i>N</i> number of particles or pairs of the HACs <i>Nu</i> _i average Nusselt number on the walls of ith heater <i>p</i> fluid pressure, (<i>Pa</i>), N m ⁻² <i>Pr</i> Prandtl number (= ν_f/α_f) <i>R</i> universal gas constant, J K ⁻¹ mol ⁻¹ <i>Ra</i> Rayleigh number $g\beta_f(T_h - T_c)H^3/\alpha_f v_f$ Re _p relative Reynolds number ($=\rho d_p u_p - u / \mu$) <i>S</i> relative density ($=\rho_p \rho$) <i>St</i> Stokes number <i>T</i> fluid temperature, K <i>T</i> o reference temperature (=(<i>T</i> _h + <i>T</i> _c)/2), K <i>t</i> time, s <i>u</i> , <i>v</i> dimensional velocity components, ms ⁻¹ <i>u</i> _i fluid velocity in the <i>i</i> direction, ms ⁻¹ <i>x</i> , <i>y</i> dimensional Cartesian coordinates, m <i>X</i> , <i>Y</i> dimensionaless Cartesian coordinates, m <i>X</i> , <i>Y</i> dimensionless temperature μ dynamic viscosity, kg m ⁻¹ s ⁻¹ <i>v</i> kinematic viscosity, kg m ⁻¹ s ⁻¹ <i>v</i> kinematic viscosity, kg m ⁻¹ s ⁻¹ <i>v</i> kinematic diffusivity, m ² s ∇ gradient Δ delta <i>Subscripts</i> <i>c</i> cold or cooler <i>f</i> base fluid <i>h</i> hot or heater <i>i</i> vector axis indicators <i>L</i> lift <i>p</i> particle <i>Th</i> thermophoresis <i>B</i> Brownian	σ φ	gravity acceleration, ms^{-2}	
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