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Numerical analysis of a fully developed non-isothermal particle-laden turbulent channel flow

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Turbulent non-isothermal fully-developed channel flow laden with small particles was investigated through Direct Numerical Simulation (DNS), combined with tracking of the individual particles. The simulations are performed at Re_τ=180 and 395, with Pr = 1.0. The Euler–Lagrange approach with point-particle modeling has neglected the influence of the particles on the fluid and inter-particle interactions. The focus is centered on the interactions between particles and turbulence and their effect on the concentration and temperature of the particles. DNS shows that the clustering and segregation of particles near the wall, due to turbophoresis, is strongly related to the quality of the velocity field and these phenomena cannot be reproduced with other types of simulation. The presented data were obtained using direct numerical simulation and show new effects related to heat exchange for the turbulent flow with small particles. It has been discovered that a large increase of concentrations of the particles close to the wall and in low-speed streaks, where temperatures differ from the mean temperature, strongly affect the mean temperature of the particles[*)].

1. Introduction

Correct prediction and understanding of the mechanisms of mass and thermal energy transport by small solid particles or droplets in non-isothermal turbulent flow, is a compelling issue in two-phase turbulent flow. This type of flow occurs, in large numbers of environmental and industrial processes e.g. cloud formation, coal combustion, catalytic cracking, filters, chemical reactors, etc. The recent problem has become more important due to the increasing requirement for heat flux in cooling and heating systems. The accurate prediction of particle behavior is important for design industrial devices and to understand physics. Experiments and numerical computations demonstrate that shear flow has a complex effect on the particles. Due to the interactions between particles and turbulence, both can be largely modulated and their properties can

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be highly influenced. Small heavy particles immersed in a turbulent flow tend to accumulate, creating strong inhomogeneities in concentration and form cluster structures in the low-speed streaks [4]. Due also to momentum and heat exchange, particle-turbulence interaction becomes even more complex and can influence the particles' thermal properties. The complexity of turbulent transfer phenomena which cover a wide range of flow, scales from very small to very large, brings to bear different mechanisms playing an important role in the interaction between particles and turbulent structures.

A good deals of work has been done on understanding of the influence of particle inertia on dispersed phase structure and on fluid structure using simple models [17, 19]. A numerical analysis with simple models is neither highly reliable nor applicable and fails where more accurate analysis of the flow is needed. A possible way to improve the understanding of the particle-turbulence interaction is to use accurate and reliable numerical tools such as direct numerical simulation.

For flows laden with a large number of small particles, Eulerian–Lagrangian point-particle DNS has been found quite successful in studies of the particle-turbulence dynamics in isothermal flows. Several important aspects of particle-turbulence interactions have been discussed by MAXEY and RILEY [12], KULICK, FESSLER and EATON [10], EATON and FESSLER [4] and CHUN *et al.* [3]. DNS studies on turbulent particle dispersion in wall-bounded flows have proven their ability to predict particle turbulence interactions and made possible the qualitative and quantitative analyses on the processes [18] and [1]. The application of DNS to study particle deposition in boundary layers by WANG and SQUIRES [22] has clearly shown the accumulation of heavy particles in the low velocity streaks.

Most of the recent works done on the issue focuses on isothermal flow but few studies deal with non-isothermal particle-laden flow. HETSRONI, ROSENBLIT and YARIN [6] and HETSRONI, MOSYAK and POGREBNYAK [5] used infrared thermography to study the thermal interaction between particle-laden turbulent flow and a heated plate. By adding particles, they enhanced the heat transfer. ZONTA, MARCHIOLI and SOLDATI [23] performed DNS for hydrodynamically and thermally developing turbulent channel flow. They observed increase and decrease in heat transfer depend on the particle size.

Several DNS analyses have been performed to investigate turbulent heat transfer in wall-bounded flows [2, 11]. Quite systematic analyses of the influence of the Reynolds and Prandtl number in single phase flow on the heat transfer process, were done by KASAGI [8] and LYONS, HANRATTY and MCLAUGHLIN [11]. In their research, HETSRONI, MOSYAK and POGREBNYAK [5] show that the particles cause an increase in wall-normal turbulent flux. This effect may be directly caused by the "film scraping" on "particle convection", assumed by SUBRAMANIAN, RAO and GOPICH [20], or indirectly by turbulence modifications (mainly a change in the level of wall-normal fluctuations), as suggested by M. RASHIDI,

G. HETSRONI and S. BANERJEE [16] and KAFTORI, HETSRONI and BANERJEE [7]. CHAGRAS, OESTERLE and BOULET [2] did numerical studies focused on particle collisions in a heated pipe flow, reporting that flow dynamic alternation induced by particle-wall and inter-particle collisions results in significant modulation of the heat exchange rate, but direct heat exchange during inter-particle collisions (solid to solid) and for particle-wall collisions is negligible.

The author is unaware of the existence of a comprehensive analysis that would account for mass, momentum and heat transfer in particle-laden flow and for an understanding of the modifications of the heat transfer mechanisms that occur in particle flow has yet to be elaborated.

The present paper focuses on particle-turbulence interaction in a wall-heated fully-developed turbulent channel. The chosen wide range of particle time scales starts from $\tau_V^+ = 2$ (St = 2) and goes up to $\tau_V^+ = 29$ (St = 29) and for $\tau_T^+ = 3$ up to 435. The choice allows us to discriminate between different mechanisms of particle interactions and covers the range of particles most responsive to the flow structures. To that end, extension in the point-particle approach has been done in order to deal also with heat transfer. The temperature is considered as a passive scalar, and only one-way coupling, from both the hydrodynamic and thermal perspectives, are considered (i.e., the influence of the particles on the turbulence and particle collisions are not taken into account). In that approach, difference in particle mass fractions have no effect on flow nor particles. The interaction generated by the solid particles on the temperature of the particles, the exchange heat rate and on the correlation between the properties of the particles and of the surrounding fluid, have all been examined.

2. Mathematical model

For current studies of wall-bounded turbulent particle-laden flow, the Eulerian–Lagrangian point-particle approach [14] has been used. Particles are dispersed in a pressure-driven heated flow of gas, assumed to be incompressible and Newtonian. Periodic boundary conditions are imposed on the fluid velocity and temperature field in streamwise and spanwise directions, no slip boundary conditions are enforced to the wall. Detailed information about implementation of periodicity can be found in [11]. Assuming very small values of the volume fraction of particles and small particle size, the particles will have a negligible effect on turbulence and the interactions between the particles and turbulence is a one-way coupling. It has also been assumed that for very small particle number density, with small particle size, heat exchange between the particles and the turbulence has an insignificant effect on the flow temperature.

The continuous-phase is solved using standard direct numerical simulation techniques for incompressible flow, together with the tracking of the individual particles. The transfer of momentum between the particle and the fluid is considered through a force located at the particle center, which is determined by the velocities of the particle and of the surrounding fluid. The heat transfer is determined based on velocities of the particle and fluid and the temperatures of the particle and the surrounding fluid. Those approaches are valid if the particles are significantly smaller than the smallest flow scales.

To consider only the particle-turbulence interactions, the simulations are performed in a channel without gravity. The geometry of the problem under consideration is sketched in Fig. 1.

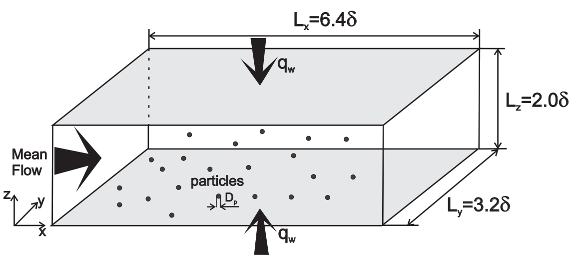

Fig. 1. Particle-laden channel flow.

The streamwise wall normal and spanwise coordinate are denoted x, y, z. The wall heat flux q_w is assumed to be uniformly distributed on the walls and the working fluid is assumed to be Newtonian with constant properties. The temperature is treated as a passive scalar. Given these assumptions for the continuous phase, the continuity, Navier–Stokes and energy equations can be written, as follows:

$$\frac{\partial u_i}{\partial x_i} = 0, \tag{2.1}$$

$$\frac{\partial u_i}{\partial t} = -u_j \frac{\partial u_i}{\partial x_j} + \frac{1}{\mathrm{Re}_\tau} \frac{\partial^2 u_i}{\partial x_j^2} - \frac{\partial p}{\partial x_i} + s_i, \tag{2.2}$$

$$\frac{\partial T}{\partial t} = -u_j \frac{\partial T}{\partial x_j} + \frac{1}{\mathrm{Re}_\tau \mathrm{Pr}} \frac{\partial^2 T}{\partial x_j^2} + q_i. \tag{2.3}$$

For small heavy particles, the only significant force is the drag force [17]; the equation of motion for a particle can be written:

$$\frac{dv_i}{dt} = C_d \frac{\mathrm{Re}_p}{24} \frac{1}{\tau_V} \left(u_i - v_i\right), \tag{2.4}$$

where u_i is the velocity of the fluid interpolated at the center of the particle. The particle Reynolds number Re_p, and the hydrodynamic particle-relaxation-time τ_V, are defined as:

$$\mathrm{Re}_p = \frac{|(u_i - v_i)| D_p}{\nu}, \qquad \tau_V = \frac{\rho_p}{\rho} \frac{D_p^2}{18\nu}, \tag{2.5}$$

where ρ_p and ρ are the particle and fluid densities, D_p is the diameter of the particles and C_d is the drag coefficient that in the case of Stokes flow becomes $C_d = 24/\mathrm{Re}_p$. The equation for the particle temperature, assuming a Biot number less than 0.1 (uniform particle temperature) can be written:

$$\frac{dT_p}{dt} = \frac{\mathrm{Nu}}{2}\frac{1}{\tau_T}\left(T - T_p\right), \tag{2.6}$$

where T is the temperature of the fluid interpolated at the center of the particle, and τ_T is the thermal particle-relaxation-time given:

$$\tau_T = \frac{\rho_p c_p D_p^2}{12k} \qquad \text{or} \qquad \tau_T = \tau_V \frac{3}{2}\frac{c_p}{c}\mathrm{Pr}. \tag{2.7}$$

The Nusselt number was calculated from the Ranz–Marshall correlation:

$$\mathrm{Nu} = 2 + 0.6\mathrm{Re}_p^{0.5}\mathrm{Pr}^{1/3}. \tag{2.8}$$

The position, flow and particle quantities are normalized by the channel half-width, δ, the friction velocity, u_τ, and the friction temperature, T_τ. The convective and diffusive terms in all the equations are discretized using a second-order central scheme, and a second-order Adams–Bashforth scheme is used for time advancement. The particle motion and particle temperature algorithms are obtained with a second-order Adams–Bashforth scheme for the time-advancement, and a tri-linear interpolation for the velocity and temperature. The flow is heated from walls by a uniform heat-flux. Periodic boundary conditions are imposed in streamwise and spanwise directions.

3. Results

The calculations are performed on a computational domain of $6.4 \times 3.2 \times 2.0\,\delta$ in x, y and z, discretized with $128 \times 128 \times 66$ (for $\mathrm{Re}_\tau = 180$) and $256 \times 256 \times 128$ (for $\mathrm{Re}_\tau = 395$) control volumes. For the streamwise and spanwise directions, the uniform grid spacing was used. For wall normal, the non-uniform grid spacing with a hyperbolic-tangent stretching. The shear Reynolds number of the flow was $\mathrm{Re}_\tau = 180$ and 395, based on the shear velocity and half channel height. To obtain good particle statistics for the simulations presented here, 1.5×10^6 particles were considered.

The simulations were started from arbitrary conditions (random flow and temperature field) and flow field was time-advanced to get a statistically-steady state for velocity and temperature. When a statistically steady state was reached, particles were injected uniformly over the computational domain. Their initial velocity was assumed to be the same as the fluid in the center of the particles' location. The particles need to adapt to the new velocity and temperature, which usually takes a few particle response times and then much longer time is required to ensure a statistically-steady state for the particle conditions required to produce reliable statistics (to obtain a statistically steady state for particles needs more time than it does for the flow field; it also takes more time for particles with larger response times). After an initial big change in the particle concentration profile, particles continue to very slow process of accumulate near the walls. As Portela and Oliemans [15] has shown, this process can take an enormous amount of time. In the present computations, the time before the particles start to be averaged takes at least $t^* = 200$. The statistics for the fluid and particles were averaged for $100\delta/u_\tau$ at $\mathrm{Re}_\tau = 180$ and for $40\delta/u_\tau$ at $\mathrm{Re}_\tau = 395$. The particle properties were obtained by averaging over rectangular slices, using a simple linear model based on centre of particle locations and distance from reference points, which correspond to flow computational grid points. The mean streamwise velocity and mean temperature profile and other mean turbulence quantities for fluid phase are compared with the DNS data provided by other re-

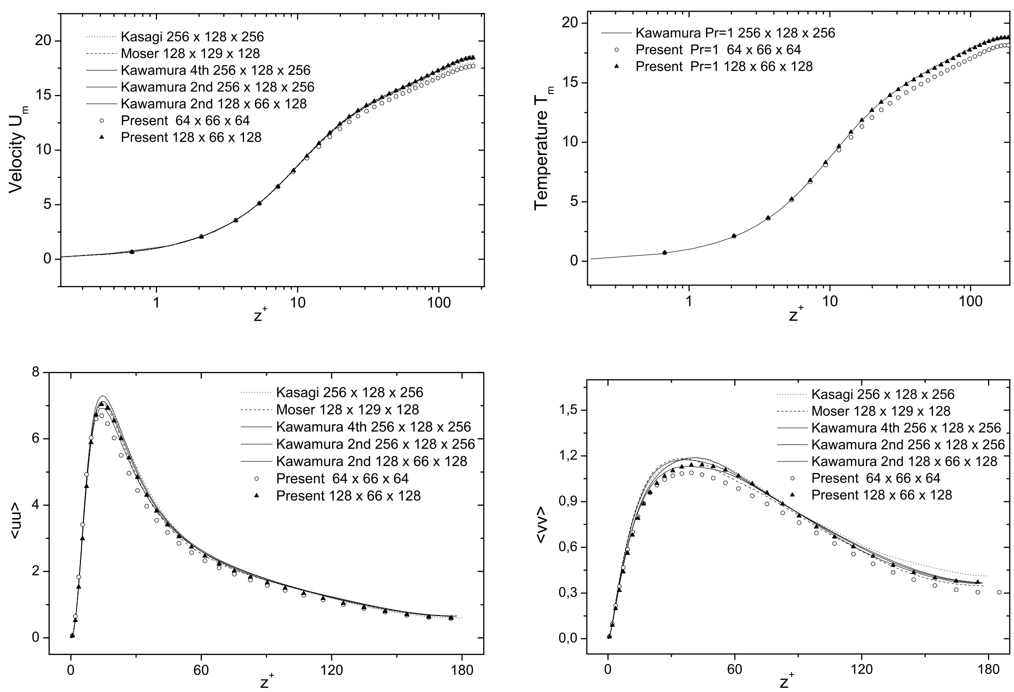

Fig. 2. Computed quantities for continuous phase: mean streamwise velocity component, mean temperature and velocity correlation for streamwise and spanwise component and for $\mathrm{Re}_\tau = 180$, $\mathrm{Pr} = 1.0$, in comparison with other Direct Numerical Simulations for single phase data available the in literature.

searchers (MOSER, KIM and MANSOUR [13], KASAGI [8] and KAWAMURA, ABE and MATSUO [9]) shown in Fig. 2. Good agreement with the work done by other authors can be said to exist insofar as small difference are found between the data from databases, which would be mainly caused by a different method of solution and differences in the grids.

It is known that in wall-bounded shear flow, particles concentrate near the wall and particle concentration is non-uniform, which provides the highest concentration in low-speed streaks due to particle interactions with the local turbulent flow structure. But it is also important to know how this non-uniformity influences the temperature or heat fluxes. The particle mean streamwise velocity, together with mean particle temperature and concentration profiles, are shown in Fig. 3. Very high particle concentrations near the wall can be observed for all cases. Particle concentration is by two orders of magnitude higher than in core flow and remains uniform only for a small area close to the channel center line. Even for a relatively light particle with $\mathrm{St} = 2$, the concentration is one order of magnitude higher than the value in the center of the channel. The small concentration of particles in the core region of the channel shows that in order to get accurate good statistical results, the number of particles must be large. Results of the concentration are sensitive to the method of and binning size(here related to grid size for scalar). Nevertheless, the trends are always the same. The mean streamwise-velocity profiles and mean temperature for particle and fluid are also shown in Fig. 3. For $\mathrm{Re}_\tau = 180$ and up to $z = 0.5\delta$ the particle velocity is slightly smaller than the fluid velocity (except very close to the wall) and this difference increases with increasing τ_V, with maximum difference around $z = 30$ in wall units. For higher z the particle velocity can be slightly larger than the fluid velocity and maximum deviation was seen for a particle with $\tau_V = 7$. A similar effect can be seen for $\mathrm{Re}_\tau = 395$. For all cases, the particle temperature is smaller than the fluid temperature for all distances z (except for the small region in the core of flow). This differs from the profile of the streamwise velocity where in the core of the channel, the particle velocity overlaps the fluid velocity. However, the main difference can be seen close to the wall where the temperature of the particle, even very close to the wall, is much smaller than the fluid temperature. This effect also occurs for relatively light particles and is more pronounced for high Reynolds number. Clearly, the uniform mixing of particles in turbulent flow can be a non-trivial task.

Figure 4 shows the correlation between the velocity streamwise component for fluid-fluid, fluid-particle and particle-particle correlation for two Reynolds numbers $\mathrm{Re}_\tau = 180$ and $\mathrm{Re}_\tau = 395$ and for Stokes number for particle $\mathrm{St} = 2, 7, 29$. It can be seen that with the increasing Stokes number, the correlation between the fluid and particles decreasse whereas the particle correlation component increases. The effect is even more pronounced for a higher Reynolds number.

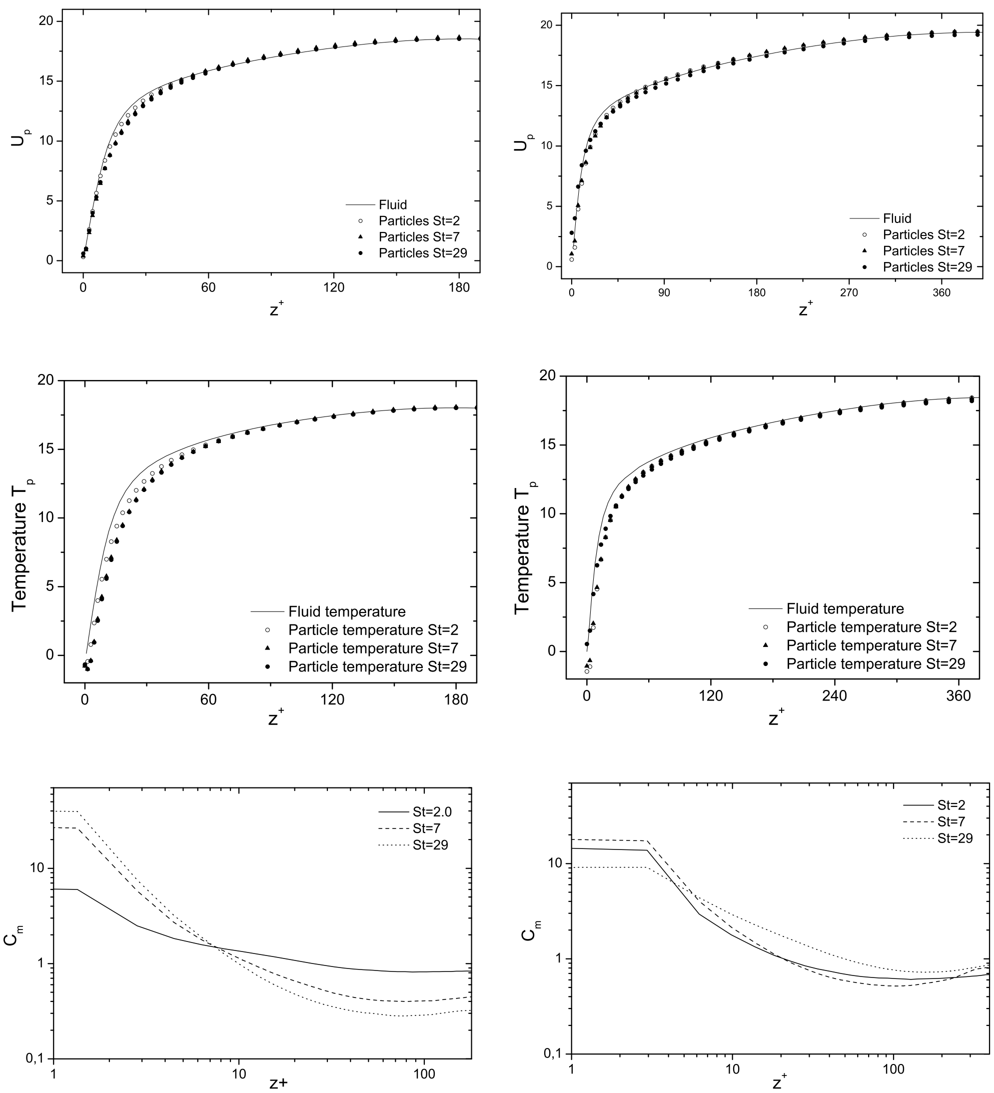

Fig. 3. Computed mean quantities for fluid and particle: streamwise velocity component, temperature and particle concentration for two Reynolds number $\mathrm{Re}_\tau = 180$ (left) and $\mathrm{Re}_\tau = 395$ (right), Prandtl number $\mathrm{Pr} = 1.0$ and for Stokes number for particle $\mathrm{St} = 2, 7, 29$ and Stokes for thermal response $\mathrm{St}_T = 3, 10, 43$ respectively.

Figure 5 presents the thermal quantities for fluid and particles. Velocity-temperature correlations are presented for fluid and for particles, for fluid with Prandtl number $\mathrm{Pr} = 1$ and for three types of particles with $\mathrm{St} = 2, 7, 29$ and St_T from 0.3 up to 435 and for two Reynolds numbers $\mathrm{Re}_\tau = 180, 395$ and $\mathrm{Pr} = 1.0$. Correlations of streamwise velocity fluctuations and temperature for the parti-

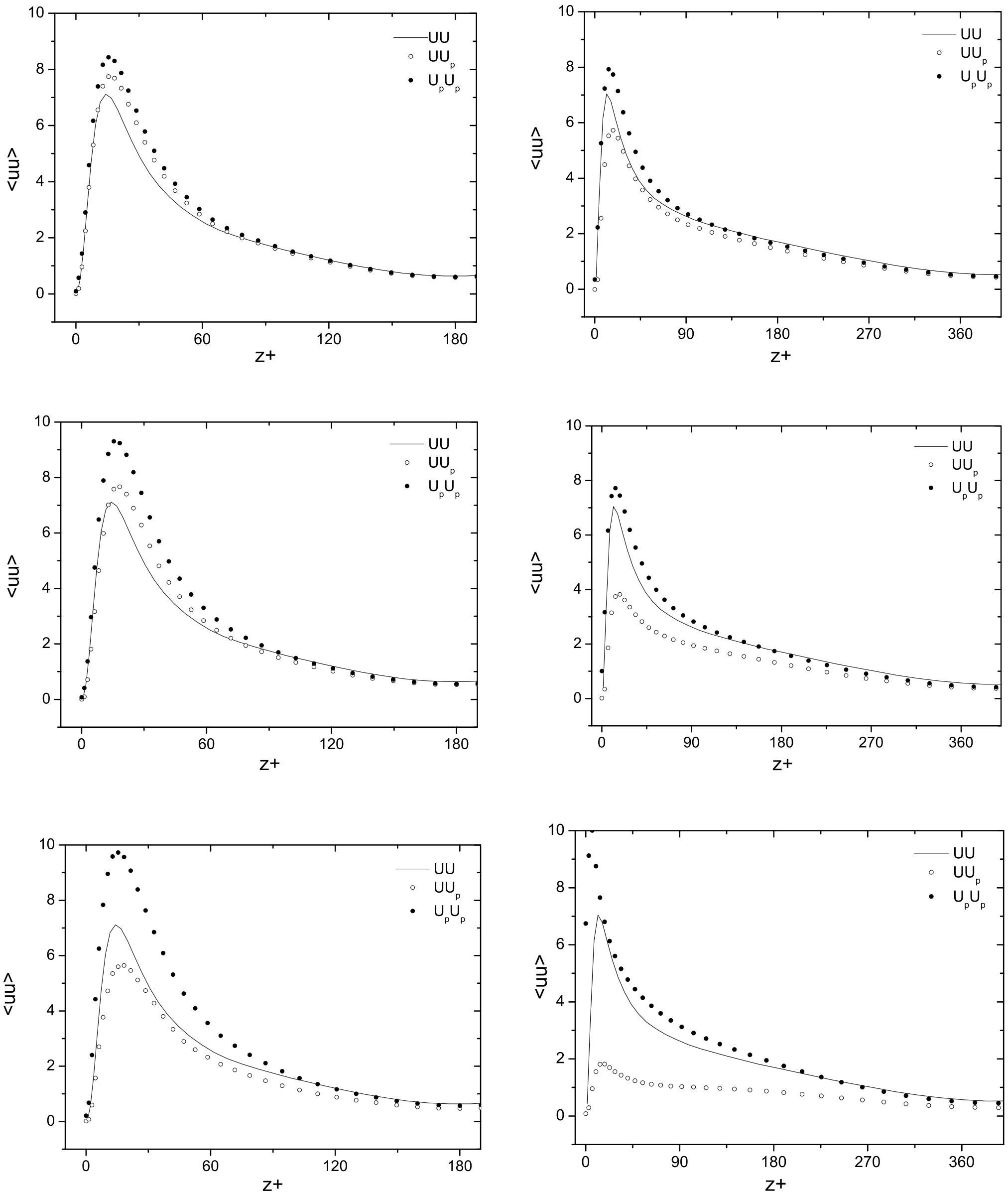

Fig. 4. The correlation between the velocity streamwise component for the fluid-fluid, fluid-particle and particle-particle correlation, for Reynolds number $\mathrm{Re}_\tau = 180$ (left) and $\mathrm{Re}_\tau = 395$ (right) and for Stokes number for particle $\mathrm{St} = 2, 7, 29$ (top, middle and bottom respectively).

cle are much larger than for the fluid and the difference increases along with the particle response time. Correlation $\langle w\theta \rangle$ (not presented here) for light and heavy particle is smaller than for the fluid but for a particle with response time

$\tau_V^+ = 7$ for most of z, is equal to the value for the fluid or slightly exceeds that value. Comparing this component with the $\langle uw \rangle$ component illustrates that also for $\langle uw \rangle$, the maximum value is higher for the middle response particle than for the light and heavy ones, which are the closest to the fluid correlation [14].

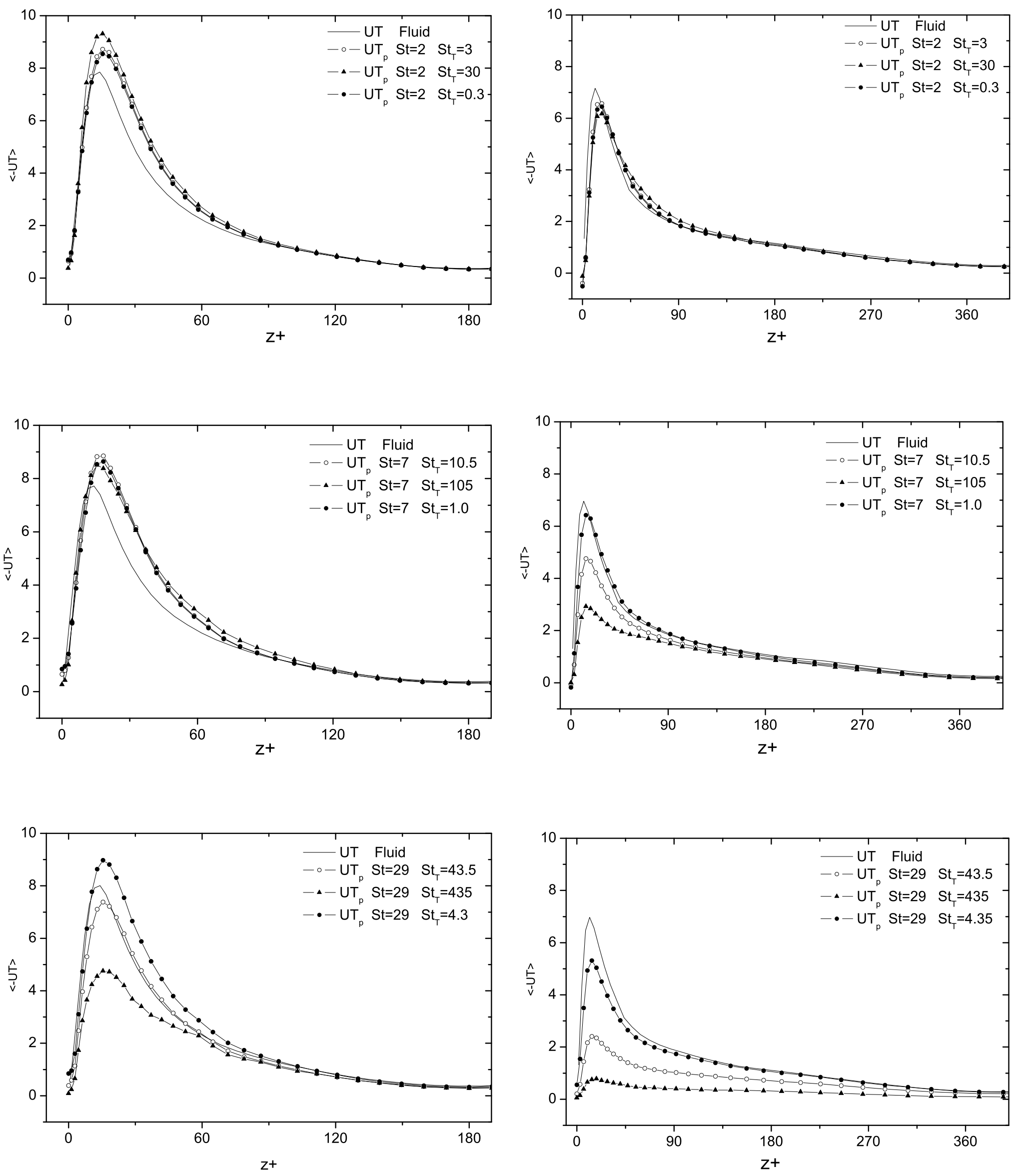

FIG. 5. Thermal quantities for the fluid and for the particles, for particle Stokes number St $= 2, 7, 29$ and St_T from 0.3 up to 435.

Decreasing of the thermal response time represented by St_T by one order of magnitude, causes a very fast response for the thermal response but not necessarily for the total response which also includes hydrodynamic response. For fast thermal response, the particle may still be decorrelated from the flow field. This means that in this effect, the hydrodynamic behavior of streamwise velocity plays a primary role.

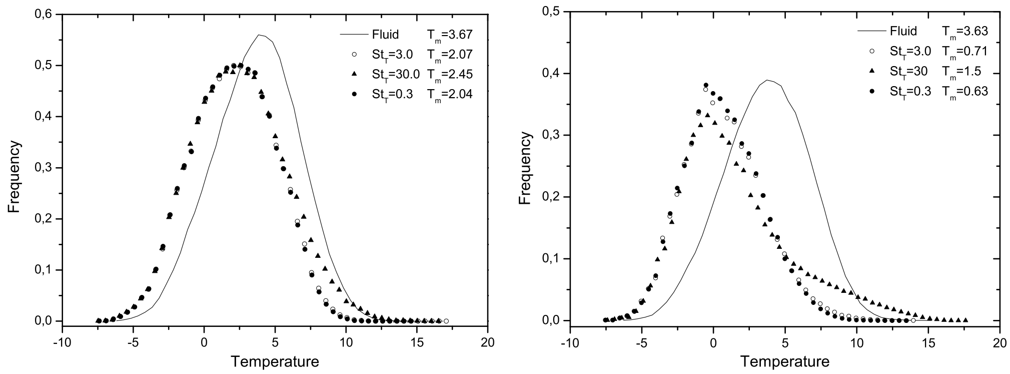

FIG. 6. The distributions of the temperature at $z^+ = 3.6$ and for St $= 2$ and $\mathrm{St}_T = 3, 30, 0.3$ and for $\mathrm{Re}_\tau = 180$ (left), 395 (right), Pr $= 1.0$.

To explore this effect, we have drawn in Fig. 6 average distributions (the frequency at which the temperature will occur in that region for particle or for the small fluid element) of the temperature in the plane x-y for $z^+ = 3.6$. For the fluid in this region, the mean temperature is around $T_m = 3.6$ but for the particle it depends on the momentum and thermal response time. For most light particles, the mean temperature is around $T_m = 2.0$ and does not decrease if the thermal response time is 10 times faster. For heavy particle the mean particle temperature is around $T_m = 0.8$ and decreasing slightly with decreasing τ_θ^+. This shows that particle response time is fast enough for particles to converge thermally but not hydrodynamically. Due to preferential concentration, particles are not randomly distributed in the fluid but located in streaks more often than in other positions. This influences the statistics for thermal components. This behaviour can be seen in Fig. 7 which shows particles and fluid instantaneous temperature contour for x-y plane at $z_+ = 3.6$ and for the $\mathrm{Re}_\tau = 395$. The particles field shows the streak structure of the near-wall region. The particles are greyed with the particle temperature. The fluid temperature has been plotted at the same time. It is clear from the figure that particles are well organised for the near-wall region (and at the same time almost randomly distributed not presented here) for the center of the channel flow.

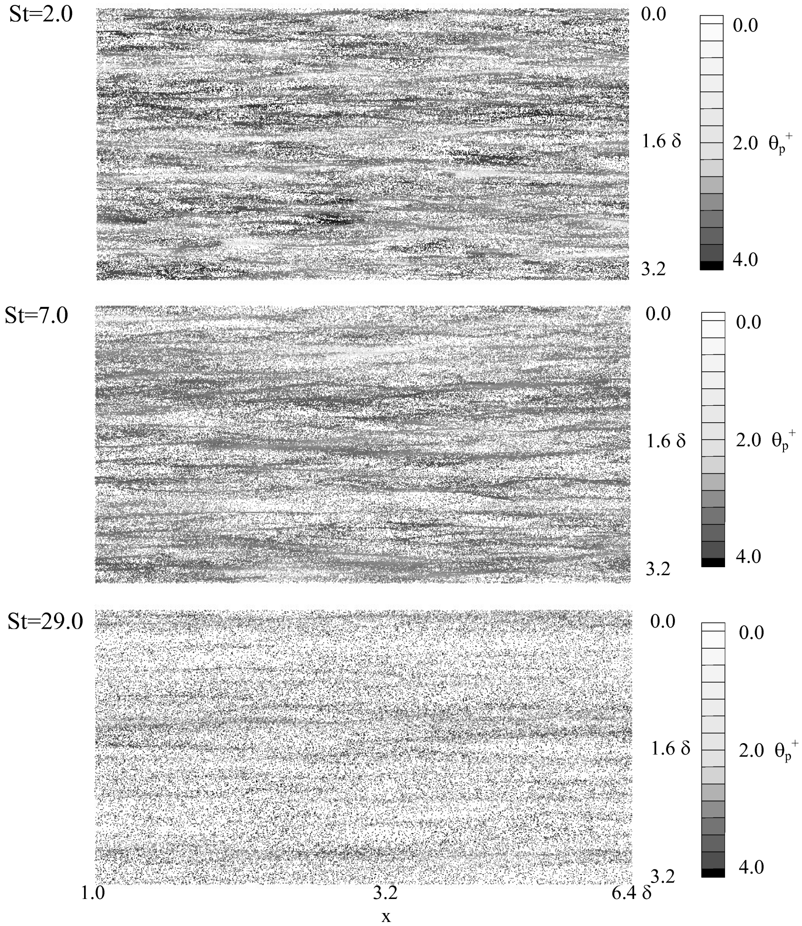

Fig. 7. Instantaneous field of particles temperature at x-y plane and for cross-section at $z^+ = 2.0$, and for Re_τ=395 and St $= 2, 7, 29$.

4. Conclusion

We extended the Eulerian–Lagrangian point-particle DNS approach in order to include heat transfer and to have data for the validation of Large Eddy Simulation. DNS was carried out to study particle transport and heat transport in wall-bounded turbulent flow at $\mathrm{Re}_\tau = 180$, and 395. Hydrodynamically fully developed and thermally developed conditions have been considered in order to investigate the heat transport and thermal interaction between the turbulent flow and particles. Three different sets of particles are considered, and are characterized by dimensionless inertia response times equal to $\mathrm{St} = 2, 7, 29$, and by dimensionless thermal response times equal to be different varied from $\mathrm{St}_T = 0.3$

up to 435. The statistical quantities of the velocity field, the temperature field and particles dispersion are discussed to understand the role of the particles' properties on heat transfer in channel flow.

Several statistical quantities for particle velocity, temperature and concentrations and flow-particle correlations for the correlations between continuous-phase and dispersed phase were obtained form the calculations. All results for the fluid phase (mean fluid velocity, mean temperature and correlations) show good agreement with direct numerical results obtained from the literature [8, 9, 13]. The qualitative analysis of the turbulence and particle structures shows streaky patterns for the hydrodynamics and indicates how these patterns are associated with the patterns for the temperature of the particles. Particles tend to be highly concentrated in the region close to the wall but with an increasing Reynolds number, the concentrations of particles in the region close to the wall do not increase. The particles also agglomerate in the form of long strikes; the behavior is known as preferential concentration is very strong close to the wall but it can also be observed across nearly the entire domain. It has also been shown that the mean temperature of the particle is much smaller than that of the fluid, which is true for all types of particles, though the effect for the heat flux boundary condition is more pronounced near the wall and even on the wall itself. Mean streamwise velocity fluctuation in the boundary layer is different for the fluid and for the particle, and decorrelates with the increasing time response. The opposite effect has been observed for mean wall-normal components; their value for particles is smaller than for the fluid; its value for particles decreases with increasing response time. This affects the velocity-temperature correlations which are proportional to the turbulent heat fluxes. The heat flux transported by the particles in the streamwise direction can be by 50% larger (most heavy particles) compared to the fluid. The same similarity between streamwise velocity fluctuation and temperature fluctuations has been found. Distributions of the temperature close to the wall show that particle temperature and fluid temperature can be shifted for the local mean value; the shift can be relatively large. The mechanisms described here are important in many fields and industrial processes. Nonhomogenity in particle concentration can have a strong negative effect on numerous chemical processes. On the other hand, particle turbulent heat flux exerts an influence on overall heat transfer.

Acknowledgments

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