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The influence of low Prandtl numbers on the turbulent mixed convection in an horizontal channel flow: DNS and assessment of RANS turbulence models

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ABSTRACT

In this paper, the turbulent mixed convection in a channel flow with differentially heated walls is considered for a fixed Richardson number ($Ri_b = 0.5$) and three different Prandtl numbers ($Pr = 1, 0.1$ and 0.01). Numerical simulations are conducted assuming constant fluid properties and the effect of the buoyancy is taken into account by means of the Boussinesq approximation. Direct Numerical Simulations (DNS) are performed first and the effect of the buoyancy on the first and second order statistics of the fluid and thermal fields is highlighted. Furthermore, it is found that in mixed convection the Prandtl number has a much larger effect on the results than in the case of forced convection. The obtained DNS results are then used as a validation database for two different RANS turbulent heat flux models, *i.e.* the classical Reynolds analogy and a recently proposed three-equation algebraic heat flux models called AHFM-NRG+. It is observed that, as expected, the Reynolds analogy fails to predict the thermal field even for unitary Prandtl numbers fluids. On the other hand, it is shown that the AHFM-NRG+ is in a reasonable agreement with the reference DNS over the entire range of Prandtl numbers considered in the study.

1. Introduction

The mixed convection is a process in which momentum and heat are transferred within the fluid flow due to the combined effects of shear and buoyancy. This phenomenon represents an important mechanism of heat transfer which can be found in several applications such as heat exchangers, nuclear reactors and cooling systems for electronic components. Practically speaking, the mixed convection regime is bound by the two extreme cases: the forced convection and the natural convection regimes. Nevertheless, the results in mixed convection regime are far from being just the combination of those in the two extreme cases.

With respect to the forced convection regime, the pressure-driven turbulent flow in a plane channel (*i.e.*, the Poiseuille flow) has been used extensively as a representative configuration. Starting from the seminal work of Kim et al. [1], several DNS of planar channel flows in forced convection have been performed. When thermal effects are considered, the temperature is simply assumed to be a passive scalar transported within the fluid flow and the parameters that define the problem are the Reynolds and the Prandtl numbers. In addition, simulations with imposed thermal boundary conditions [2–5] as well as simulation with conjugate heat transfers [6–8] were considered.

On the other hand, the Rayleigh-Bénard convection (RBC) has been widely considered as the prototypical case for the natural convection regime. It corresponds to a free convection between two differentially heated walls and it has been extensively studied both numerically and experimentally [9–11]. In this case, the controlling parameters are represented by the Grashof number (Gr) and the Prandtl number.

Both experimental and numerical investigations of the mixed convection regime have been less frequent so far; this is due to: (i) the challenging nature of the mixed convection regime, which includes features typical of both forced and natural convection, (ii) the lack of an single representative prototypical case for this regime. With respect to the latter point, the Poiseuille-Rayleigh-Bénard (PRB) flow is an attractive option since it represents a combination of the main features of the prototypical cases of forced and natural convection. In fact, the PRB is a pressure-driven Poiseuille flow where buoyancy effects are induced through an imposed temperature difference between the bottom and the top walls of the channel. The most interesting PRB configuration is the one in which the bottom wall of the channel is kept at a higher

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temperature than the top wall since, due to the effect of the buoyancy forces, it results in an unstable thermal stratification. This PRB configuration has been the subject of early experimental studies [12–14] carried out at low and moderate Richardson numbers (Ri_b) and at unitary Prandtl number. It was observed that, compared to the forced convection regime, the buoyancy significantly alters the near-wall turbulence mechanism, leading to the onset of large scale convective thermal plumes. With respect to numerical investigations, an early simulation of the RBC with superimposed shear was performed in [15] in order to assess the combined effects of the natural convection and the mean shear on the flow. It was observed that the unstable stratification condition enhances the diffusion of the turbulent kinetic energy between the near-wall and the bulk regions. Subsequently, DNS of the PRB flow at friction Reynolds number $Re_\tau = 150$ and at low and moderate Richardson numbers have been carried out by Iida and Kasagi [16]: the statistics for both the fluid and the thermal fields were studied and it was observed that the buoyancy effects have a substantial impact on the near-wall turbulence, resulting in an increase in both the skin friction and the wall heat transfer. In the DNS study of Zonta and Soldati [17], the PRB flow was investigated at different friction Reynolds numbers (Re_τ from 110 to 180) and different friction Richardson numbers (Ri_τ from 926 to 346) and for the Prandtl number $Pr = 3$. It was found that, with respect to the mixed convection case, in the PRB flow the wall-normal transport of momentum and heat is enhanced due to the presence of large scale convective structures similar to those observed in RBC. In the same work, the effects of temperature-dependent fluid properties on the PRB flow were also investigated. In the work of Sid et al. [18], a DNS of the PRB flow was performed at two different friction Reynolds numbers ($Re_\tau = 180$ and 395) and two different Richardson numbers ($Ri_b = 0.1$ and 1) and at unitary Prandtl number. The study confirmed that both the skin friction and the wall heat transfer are enhanced under unstable stratification for sufficiently large Richardson numbers. The authors also showed the breakdown of the constant turbulent Prandtl number (Pr_t) assumption under the considered conditions. In a very recent work, Pirozzoli et al. [19] performed DNS of several mixed convection cases in an horizontal channel flow for a wide range of Reynolds and Rayleigh numbers and they showed that the mixed convection regime is characterized by the presence of longitudinal rollers within the channel height; these rollers are characterized by a large spanwise aspect-ratio.

In addition to the previous observations, it should be pointed out that the RANS approach still represents the workhorse for the modelling of the turbulent heat transfer in complex flow configurations of industrial relevance, mainly due to its reduced computational costs. In this respect, a large number of models have been proposed and assessed for the closure of the turbulent momentum flux, whilst relatively little attention has been paid to the modelling of the turbulent heat flux (THF) term [20]. In particular, in most commercial CFD codes the so-called Reynolds analogy is often the only option available for the latter purpose. This approach assumes similarity in the turbulent transport of momentum and energy, and is extremely popular due to its robustness and simplicity. Nevertheless, it presents well-known limitations especially in applications involving low-Prandtl fluids and/or non-negligible buoyancy effects. This has led to a growing interest towards the development of more advanced THF closures which would allow to overcome, at least to some extent, the shortcomings of the Reynolds analogy [21,22]. On the other hand, it is widely recognized that one of the main hampering factors for the development of such models is represented by the lack of reliable reference data [21,23,24].

In the present work, several DNS of the PRB case at moderate Reynolds number and at unitary and lower Prandtl numbers are considered. The focus of the work is on assessing the impact of the Prandtl number on the fluid and thermal fields under the effects of the buoyancy forces. To this purpose, DNS calculations at fixed bulk Reynolds number $Re_b = 5639$, corresponding to $Re_\tau = 180$ in forced convection, and Richardson number $Ri_b = 0.5$ are performed for different values of the Prandtl number: $Pr = 1, 0.1$, and 0.01. The choice of low values of the Prandtl number is particularly interesting for nuclear applications and has not been considered yet in the existing literature. Furthermore, the DNS database generated in this work can be regarded as a valuable tool to develop, calibrate and assess turbulence models in the RANS framework. Consequently, the present DNS results are employed to assess the performance of two different RANS closures for the THF term. In particular, the classical Reynolds analogy and a recently proposed algebraic closure, the so-called AHFM-NRG+ [23,25], are considered. The former closure has been chosen, despite its well-known limitations, since it still represents the most common approach employed in the RANS framework. On the other hand, the latter model has been considered since it has been developed with a focus on low-Prandtl fluids and buoyant flows. The remaining of the paper is organised as follows: Section 2 presents a description of the considered cases. The DNS methodology and the related results are discussed in Section 3. Then, the set-up of the RANS simulation and the results obtained for the different cases are described in Section 4. Finally, conclusive remarks are given in Section 5.

2. Test case description

In this work, a turbulent planar channel flow with differentially heated walls and constant fluid properties is considered. The streamwise direction is parallel to the x-axis, the wall-normal direction is parallel to the y-axis and the spanwise direction is parallel to the z-axis, as shown in Fig. 1.

The fluid flow is driven by an imposed mass flow rate and the bulk Reynolds number of the channel flow is $Re_b = U_b L_y / \nu = 5639$, where U_b is the bulk velocity and ν is the kinematic viscosity of the fluid. For a forced convection case, this corresponds to a friction Reynolds number $Re_\tau = u_\tau \delta / \nu = 180$, where $u_\tau = \sqrt{\tau_w / \rho}$, with τ_w the wall shear stress. The gravity ($\mathbf{g}$) acts downward along the y-axis. The bottom wall is kept at the uniform high temperature ($T_h = 1$) and the top wall is kept at the uniform low temperature ($T_c = 0$). As a consequence, the wall-normal temperature difference ($\Delta T = T_h - T_c$) between the bottom and the top walls is responsible for the buoyancy effects in the flow field. For the thermal field, a fixed Richardson number $Ri_b = g\beta\Delta T\delta / U_b^2 = 0.5$ is imposed, with β the thermal expansion coefficient. Three different Prandtl numbers ($Pr = \nu\rho c_p / k$) are considered, namely $Pr = 1, 0.1$ and 0.01 with, ρ the fluid density, c_p the specific heat and k the thermal conductivity.

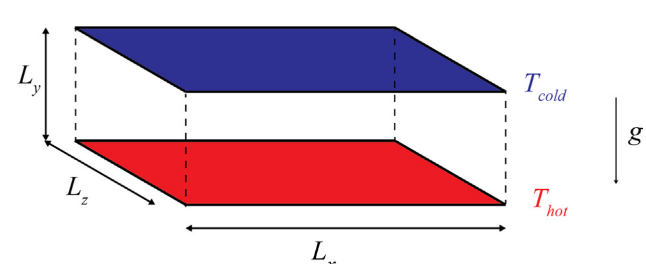

Fig. 1. Sketch of the three-dimensional computational domain for the three-dimensional mixed convection simulations.