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DNS of thermal channel flow up to $Re_\tau = 2000$ for medium to low Prandtl numbers

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ABSTRACT

Direct Numerical Simulations of turbulent heat transfer in a channel flow are presented for three different Reynolds numbers, namely $Re_\tau = 500, 1000$ and 2000. Medium and low values of the molecular Prandtl number are studied, ranging from 0.71 (air), down to 0.007 (molten metals), in order to study its effect on the thermal flow. Mixed boundary conditions at both walls are used for the thermal flow. Mean value and intensities of the thermal field were obtained. Two different behaviors were observed, depending on the Prandtl and Péclet numbers. The expected logarithmic behavior of the thermal flow completely disappears for Prandtl below 0.3. This is a direct effect of the thicker viscous thermal layer generated as the Prandtl number is reduced. Von Kármán constant was computed for cases above this Prandtl, and turbulent Prandtl and Nusselt numbers were obtained for all the cases. Finally, the turbulent budgets for heat fluxes, temperature variance and its dissipation rate are presented. As a general result, there is a scaling failure near the wall in very cases studied, which is accentuated for lower Prandtl numbers. The statistics of all simulations can be downloaded from the web page of our group.

1. Introduction

Turbulent flows are intrinsic to almost any flow in engineering. Particularly, they play a crucial role in the transport of heat. In a recent study for NASA, Slotnick et al. [1] highlighted the importance of thermal flows in aeronautics applications for the foreseeable future. As an example, the performance of the high pressure turbines present in aircraft engines is limited by the maximum temperature that can be reached without deforming the blades. An improvement in the knowledge of thermal flow around the blade could then increase the efficiency and reduce the emissions of the engine [2,3]. To cite only a couple of examples, for low and very low Prandtl numbers a better knowledge of the dynamics of thermal flows is needed for the simulation of nuclear Liquid Metal Reactors (LMR) [4,5]. Also, a direct application of the very low Prandtl cases is concentrated solar power (CSP), as stated in Cachafeiro et al. [6]. However, the dynamics of turbulent flows is still an open problem in physics. If thermal flows are included, the situation is even worse, due to the complexity of thermal flows experiments. Thus, Direct Numerical Simulation (DNS) has become one of the main tools to study the behaviour of thermal flows where little is known.

The first DNS of a thermal flow was carried out by Kim and Moin in 1987 [7], for $Re_\tau = u_\tau h/\nu \approx 180$ and $Pr = 0.1, 0.71$ and 2, where u_τ is the friction velocity, h is the half channel height and ν is the kinematic viscosity. The friction Reynolds number, Re_τ, characterize the turbulent behaviour of the flow. The molecular Prandtl number, Pr, is the ratio between the momentum diffusivity (kinematic viscosity) to the thermal diffusivity. In this work, values from 0.007 (melted sodium) to 0.71 (air) are studied. Another dimensionless number that can be derived from Re_τ and Pr is the friction Péclet number, $Pe_\tau = Re_\tau Pr$. Pe_τ plays the same role in the thermal equation than Re_τ does in the momentum equations. Therefore, Pe_τ can be understood as a parameter of how viscous or turbulent the thermal flow is.

Kim and Moin [7] obtained first order turbulence statistics, including the turbulent Prandtl number, defined later. In addition, for $Pr = 0.71$, correlations between the velocity and the temperature were also calculated. A somewhat artificial boundary condition was imposed in which heat was generated internally and removed from both cold isothermal walls. This condition for the thermal flow plays an analogous role to that of the pressure gradient does for the velocity field. Later, Lyons et al. [8] performed a simulation for $Re_\tau \approx 150$ and $Pr = 1$. The boundary condition used in this later work consisted in both walls kept at different temperatures. Finally, Kasagi et al. [9] performed a DNS for $Re_\tau \approx 150$ and $Pr = 0.71$ with a more realistic boundary condition, the Mixed

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Nomenclature

B	logarithmic profile constant
c_p	specific heat at constant pressure
h	channel half height
$\mathfrak{h}$	convective heat transfer coefficient
Nu	Nusselt number
P	pressure
Pe_τ	Péclet number ($=Re_\tau Pr$)
Pr	Prandtl number ($=\nu/\alpha$)
Pr_t	turbulent Prandtl number
q_w	normal heat flux to the walls
q_{total}	total heat flux
Re	Reynolds number ($=U_b h/\nu$)
Re_τ	Reynolds friction number ($=u_\tau h/\nu$)
t	time
T_τ	friction temperature ($=q_w/(\rho c_p u_\tau)$)
u_i	velocity fluctuation
u_τ	friction velocity $\left(=\sqrt{\tau_w/\rho}\right)$
U_i	velocity in the direction x_i
U_b	bulk velocity $\left(=\langle U_1\rangle_{x,y,z,t}\right)$
x_i	coordinate x_i ($\equiv x,y,z$)

Greek

α	thermal diffusion coefficient
θ	temperature fluctuation
Θ	transformed temperature
κ	thermal conductivity
κ_t	thermal von Kármám constant or thermal eddy diffusivity
ν	viscosity
ν_t	momentum eddy diffusivity
ρ	density
τ_w	statistically averaged wall shear stress

Superscripts

$\bullet'$	root mean square
$\bar{\bullet}$	statistically averaged
$\bullet$	normalized by h, U_b and ν
$\bullet^+$	normalized by u_τ, T_τ and ν

Subscripts

$\langle\bullet\rangle_{x_i}$	mean value in x_i direction

Boundary Condition (MBC from now on). For this condition, the average heat flux over both heating walls is constant and the temperature increases linearly in the streamwise direction. The instantaneous heat flux may vary with respect to time and position. This is the boundary condition used in this work.

In the work done by Piller [10], three different boundary conditions were used and the differences in the temperature field were studied. The first one, ideal isoflux boundary condition, assumes that the instantaneous wall heat flux is both uniform in space and constant in time. Therefore, the time-averaged temperature is linear with x. For the ideal isothermal boundary condition, the time-averaged wall temperature is uniform and constant, resulting in an exponential variation of the time-averaged temperature difference. The last one was the MBC, the one used in this work (explained above). He found that the MBC acts as an ideal isothermal boundary condition in the inner layer and as an ideal isoflux boundary condition in the outer layer.

After these simulations were made, the trend has been to increase the friction Reynolds number for different molecular Prandtl numbers. However, values of Re_τ and Pr are limited by the computational cost, which can be approximated by $L_x^2 L_y Re_\tau^4 Pr^{3/2}$ [11]. Thus, the Reynolds number achieved is still low for a majority of Prandtl numbers. Kawamura et al. [12] made an exhaustive analysis of the Prandtl number influence for $Re_\tau \approx 180$. Pr varied for a wide range from 0.025 to 5. First order turbulent statistics were calculated, but also the budgets of the transport equations for the turbulent heat flux and the temperature variances were obtained. One year later, Kawamura et al. [13] performed a new simulation increasing the Reynolds number up to a value of $Re_\tau \approx 395$ and for $Pr = 0.025, 0.2$ and 0.71. They obtained the same set of results than in the previous paper and also images of the instantaneous velocity and thermal field were visualized to analyze the structure of the vortices.

Abe et al. [14] reached Reynolds numbers of $Re_\tau \approx 640$ and 1020 for $Pr = 0.025$ and 0.71, in both cases. Seki et al. [15] made a simulation for $Re_\tau \approx 180$ and for $Pr = 0.71, 1, 2$ and 10. The values of $Pr = 0.025$ and $Pr = 10$ are, up to the knowledge of the authors, the lowest and highest values, respectively, used in a DNS of a thermal channel flow. To increase the Reynolds number, one of the alternatives would be to reduce the length and width of the computational box. This box, however, has to be large enough to accurately describe the flow. Lozano-Durán and Jiménez for isothermal channel flow [16], and Lluesma et al. for thermal ones [17], found out that a relatively small computational box of stream- and spanwise sizes of only $2\pi h \times \pi h$ can satisfactorily recover the one-point statistics of the flow. Using this box, Lluesma et al. [17] ran a simulation for $Pr = 0.71$ and $Re_\tau = 2000$. Among other things, they found that for these two parameters the thermal flow shows the first stages of a thermal logarithmic layer for a thermal von Kármán constant of 0.44. This constant seems to be actually constant in the range of Reynolds numbers studied. In 2016, Pirozzoli et al. [18] ran different simulations for three different Prandtl numbers: $0.2, 0.71$ and 1 using a similar boundary condition to [7]. Four different friction Reynolds numbers were used: $550, 1000, 2000$ and, for the first time up to the knowledge of the authors, 4000. A comparison of Pirozzoli et al.'s data and the one obtained in this work is presented in Section 3.5.

In this paper, moderated Reynolds numbers of values $500, 1000$, and 2000 are simulated. The behaviour of the thermal flow for medium to low Prandtl numbers is studied. Table 1, summarizes the simulations made for this work. Already available simulations and the new ones are shown. Most of these simulations are new and, for the first time, Prandtl number below 0.01 have been simulated for turbulent channel flows. First order turbulent statistics and turbulent budgets have been obtained and will be discussed.

Table 1
Summary of cases studied. The x indicates a published simulation at close values of Re_τ and Pr. The $\circ$ denotes a new simulation.

$Pr \mid Re_\tau$	500	1000	2000
0.71	x [14]	x [14]	x [17]
0.5	$\circ$	$\circ$	$\circ$
0.3	x [14]	x [18]	x [18]
0.1	x [14]	x [18]	x [18]
0.05	$\circ$	$\circ$	$\circ$
0.02	x [14]	x [14]	$\circ$
0.01	$\circ$	$\circ$	$\circ$
0.007	$\circ$	$\circ$	$\circ$