HEAT TRANSFER IN ROTATING CHANNEL FLOW

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ABSTRACT

In the present study (Brethouwer, 2018, 2019) heat transfer in rotating turbulent channel flow is investigated through DNS at moderate Reynolds numbers. It is shown that rotation has a large influence on the mean temperature profiles and heat fluxes and also on the structure of the temperature field. The turbulent Prandtl number on the unstable side is strongly reduced by rotation, implying that the Reynolds analogy for momentum-heat transfer does not necessarily hold for rotating turbulent channel flow.

INTRODUCTION

The influence of spanwise rotation on turbulent channel flow has been investigated intensively, see, for example, Johnston *et al.* (1972) and Kristoffersen & Andersson (1993). A recent study of the influence of rotation on the turbulence statistics and structures at moderate Reynolds numbers is presented in Brethouwer (2017). Also the higher-order moments of the streamwise velocity fluctuations (Xia *et al.*, 2018) and the linear instabilities that can occur in rotating channel flow (Brethouwer, 2016) have been studied at various Reynolds numbers. By contrast, the influence of spanwise rotation on the mass or heat transfer in turbulent channel flow has received much less attention. However, Nagano & Hattori (2003) and Liu & Lu (2007) have examined the transport of a passive scalar in spanwise rotating channel flow at low Reynolds numbers through DNS and observed that this influence is significant. In the present study (Brethouwer, 2018, 2019) heat transfer in rotating turbulent channel flow is further investigated through DNS at more moderate Reynolds numbers. It is shown that the Reynolds analogy for momentum-heat transfer does not necessarily hold for rotating turbulent channel flow.

DIRECT NUMERICAL SIMULATIONS

DNS of heat transfer in turbulent channel flow subject to rotation about the spanwise direction have been carried with a pseudo spectral code. It is assumed that the temperature variations are small so that buoyancy forces can be neglected. This implies that the heat transfer can be examined by means of a passive scalar in the DNS. In the first DNS series the Reynolds number $Re = U_b h/\nu$ based on the the bulk mean velocity U_b and the channel half gap h is fixed at 20000 and the rotation number $Ro = 2\Omega h/U_b$ is varied from 0 to 1.2, where Ω is the system rotation rate. In this DNS series the scalar is constant but different at the two walls, leading to steady scalar transport across the channel. Further details and numerical parameters of the DNS can be found in Brethouwer (2018). In the second DNS series Re is fixed at 14000 and $Ro = 2\Omega h/U_b$ is varied from 0 to 0.75. In this DNS series, two different boundary conditions for the scalar are employed in order to investigate the influence of the boundary conditions on passive scalar transport in rotating channel flow (Brethouwer, 2019). In one case, the scalar transport is driven by an assigned scalar difference at the walls as in the first DNS series, leading to a wall-normal mean scalar gradient. In the other case, a constant streamwise mean scalar gradient is imposed.

RESULTS

When turbulent channel flow with a passive scalar is subject to spanwise system rotation we can observe an unstable channel side with relatively strong turbulence and turbulent scalar transport, and a stable channel side with relatively weak turbulence or laminar-like flow, weak turbulent scalar transport but large scalar fluctuations and steep mean scalar gradients. Around $Ro = 0.15$ large counter-rotating vortices can be observed on the unstable and these leave a clear imprint on the scalar field, see figure 1.(a). Distinct turbulent-laminar patterns are observed at certain values of Ro on the stable channel side and these induce similar patterns in the scalar field, see figure 1.(b).

Mean scalar profiles of the second DNS series with two different scalar boundary conditions are shown in figure 2. In the case with the assigned scalar difference at the walls (figure 2.a) the mean scalar value decreases with Ro on the unstable (left) channel side whereas on the stable (right) channel side the mean scalar gradient becomes large at high Ro. This is the result of the relatively strong and weak turbulent scalar transport on the unstable and stable channel side, respectively. The mean scalar profile in the case with a constant mean streamwise scalar gradient is naturally symmetric if $Ro = 0$ but becomes asymmetric under the influence of rotation (figure 2.b). At higher Ro the mean scalar gradient becomes very small on the unstable channel side.

Figure 3(a) and (b) show for the first DNS series with the assigned scalar difference at the walls the correlation coefficients $\rho_{u\theta} = \overline{u\theta}/(u'\theta')$ and $\rho_{v\theta} = -\overline{v\theta}/(v'\theta')$ respectively, where u and v are the streamwise and wall-normal fluctuations, respectively, θ the scalar fluctuation and a prime $'$ denotes root-mean-square values. On the unstable channel side $\rho_{u\theta}$ is strongly reduced due to rotation and this leads to an alignment between the turbulent scalar flux vector and mean scalar gradient. On the stable channel side $\rho_{v\theta}$

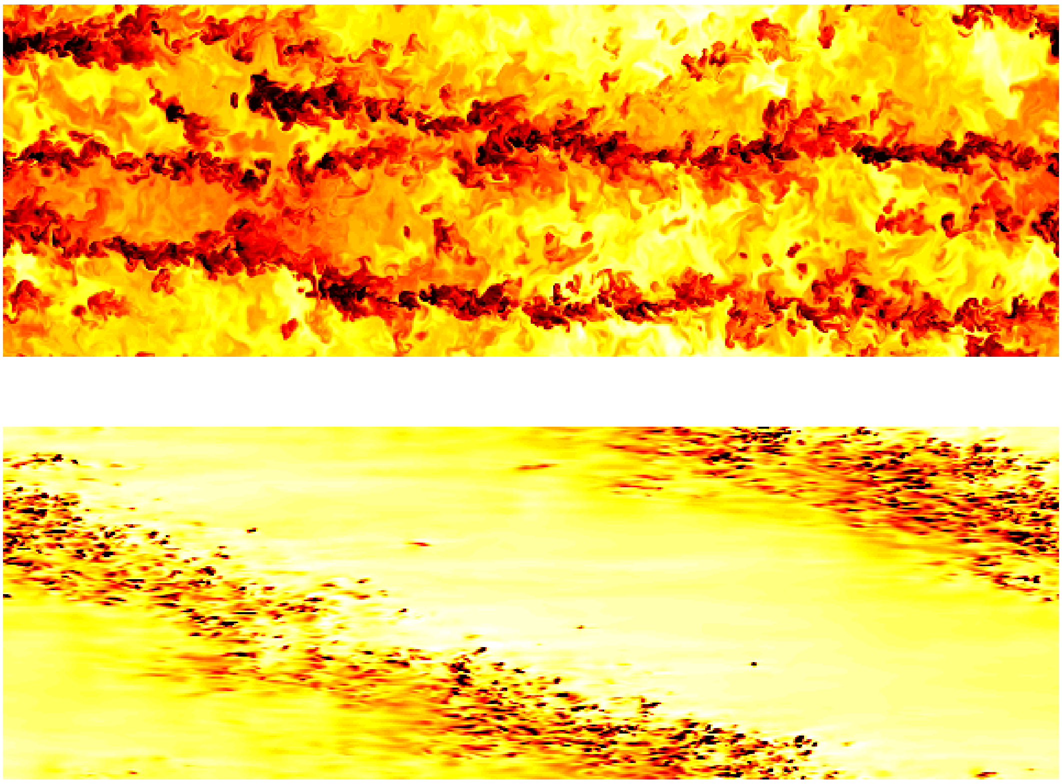

Figure 1. Visualizations of (a) the scalar field in an x-z plane on the unstable side at $y = -0.5$ at $Ro = 0.15$ and (b) of the scalar gradient at the wall at $y = 1$ on the stable side at $Ro = 0.45$.

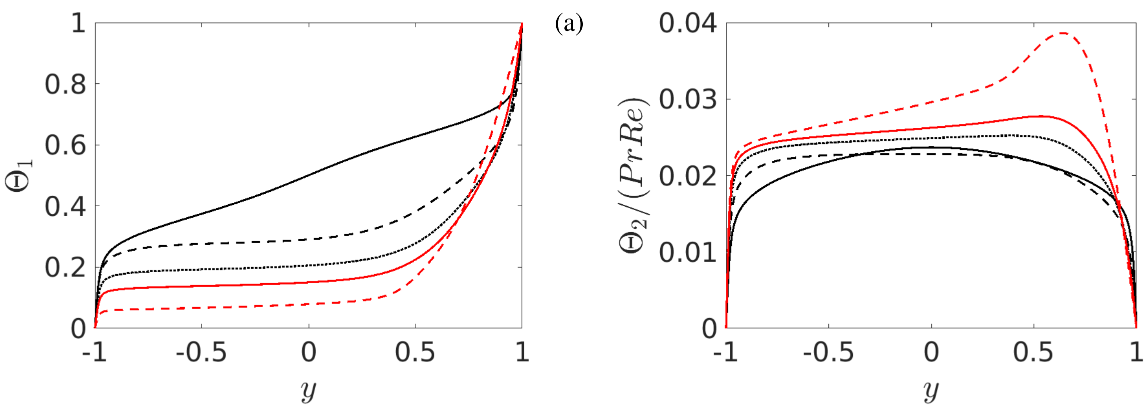

Figure 2. Mean scalar profiles (a) in the case with the assigned scalar difference at the walls and (b) the case with the constant mean streamwise scalar gradient at $Ro = 0$ (black solid), $Ro = 0.15$ (black dashed), $Ro = 0.3$ (black dotted), $Ro = 0.45$ (red solid), $Ro = 0.75$ (red dashed).

is much reduced by rotation, which contributes to a weak turbulent scalar transport.

Mean scalar profiles and other scalar statistics differ in the two cases with different boundary conditions but are similar in the near-wall region in terms of local wall units (Brethouwer, 2019). Budgets of the governing equations of the scalar energy and scalar fluxes as well as other statistics relevant for turbulence modelling have been computed and are presented in Brethouwer (2018).

The main conclusions of the present study are that rotation reduces the similarity between the scalar and velocity field and that the Reynolds analogy for scalar-momentum transport does not hold for rotating turbulent channel flow. Rotation influences the turbulent scalar flux differently than the Reynolds shear stress. This results in a strongly reduced turbulent Prandtl number Pr_t of less than 0.2 on the unstable channel side away from the wall at higher Ro (figure 4). On the unstable channel side, scalar scales become larger than turbulence scales according to the computed one-dimensional streamwise and spanwise spectra. This is in contrast to non-rotating channel flow where the scalar and velocity scales are much more similar and the turbulent Prandtl number is near unity. The conclusion that the Reynolds analogy for scalar-momentum transfer does not apply to rotating channel flow is not influenced by the scalar boundary conditions. More results and further discussions can be found in Brethouwer (2018) and Brethouwer (2019).

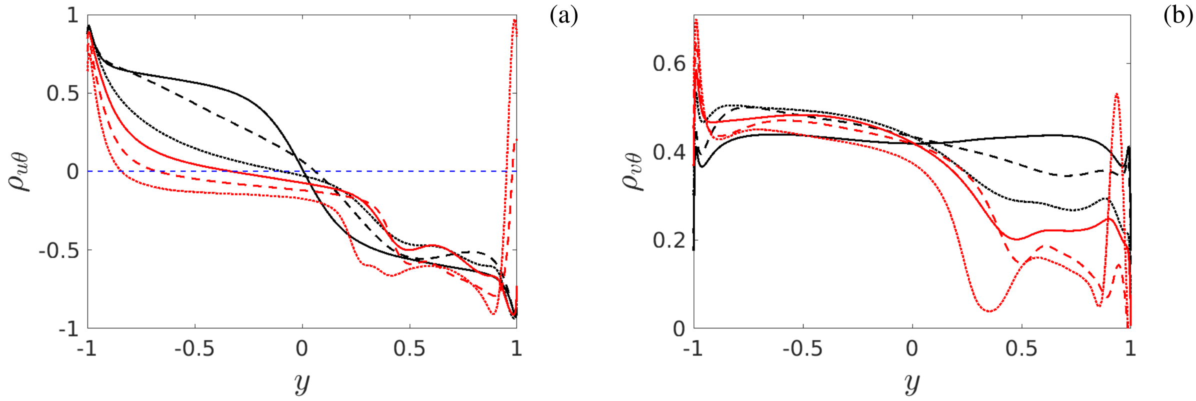

Figure 3. Profiles of (a) $\rho_{u\theta}$ and (b) $\rho_{v\theta}$. $Ro = 0$ (solid black), $Ro = 0.15$ (dashed black), $Ro = 0.45$ (dotted black), $Ro = 0.65$ (solid red), $Ro = 0.9$ (dashed red), $Ro = 1.2$ (dotted red).

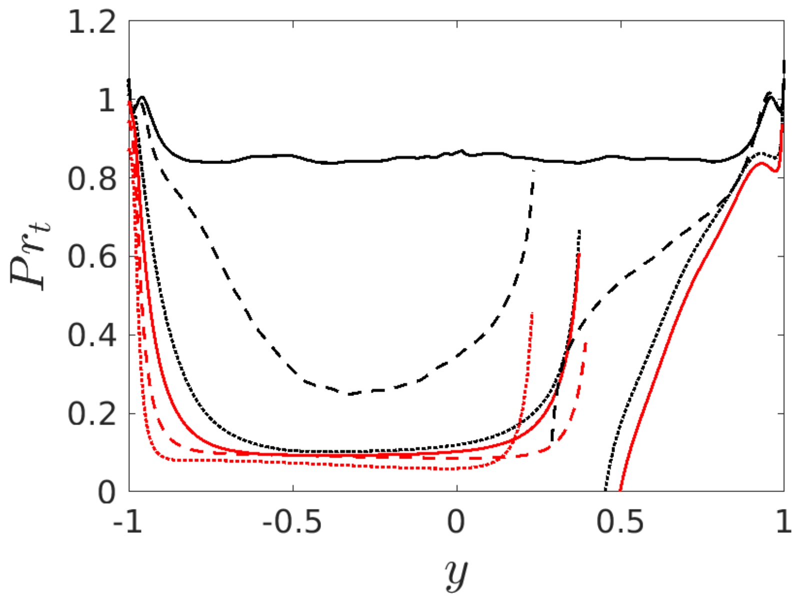

Figure 4. Turbulent Prandtl number Pr_t. Lines as in figure 3.

REFERENCES

Brethouwer, G. 2016 Linear instabilities and recurring bursts of turbulence in rotating channel flow simulations. *Phys. Rev. Fluids* **1**, 054404.

Brethouwer, G. 2017 Statistics and structure of spanwise rotating turbulent channel flow at moderate reynolds numbers. *J. Fluid Mech.* **828**, 424–458.

Brethouwer, G. 2018 Passive scalar transport in rotating turbulent channel flow. *J. Fluid Mech.* **844**, 297–322.

Brethouwer, G. 2019 Influence of spanwise rotation and scalar boundary conditions on passive scalar transport in turbulent channel flow. *Phys. Rev. Fluids* **4**, 014602.

Johnston, J. P., Halleen, R. M. & Lezius, D. K. 1972 Effects of spanwise rotation on the structure of two-dimensional fully developed turbulent channel flow. *J. Fluid Mech.* **56**, 533–559.

Kristoffersen, R. & Andersson, H. I. 1993 Direct simulations of low-Reynolds number turbulent flow in a rotating channel. *J. Fluid Mech.* **256**, 163–197.

Liu, N.-S. & Lu, X.-Y. 2007 Direct numerical simulation of spanwise rotating turbulent channel flow with heat transfer. *Int. J. Numer. Meth. Fluids* **53**, 1689–1706.

Nagano, Y. & Hattori, H. 2003 Direct numerical simulation and modelling of spanwise rotating channel flow with heat transfer. *J. Turbulence* **4**, 010.

Xia, Z., Brethouwer, G. & Chen, S. 2018 High-order moments of streamwise fluctuations in a turbulent channel flow with spanwise rotation. *Phys. Rev. Fluids* **3**, 022601(R).