Passive Scalar Transport in Rotating Turbulent Channel Flows

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The direct numerical simulation (DNS) of turbulent heat transfer in rotation channels has been carried out in order to investigate the effect of rotation orientation on the thermal fields. The study aims at providing clear understanding of heat transfer mechanism near the wall of rotating passages. The fully developed turbulent channel flow with constant, but different wall temperatures has been simulated under streamwise mode of rotation. The temperature is considered as a passive scalar with no buoyancy effect. Prandtl and Reynolds numbers are kept at 0.71 and 150, respectively.

Keywords: turbulent heat transfer, system rotation, channel flow, DNS.

INTRODUCTION The transport of heat in rotating passages is of great importance in the design of highly efficient small and micro gas turbines recently under development. Clear understanding of heat transfer mechanism near the wall of rotation passages inside gas turbine rotors is essential if higher levels of temperature would be attained. With the aid of DNS, detailed information about the thermal field can be obtained under the effect of various body forces while changing the flow and scalar field parameters [1]. The transport of passive scalar in turbulent channel flows has been studied extensively by using DNS [2-4]. Specifically, for the Prandtl number of 0.71, Kasagi et al. [5] provided detailed budgets at $Re_\tau = 150$. The databases of DNS of turbulent channel flows have been used for modelling of passive scalar transport for gases [6]. The effect of system rotation on turbulent channel rotating in spanwise [7] and streamwise [8] modes has been studied without heat transfer. The combined effect of buoyancy and Coriolis forces showed four different complicated cases depending on the orientation of both body forces when the spanwise rotating was imposed [9]. The present study aims at studying the effect of streamwise rotation on the turbulent heat transfer considering the temperature as passive scalar and neglecting the buoyancy effect.

NUMERICAL METHOD DNS using spectral methods has been performed for fully developed channel flow. Coarse grids of 64^3 in all directions are used. The Reynolds number Re_τ (based on channel half width and friction velocity) and Prandtl number Pr are fixed at 150, and 0.71, respectively, while two rotation numbers Ro_t of 2.5 and 7.5 will be presented. The computational size is 5pd x 2d x 2pd in the streamwise, wall-normal, and spanwise directions, respectively. The two walls are kept at two different, but constant temperatures.

RESULTS AND DISCUSSIONS In the streamwise rotating channel, anti-symmetric mean velocity profiles are noticed for the spanwise component W with four regions of opposite motions in the cross-stream plane, as shown in figure 1. Symmetric and more flatten profiles in the streamwise component U can be observed with increasing the rotation number.

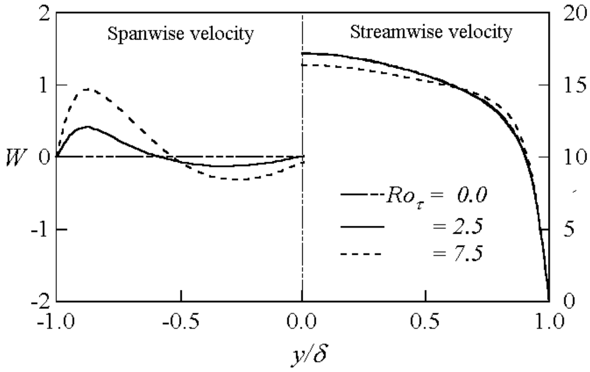

Figure 1 Mean streamwise and spanwise velocities

All the components of Reynolds stresses are non-zero, unlike the spanwise rotating case. The normal stress that most affected by system rotation is the $\overline{ww}$ component, which is drastically enhanced not only near the wall but also in the core region (see figure 2). The wall-normal stress reveals enhancement within the channel centre along with little decrement in near wall region. The off-diagonal correlation $\overline{uw}$ is created having its peak values near the walls with anti-symmetric profiles as shown in figure 3. The $\overline{vw}$ on the other hand is symmetric and nearly constant over $|y/d| \le 0.8$.

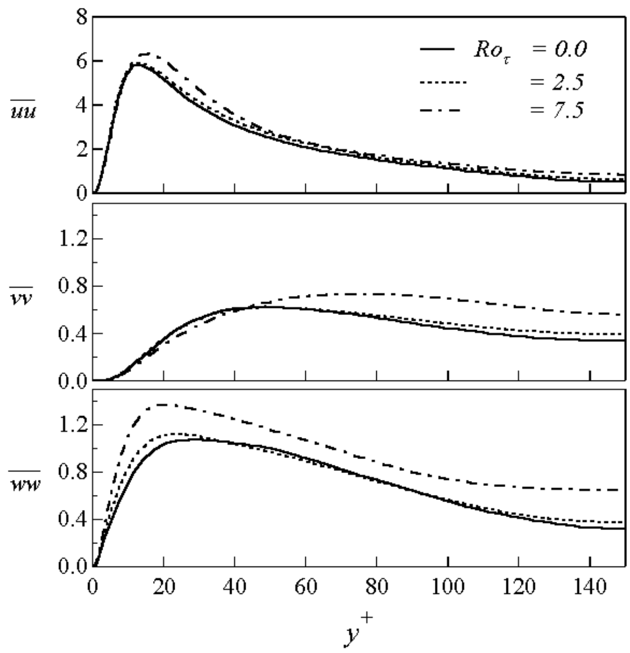

Figure 2 Normal stresses in streamwise rotating channel

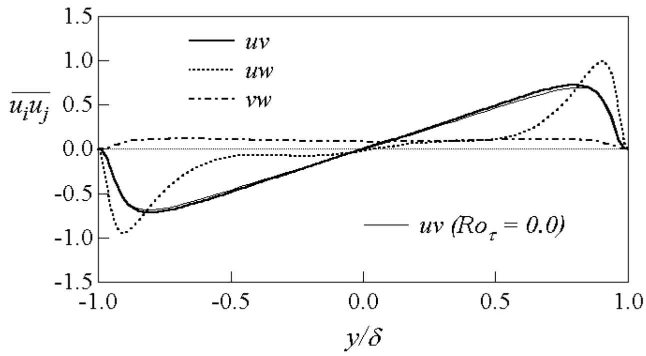

Figure 3 Off-diagonal Reynolds stresses components at Ro = 7.5

The mean temperature profiles under spanwise and streamwise mode of rotation are shown in figure 4. While the temperature increases rapidly in the pressurized half under spanwise rotation, it shows anti-symmetric reflection at the centreline in the streamwise case with decrement/enhancement near the trailing/leading walls, and the change is evidence at the higher rotation number.

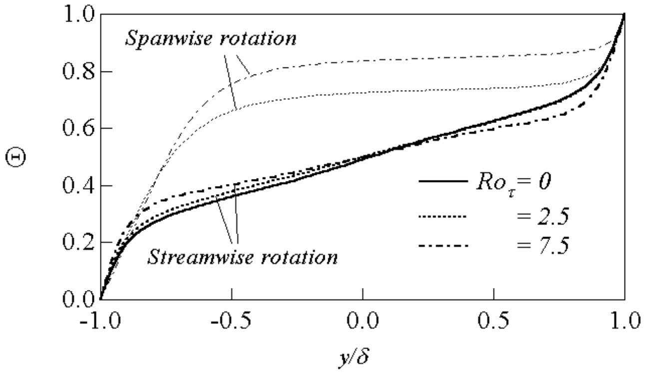

Figure 4 Mean temperature profiles

The skin friction C_f and Nusselt number Nu normalized by their corresponding non-rotating values are listed in table 1. While the pressure side shows the much enhancement in Nu with associated increment in C_f, the corresponding coefficients at the suction side decrease, and the net effect is not remarkable. The Nusselt shows enhancement in streamwise rotation case with the increase of Ro_t with less penalty of C_f increase. The enhancement in Nu may be attributed to higher mean temperature gradient at the walls.

Table 1 Friction and heat transfer coefficient

	Ro_t = 2.5		Ro_t = 7.5	
	C_f/C_{fo}	Nu/Nu_o	C_f/C_{fo}	Nu/Nu_o
Spanwise S.S.	0.587	0.671	0.512	0.508
Spanwise P.S.	1.4	1.712	1.378	1.737
Streamwise	1.003	1.048	1.096	1.216

The rms value of temperature fluctuations, shown in figure 5, gives higher values near wall and decrement at the channel core with increasing rotation number. The mean gradient of temperature, again, is responsible for that since it directly affects the production of temperature variance as shown in figure 6.

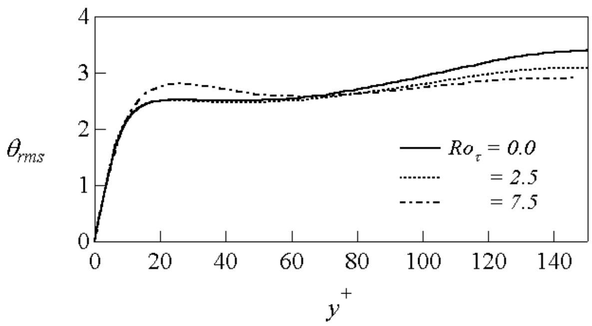

Figure 5 Rms temperature fluctuations for streamwise rotation

The streamwise heat flux, shown in figure 7(a), reveals higher levels within the buffer region with little decrement far from the walls. The wall-normal heat flux shows reverse trend while increasing Ro_t; first reduction in the core and little increment near wall at the lower Ro_t, then the opposite trend at Ro_t of 7.5, as shown in figure 7(b). This may be attributed to the induced production term due to rotation, and the behaviour of wall-normal stress near and far from the walls.

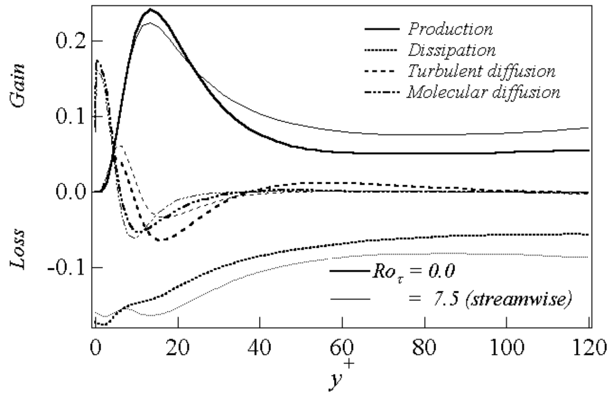

Figure 6 Budgets of the temperature variance k_q.

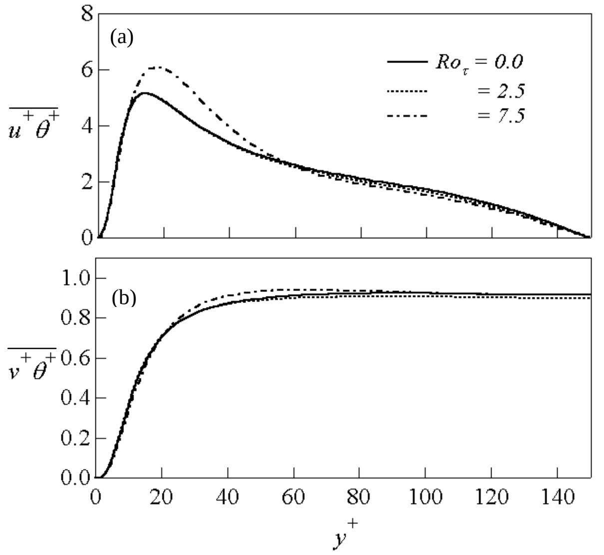

Figure 7 Heat fluxes; (a) streamwise, and (b) wall-normal components

CONCLUSIONS The effect of rotation on the transport of a passive scalar has been investigated by a series of DNS for streamwise rotation. The study shows the behaviour of temperature variance and wall-normal heat flux, which is different from those in the spanwise case but in general closer to the non-rotating case. Enhancement in heat transfer can be achieved with a moderate increase in skin friction.

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