DNS of heat transfer in a high Reynolds number turbulent channel flow with local forcing

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ABSTRACT
Direct Numerical Simulations (DNS) of the velocity/temperature fields at a Reynolds number of 10400 (based on the centerline velocity) in a turbulent channel flow, with periodic normal blowing/suction velocity disturbances located cyclically along the channel at both walls, are presented. In this opportunity, we include the analysis of the local forcing influence on the turbulent heat transfer as a continuation of a previous study [1].

INTRODUCTION
Skin friction reduction in turbulent flows has been the topic of several investigations, not only experimental but numerical approaches can be found in the literature. The different techniques for drag reduction may be categorized into active or passive ones, according to the requirement or not of external energy for normal operation. On the other hand, when dealing with the energy transport equation, it is usually desired the achievement of a heat transfer augmentation. Unfortunately, due to the inherent similarity between the momentum and scalar transport, especially, in the vicinity of the wall, it is difficult to achieve drag reduction and heat transfer augmentation simultaneously, when passive control methodologies are employed.
Special interests have recently been focused on reducing skin friction by controlling the coherent structures that arise when a periodic disturbance is imposed on the flow. One simple and efficient way to create a cyclic disturbance on wall-bounded flows is by means of local forcing, which consists on perturbing the flow by a periodic blowing/suction velocity (with a specific frequency and amplitude) applied in a confined zone over the wall.
Direct numerical simulations have showed that attenuation of the streamwise vortices by means of active blowing/suction over the entire wall significantly reduces the skin friction (Choi *et al.* [2]).
Tardu [3] investigated experimentally in a wind tunnel the effect of time periodical blowing through a slot on a boundary layer, concluding that unsteady blowing strongly affected the near wall flow and the vorticity generation mechanism. The average drag reduction was approximately 20%. Mosyak and Hetsroni [4] developed a new experimental method for burst frequency detection (considering bursting as sharp intensification of production of turbulence in the wall layer) on a fully developed turbulent water channel. In the two previous studies, similar non-dimensional bursting frequencies were found in spite of the different considered conditions: around $f^+ = f\upsilon / u_\tau^2 = 0.01$, where υ is the kinematic viscosity and u_τ the friction velocity.

The idea is to understand how coherent structures may be influenced by different amplitudes and frequencies of the local perturbation; and, consequently, to analyze how turbulent thermal structures behave under this time-dependent boundary condition.

NUMERICAL PROCEDURE
Figure 1 shows the computational domain where the governing equations (continuity, momentum and energy) have been discretized in an orthogonal coordinate system using a staggered central second-order finite-difference scheme. The discretized system is advanced in time using a fractional-step method, with viscous terms treated implicitly and convective terms explicitly. The large, sparse matrix resulting from the implicit terms is inverted by performing FFT (Fast Fourier Transformation) in the homogeneous directions and applying tridiagonal solvers in the non-homogeneous directions. Details about the numerical procedure can be found in [5].

$$\nabla \cdot \vec{U} = 0 \qquad (1)$$

$$\frac{\partial U_i}{\partial t} + \frac{\partial U_i U_j}{\partial x_j} = -\frac{\partial P}{\partial x_i} + \frac{1}{Re}\frac{\partial^2 U_i}{\partial x_j^2} \qquad (2)$$

$$\frac{\partial \theta}{\partial t} + \frac{\partial \left(\theta U_j\right)}{\partial x_j} = \frac{1}{Re\,Pr}\frac{\partial^2 \theta}{\partial x_j^2} \qquad (3)$$

A mean parabolic velocity with random fluctuations is imposed as initial condition in the whole domain. A no-slip condition is considered at both walls (except in the local forcing zone). Periodic boundary conditions are assumed along the spanwise as well as the streamwise directions. Local forcing is modeled as a vertical velocity, V_f, (suction and blowing) with a sinusoidal behavior imposed at both walls in a slot of length, L_z, and width, L_s, equal to $L_x/85$. Isothermal walls are assumed for the thermal field.

RESULTS AND DISCUSSION

Figure 1 shows the dimensions of the computational box: $L_z=\pi$, $L_y=2$ and $L_x=2\pi$. The number of points selected after performing a grid independence test is 161x177x257, along the spanwise, normal and streamwise directions, respectively. The Reynolds number is 10400, based on the centerline velocity, U_C, or 395, based on the friction velocity, u_τ. The molecular Prandtl number is 0.71. The forcing frequencies $\left(\overline{f} = f\, h/U_C\right)$ are non-dimensionalized by the half height, h, and the centerline velocity, U_C, of the channel and are selected around the bursting frequency in Tardu [2] and Mosyak and Hetsroni [3]: 0.1, 0.32, 0.64 and 1.6. Furthermore, the nondimensional amplitudes $\left(A_o = V_{f\,\max}/U_C\right)$ are 0.2 and 0.35. Figure 2 depicts a comparison of the Stanton number of forcing cases with the Stanton number obtained in the unforced channel $\left(S_t/S_{to}\right)$ along the streamwise direction. High values of the Stanton number can be appreciated very close to the forcing source (a maximum local value of 1.5 is observed for S_t/S_{to} in all cases) and the maximum average heat transfer augmentation (10%) is accomplished at $\overline{f}$ = 0.64 and A_o = 0.2.

CONCLUSIONS

DNS of a fully developed turbulent channel is analyzed when cyclical local forcing is considered. The maximum heat transfer enhancement was achieved at a specific frequency of $\overline{f}$ = 0.64. Forcing frequency possesses a stronger influence on the thermal field than amplitude does.

REFERENCES

[1] G. Araya, S. Leonardi, L. Castillo and P. Orlandi (2006), *DNS of turbulent channel flow with local forcing at walls*, submitted to International Journal of Transport Phenomena.

[2] Choi H, Moin P, Kim J (1994), *Active turbulence control for drag reduction in wall-bounded flows*. J Fluid Mech 262:75–110.

[3] S. Tardu (1998), *Near wall turbulence control by local time periodical blowing*, Experimental Thermal and Fluid Science 16, 41-53.

[4] A. Mosyak and G. Hetsroni (2004), *Visual study of bursting using infrared technique*, Experiments in Fluids 37, 40–46.

[5] P. Orlandi, S. Leonardi, R. Tuzi and A.R. Antonia (2003), *Direct numerical simulations of turbulent channel flow with wall velocity disturbances*, Phys. Fluids 15, 3587–3601.

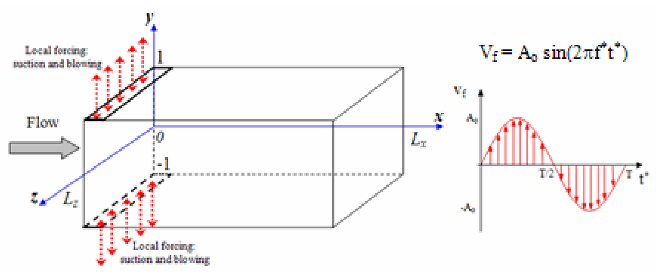

Fig. 1: Schematic of the channel with local forcing.

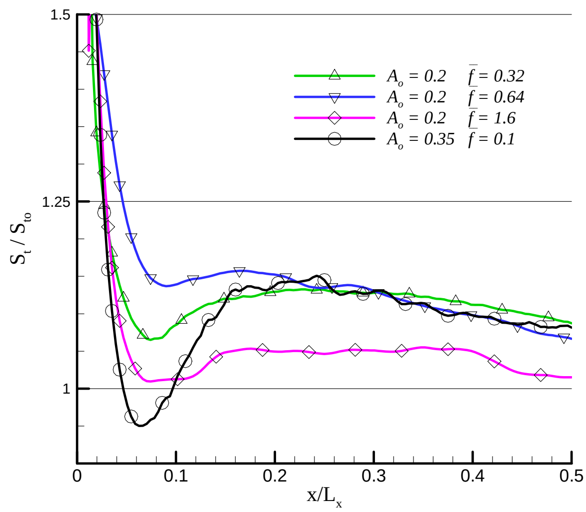

Fig. 2: Variation of the Stanton number along x.