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DIRECT NUMERICAL SIMULATIONS OF PIPE FLOW WITH WALL TRANSPIRATION

Milena Jordão Rempto
Hamidreza Ambarlooei
Atila Pantaleão Silva Freire
Universidade Federal do Rio de Janeiro - Programa de Engenharia Mecânica/COPPE, Rio de Janeiro, Brazil

Abstract. *Despite being found in many industrial applications, the study of internal flows with wall transpiration is mainly absent in literature. Direct Numerical Simulation, or DNS, is used in this work in order to characterize pipe flows for five different transpiration rates at the wall, both for injection and suction. Results are compared to formulations for impervious wall pipes and the flow velocity profile in the near wall region is analysed, both for the mean velocity and the turbulent fluctuations.*

Keywords: *DNS, pipe flow, wall transpiration, turbulent boundary layer*

1. INTRODUCTION

Internal flows submitted to wall injection are found in many industrial applications, from turbine cooling to oil production in wells. This flow configuration is challenging for DNS since the addition of mass at the wall implies that the main flow accelerates throughout the computational domain. The implication is that the use of cyclic boundary conditions at inlet and outlet is no longer valid. To avoid this difficulty, the literature on the numerical simulations of flows with wall transpiration usually considers only Poiseuille flows with injection at, say, the bottom wall and suction at the top wall. The addition and suppression of mass at the same rate guarantees parallel conditions for the mean flow and the use of cyclic boundary conditions (Sumitani and Kasagi, 1995; Nikitin and Pavel'ev, 1998; Avsarkisov *et al.*, 2014). This condition unfortunately does not represent the industrial applications of interest, where generally only injection or suction are present at a given time. It also introduces an artificial flow asymmetry in the normal direction. Furthermore, the application of this numerical artifice is not possible for pipe flows. In this study, DNS of pipe flows with either injection or suction at both walls – bottom and top – is performed and compared to formulations and the experimental data of other authors.

2. COMPUTATIONAL PROCEDURE

The numerical domain is as shown in Figure 1. The pipe on the left has an impervious wall and the outlet is cyclically mapped to the inlet. Its outlet is also mapped as the inlet condition for the second pipe, on the right, where fluid is transpired at the wall at a constant rate of v_w (the velocity normal to the wall). Both negative and positive transpiration rates were simulated: three injection cases (v_w/u_τ equals 0.095, 0.053 and 0.015, at $x = 24D$) and two suction cases (v_w/u_τ equals -0.015 and -0.063, at $x = 24D$). At the outlet of the right pipe, a convective boundary condition is applied (Ferziger and Peric, 2002). The convective velocity is calculated at every time step as the average velocity at the outlet of the second pipe. The mesh used has 12 million elements and achieves $y^+ = 1$ at the wall. The friction Reynolds number for the flow at the impervious wall region is about 360.

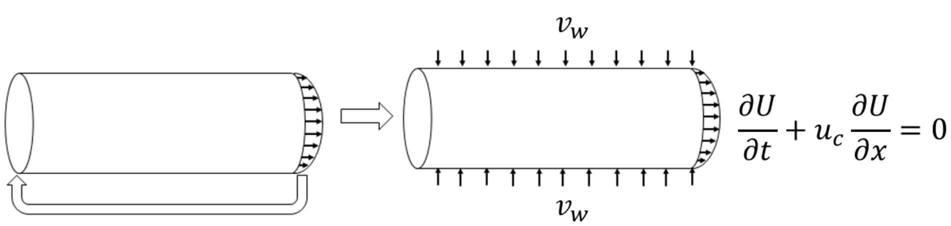

Figure 1. Numerical domain

3. RESULTS

A summary of the simulations performed is shown in Tab. 1, where $v_w > 0$ represents injection while $v_w < 0$ stands for suction. For an internal flow, when there is addition or subtraction of mass at the wall, the flow will accelerate or decelerate, respectively, along x (the main flow direction). Transpiration at the wall will therefore present a dual effect: while it changes the structure of the boundary layer, at the same time it also accelerates the main flow.

As flow rate changes along x, properties such as the pipe centreline velocity and the friction velocity at the wall will have to be determined locally, being thereby a function of x. The friction velocity (u_τ) was obtained through the balance of momentum at a given pipe section, as shown in Eq. 1. The values of u_τ and $v_w^+ = v_w/u_\tau$ (non-dimensional transpiration rate) are given in Tab. 1 for $x = 24D$, where D is the diameter of the pipe and $x = 0$ is the inlet of the impervious wall pipe (see Fig. 1). In pipe flows, the wall friction (τ_w) was found to increase with injection and to decrease with suction.

$$\tau_w = \rho u_\tau^2 = \frac{D}{4}\left(-\frac{d\overline{p}}{dx} - \rho\frac{d}{dx}\right) = \frac{D}{4}\left(-\frac{d\overline{p}}{dx} - 2\rho\overline{u}\frac{4v_w}{D}\right) \qquad (1)$$

The mean velocity profiles obtained from DNS at $x = 24D$ are plotted in non-dimensional parameters in Fig. 2. At the fully turbulent region the results significantly diverge from the classical log-law ($u^+ = (1/\varkappa)\ln y^+ + A$). It is clear than that the log-law becomes inapplicable for flows over transpired walls. Therefore new laws of the wall, as those proposed by Clarke *et al.* (1955), Silva Freire (1988) and Guimarães (2016), are needed. An evident characteristic of the mean velocity profiles is that injection of fluid at the wall increases the slope of the curve $u^+(\ln y^+)$, while suction decreases it. For the injection cases, a nearly asymptotic behaviour was found for u^+ as a function of $\ln y^+$ for different injection rates v_w^+.

A secondary critical effect of wall transpiration is its influence on the distribution of turbulent fluctuations. That can be taken from the Fig. 3, where turbulent kinetic energy is plotted for the different transpiration rates simulated. The turbulent kinetic energy (k) is calculated as in Eq. 2, where u' stands for the turbulent velocity fluctuation at a given direction and the subscripts x, r and θ refer to the axial, radial and azimuthal directions, respectively.

In Figure 3, the main difference between transpiration rates is found on the magnitude of k. The injected walls present a higher peak value of k, while suction walls show the exactly opposite effect, with a decrease on the maximum k. This behaviour suggests that the injection at the wall tends to stimulate turbulence, while suction tends to suppress it, relaminarizing the flow.

$$k = \frac{1}{2}\left(\overline{u_x'^2} + \overline{u_r'^2} + \overline{u_\theta'^2}\right) \qquad (2)$$

Another important conclusion may be obtained from Figures 4 and 5. They illustrate the instantaneous velocity and vorticity fields, respectively, for different transpiration rates in a same pipe section ($x = 24D$). For internal flows, the injection of fluid at the walls induces not only an acceleration of the main flow (as shown by the velocity contour), but it also increases the value of vorticity in the near wall region. The exact opposite effect happens for suction: the main flow decelerates along the pipe and the vorticity is decreased near the wall. In fact, more vortical structures are found close to the wall when injection rate is increased, as observed in Fig. 5.

Table 1. Summary of simulations

${v_w}^{+\,(1)}$	v_w [m/s]	u_τ [m/s]$^{(1)}$
0,095	0,00616	0,064973
0,053	0,00308	0,057592
0,015	0,00077	0,052667
-0,015	-0,00077	0,050679
-0,063	-0,00308	0,049129

$^{(1)}$ at x=24D

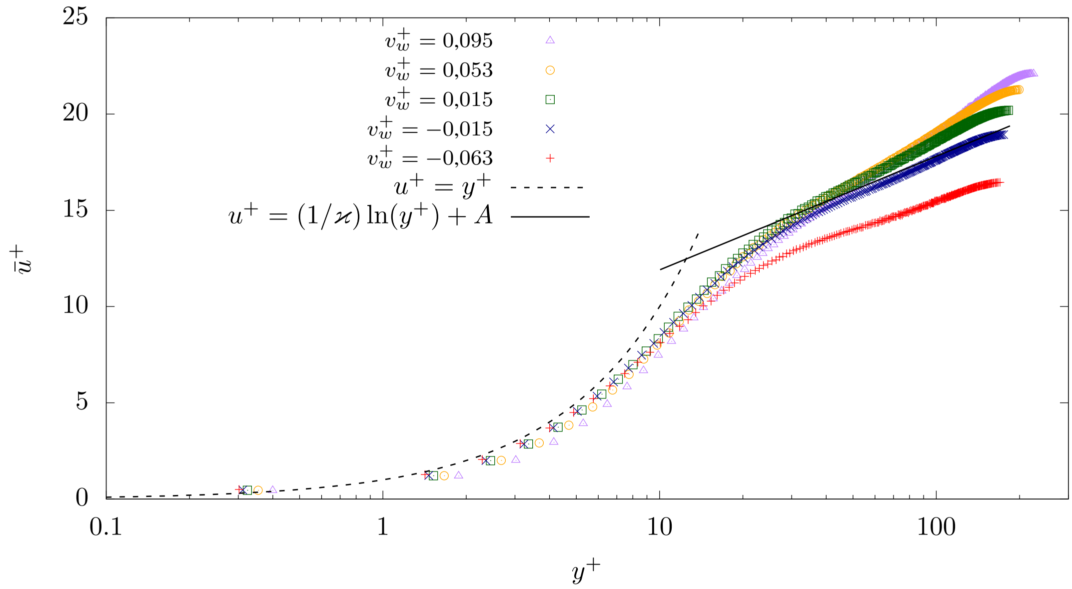

Figure 2. Mean velocity profiles in dimensionless coordinates ($u^+ = u/u_\tau$ e $y^+ = yu_\tau/\nu$) at $x = 24D$ for different transpiration rates at the wall. In the classical log-law, $A = 6{,}0$ and $\varkappa = 0,39$.

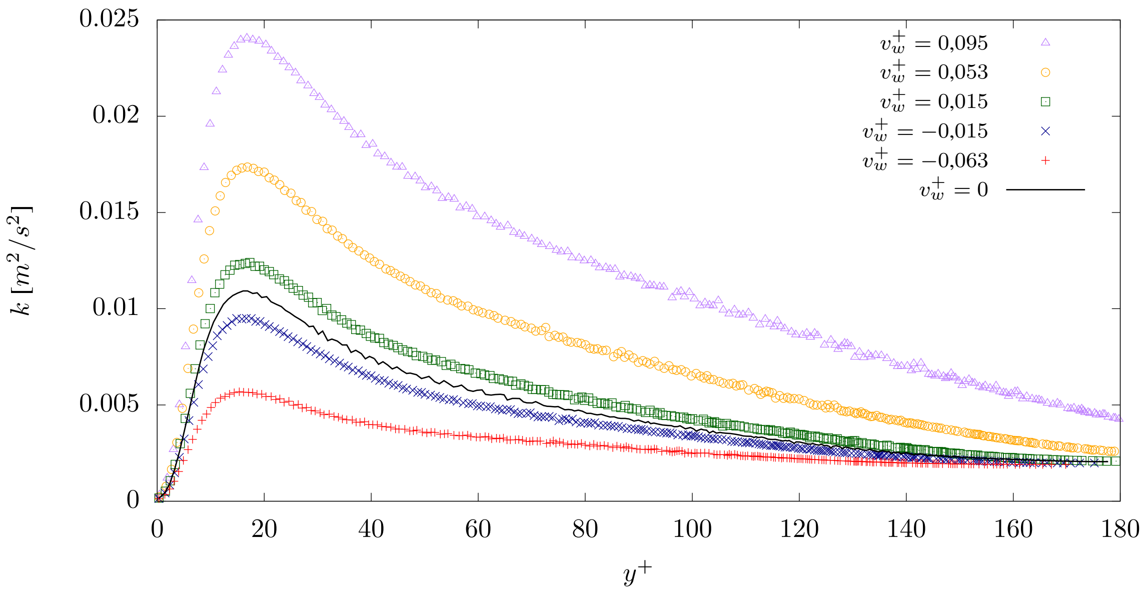

Figure 3. Mean turbulent kinetic energy (k) profiles at $x = 24D$ for different transpiration rates at the wall.

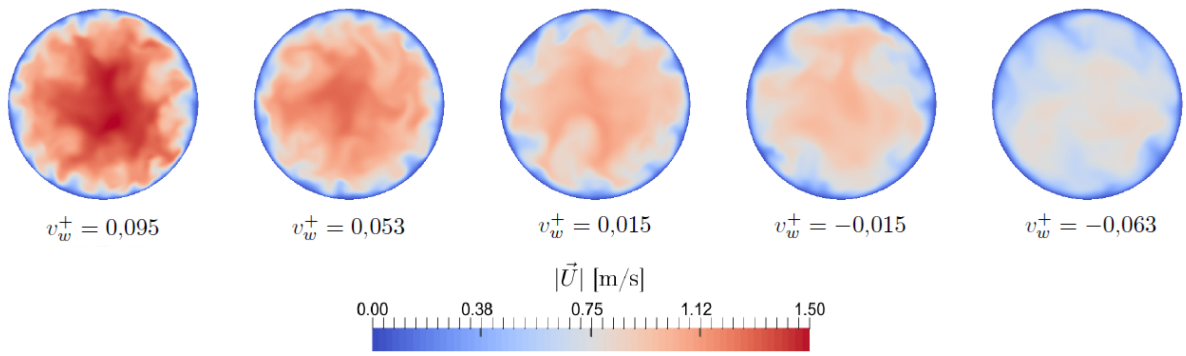

Figure 4. Instantaneous velocity contours at the pipe section where $x = 24D$.

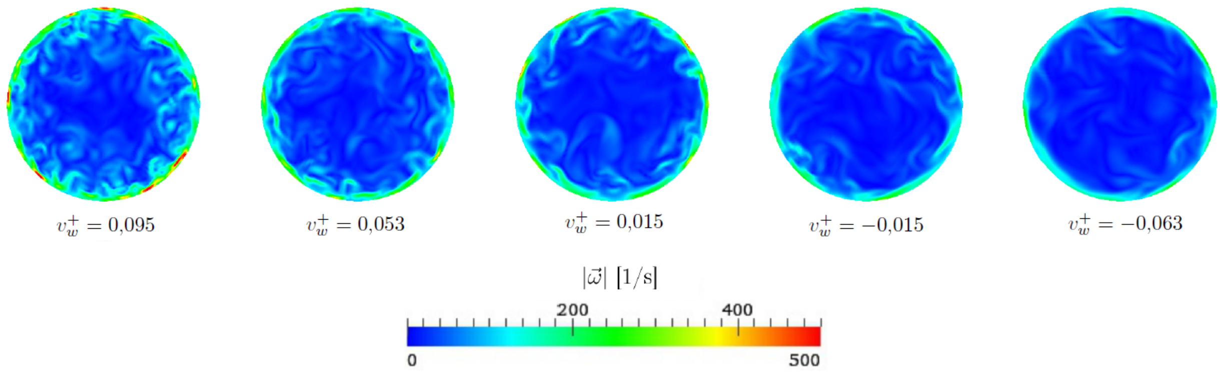

Figure 5. Instantaneous vorticity contours at the pipe section where $x = 24D$.

4. CONCLUSION

Transpiration of fluid, both injection and suction, at the wall significantly changes the structure of the turbulent flow in the near-wall region. Despite the numerous law of the walls proposed for this flow feature in literature, a further investigation on pipe geometries is still needed, since most data available are for Poiseuille flows. DNS simulations were performed for five different suction and injection rates and the results were analysed and compared to the classical laws for impervious wall pipe flow, showing a significant disagreement. It was also shown that wall transpiration not only modifies the mean velocity profile, but also the distribution of turbulent fluctuations in the near wall.

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