PRESSURE DROP AND TURBULENCE STATISTICS IN TRANSPIRED PIPE FLOW

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Abstract Measurements of turbulent flow in a horizontal pipe subjected to wall transpiration are presented. Results include data on global flow rates and pressure drop, and local mean and fluctuating velocity profiles. Two distinct flow transpiration rates are studied, $v_w^{++} = v_w/U_m$ = 0.0005 and 0.001. The effects of flow transpiration on the friction-coefficient are compared with theoretical predictions. The theory furnishes predictions accurate to 3%.

INTRODUCTION

Transpired pipe flow is a common occurrence in industry. Classical examples are the production of oil in horizontal or vertical wells, the thermal protection of walls and drag reduction. Despite the vast field of application, still few experimental works are found in literature that describe the near wall effects of flow transpiration on the turbulent properties of the flow.

The purpose of the present work is to carry out reference experiments in horizontal pipes with a permeable wall. Measurements of global flow rates and pressure drop are made for two different injection rates. In addition, the work presents local mean and fluctuating turbulent profiles obtained through Laser-Doppler Anemometry. The results are used for the validation of the law of resistance previously advanced by Loureiro and Silva Freire (2011).

RESISTANCE LAW FOR ROUGH PIPES WITH WALL TRANSPIRATION

The law of resistance introduced in Loureiro and Silva Freire (2011) is valid for single-phase flow and incorporates the effects of roughness and wall transpiration. The law is derived from an approximate local analytical solution obtained via perturbation methods (Silva Freire, 1988). This local solution can be cast as

$$\Phi = 2(v_w^+)^{-1}\left[\left(v_w^+ u^+ + 1\right)^{1/2} - 1\right] = \varkappa^{-1}\ln y^+ + A, \qquad (1)$$

where $u^+ = u/u_\tau$, $y^+ = yu_\tau/\nu$, u_τ = friction velocity, v_w = injection velocity, $v_w^+ = v_w/u_\tau$, $\varkappa = 0.4$.

The resistance formula for flow in a rough transpired pipe can be obtained by extending Eq. (1) to flow over a rough surface. Some further algebraic manipulation and an integration of the extended Eq. (1) over the cross-sectional area of a pipe results

$$\begin{aligned} 1 = \frac{\sqrt{\lambda}}{2\sqrt{2}}(2.5\ln(R/k_s) + A_k - 3.75) + v_w^+(1.56\ln^2(R/k_s) \\ + (1.25A_k - 4.68)\ln(R/k_s) + A_k^2/4 + 1.86A_k + 5.47), \end{aligned} \qquad (2)$$

with

$$\lambda = \frac{2D}{\rho U_m^2}\frac{dp}{dx}, \quad v_w^+ = \frac{v_w}{u_\tau}, \qquad v_w^{++} = \frac{v_w}{U_m}, \qquad (3)$$

where D and R denotes, respectively, the pipe diameter and radius, U_m is the mean flow velocity, $A_k = B - 512\, v_w^{++}$, k_s is a characteristic length of the roughness and B = 8.5 (completely rough regime).

In the limiting case, $v_w^{++} \to 0$, Eq. (2) reduces to the law of resistance of Nikuradse.

EXPERIMENTS

The experiments were conducted in a 15 m long porous pipe (34 mm in diameter) with uniform fluid injection. The test section consisted of three concentric stainless-steel tubes, assembled as shown in Fig. 1. The piping system consisted of fifteen 1 m long segments, all connected in line and fitted with independent pressure taps. Two inspection windows of plexiglass were installed 8 and 13 meters downstream the inlet. The windows allowed the use of the optically based measurement instruments. A schematic diagram of the experimental set up is also shown in Fig. 1.

Figure 1: Description of the test section: a) geometric arrangement, b) photograph of actual test section, c) schematic diagram.

RESULTS

The roughness length (k_s) was determined from the unblown data. Various experiments with Reynolds number varying from 6,000 to 100,000 were performed to find k_s (= 0.000334 m).

The mean velocity profile for all transpiration rates are shown in Fig. 2a. The existence of a bi-logarithmic region is evident, with the level of the log-region decreasing as v_w increases.

The pressure losses for all three present experimental conditions are also shown in Fig. 2b. The straight line for the unblown case indicates that the flow was in a completely developed state. In external flows, an increase in v_w^{++} always results in a decrease of u_τ. In transpired pipe flows, the local acceleration provoked by the wall transpiration increases the pressure drop. In fact, as shown in Fig. 2b, the highest injection rate yields an increase in pressure drop of about 5.5 times as compared with the unblown case.

The agreement provided by the predictions of Eq. (2) with the experimental data is very good despite the fact that the parameters in Eq. (2) were not particularly adjusted to fit the present experimental data. The values of the constants are the values presented in Loureiro and Silva Freire (2011), based entirely in the analysis of Silva Freire (1988).

The LDA data shows (Fig. 2c) that the magnitude of the near wall value of $\left(\overline{u'^2}\right)^{1/2}$ increases by factors of 2 and 3 for the cases with wall transpiration.

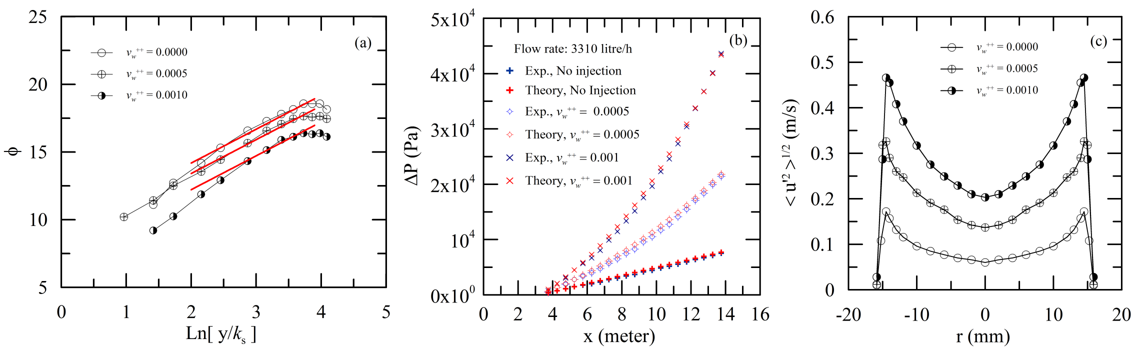

Figure 2: Comparison between the results for unblown case and for the two different transpiration rates studied: a) logarithmic mean velocity distributions, b) pressure drop distributions and c) root mean squared longitudinal fluctuating velocity distributions.

CONCLUSION

The present work has studied the behaviour of single-phase flows in horizontal pipes with fluid injection at the wall. Three different flow conditions have been scrutinized through measurements of flow rate, pressure drop and statistics of the turbulence. The results have shown that Eq. (2) furnishes predictions that are good with an accuracy of about 3%.

References

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