INVESTIGATION OF TWO PHASE FLOWS IN HORIZONTAL PIPES SUBJECTED TO TRANSPIRATION AT THE WALL

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Abstract: *The present work carries out experimental work on horizontal slug flows subject to fluid injection at the wall. Data include results on flow rates and pressure drop for ten different conditions. The properties of the two-phase flow are measured through a Shadow Sizer system. Two distinct flow transpiration rates are studied,* $v_w^{++} = v_w/U_m$ *= 0.0005 and 0.001. The effects of flow transpiration were observed to provoke bubble break-up and large changes in the passage frequency and characteristic lengths of the unit cells. The work suggests changes in the models for slug flow so that fluid injection at the wall can be accounted for.*
Keywords: *turbulence, transpiration, two-phase flow.*

1. INTRODUCTION

Turbulent flow in pipes with porous surface are the essence of producing oil wells. Be the geometry vertical, horizontal or inclined, it is the permeable nature of the producing stretch of pipe that allows oil migration from the reservoir to the surface.

The present work investigates theoretically and experimentally the pressure drop in single and two-phase flows in horizontal pipes with a porous wall. The arguments presented in Loureiro and Silva Freire al. (2011) for single phase flow are extended to two-phase flow with the help of unit-cell models. Thus, one important hypothesis of the present developments is that flow transpiration at the wall is homogeneous.

Two-phase flow over porous surfaces is a topic that has been deficiently discussed in literature. For instance, the effects of wall transpiration on some important properties of slug flow including the frequency of unit cells (ν_t) and the length (l_f) distribution of long bubbles need to be understood. The flow acceleration caused by the wall injection of fluid and the very high levels of turbulence observed in the near wall region need to have their impact assessed on the behavior of both ν_t and l_f. Here, the emphasis is on developing a mechanistic model that can be used to predict pressure drop in two-phase transpired flows.

The next section of the work briefly reviews some of the results presented in Loureiro and Silva Freire al. (2011), in particular, the theory introduced for prediction of skin-friction in transpired single-phase turbulent pipe flow. The following section briefly introduces the unit cell models of Dukler and Hubbard (1975) and Orell (2005). Both theories are then merged to yield a theory for slug flow subject to wall transpiration.

The experiments are described in a separate section, after which validation of the theoretical predictions is carried out.

2. Resistance law for single phase flow in rough pipes with wall transpiration

Define

$$\frac{p_1 - p_2}{L} = \frac{f}{D}\frac{\rho}{2}U_m^2, \tag{1}$$

where p denotes pressure, D is the pipe diameter, U_m is the mean flow velocity, L the length of the fluid portion and f the friction coefficient.

Consider further that R denotes the pipe radius, v_w = injection velocity, k_s = effective roughness.

The law of resistance for rough pipes with wall transpiration advanced in Loureiro and Silva Freire (2011) is shown next without further consideration. For a complete understanding of Eq. (2), please refer to the original work.

Let us define $Re^{++} = R/k_s$, $v_w^{++} = v_w U_m^{-1}$ and $A_k = B - 512\, v_w^{++}$. It follows immediately from Loureiro and Silva Freire (2011) that

$$\begin{aligned} 1 = \frac{\sqrt{f}}{2\sqrt{2}}(2.5\ln(Re^{++}) + A_k - 3.75) + v_w^{++}(1.56\ln^2(Re^{++}) \\ + (1.25A_k - 4.68)\ln(Re^{++}) + \frac{A_k^2}{4} + 1.86A_k + 5.47). \end{aligned} \tag{2}$$

with $B = 5$.

3. Unit Cell Models

Unit cell models consider the existence of a typical cell that repeats itself moving down a pipe. If a frame of reference exists where the liquid and gas phases can be considered to travel with about the same velocity in a fully developed state the randomness of the flow properties can be estimated from simplified steady models (Fabre and Line, 1992).

Large bubbles in a liquid stream were studied in the pioneering works of Dumitrescu (1943), Davies and Taylor (1950) and Nicklin et al. (1962). However, it appears that the unit cell concept was first really explored in the simple models for horizontal and vertical pipes introduced by Wallis (1969).

Compared to the previous works, the model advanced by Dukler and Hubbard (Dukler1975) was much more sophisticated. The observation that the fast moving liquid slug overruns the slow moving film that is shed behind the downstream Taylor bubble and mixes with the surrounding fluid due to turbulence diffusion allowed Dukler and Hubbard (Dukler1975) to decompose the pressure drop into two contributions: (i) a term related to the acceleration of the slow moving liquid film to the full slug velocity and (ii) a term related to the wall shear in the back section of the slug. The set of working equations furnishes predictions of the unit cell velocity, slug velocity, film velocity, slug length, mixing eddy length and the length of the film region.

A more simplified formulation has been recently developed by Orell (Orell2005). This author considers a uniform film thickness (resulting from a cylindrical bubble) and neglects end effects so that the flow in the film region is treated as stratified flow. The nose of the elongated bubble and the slug unit travel with the same velocity, which must be specified through an experimental correlation.

4. The effects of wall transpiration on slug flow properties

The details of the models of Dukler and Hubbard (Dukler1975) and Orell (Orell2005) are not reviewed here. The reader is referred to the original references. Below we comment on the pertinent alterations to both models so that the effects of wall transpiration can be accounted for.

Mass injection at a pipe wall changes the pressure drop since the slow moving fluid must be accelerated to the main flow velocity. The addition of mass further increases the mixture velocity and decreases the liquid friction coefficient. Thus, the pressure drop resulting from wall shear is affected by two distinct physical effects that need to be correctly assessed.

The local increase of mass at any given flow section is expected to provoke an increase in the following parameters: the slug translational velocity, the length of the unit cell (and of the liquid slug and liquid film), the frequency of slug passage and the acceleration pressure drop.

Because the length of the unit cells change with position, the mean velocity of the slug (V_s) depends on the amount of liquid that is transpired through the wall, an iterative scheme needs to be used to find V_s and all other flow properties.

In the extension of the model of Dukler and Hubbard to transpired walls, the addition of mass has to be considered in the modeled equations.

The pressure drop resulting from the acceleration effects needs to be modified to

$$\Delta P_a = \frac{x}{A}(V_s - V_{fe}) + \frac{W_w}{A} V_t, \tag{3}$$

where A = area of pipe cross section, x = rate of liquid pick-up, V_{fe} = velocity of the film just before pick-up, W_w is the wall mass flow rate.

The friction coefficient needs to be modified according to Eq. (2) so that its dependence on the injection rate and bulk velocity can be accounted for.

The changes in f_s (friction coefficient in the liquid slug) as a function of the slug Reynolds number and the injection rate are shown in Fig. 1.

The model of Orell gives predictions of parameters θ, V_f, V_G, l_s/l_u from which pressure losses can be evaluated. Of course, with mass addition at the wall, parameters V_{SL} (liquid superficial velocity, V_t (through V_m) (translational velocity of the unit cell) and R_s (Liquid hold-up in the slug) vary from cell to cell. The friction coefficients, f_f (film) and f_s (slug), vary with the local injection rate also according to Eq. (2).

An important input parameter in mechanistic slug flow models is the passage frequency of slugs, ν_s. Several correlations can be found in literature, based on empirical and mechanistic reasonings. In the following, the correlation presented in Zabaras (2000) was used. This author analized 339 data points to propose the following correlation

$$\nu_s = 0.0226 \left(\frac{V_{SL}}{gD}\right)^{1.2} \left[\frac{19.75}{V_m} + V_m\right]^{1.2} [0.836 + 2.75 \sin^{0.25}(\beta)]. \tag{4}$$

The above expression is to be used in IS units and β is the slope of the pipe.

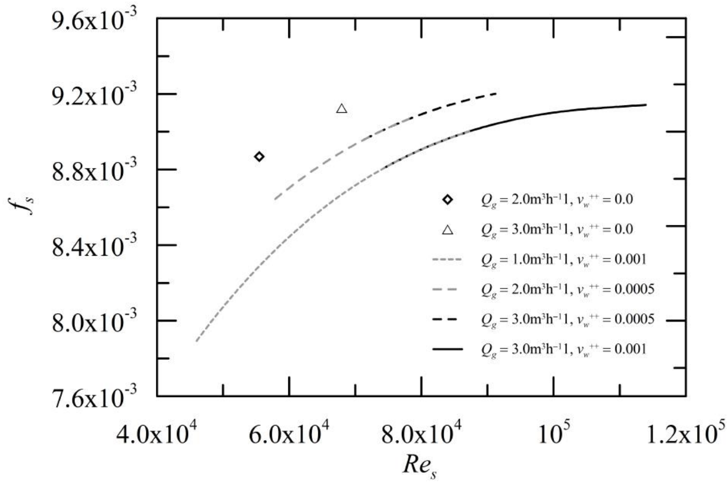

Figura 1: Dependence of f_s on Re_s and v_w^{++}.

5. Experiments

The experiments were conducted in a 15 meter long porous pipe (31.75 mm in diameter) with uniform fluid injection at the wall. The experimental apparatus consisted of three concentric stainless-steel tubes, assembled as shown in Fig. 2. The pipe system consisted of fifteen one-meter long segments, every one containing two pressure taps. The one-meter sections were connected to each other through flanges. The injection flow of every segment was adjusted and monitored by magnetic flowmeters. Special care was dedicated to the alignment of the pipes. Two plexiglass inspection windows were installed to allow local velocity measurements and characterization of the two-phase flow properties. Air and water were mixed in a T-junction located one meter upstream of the inlet of the porous pipe. A schematic diagram of the experimental setup is shown in Fig. 3.

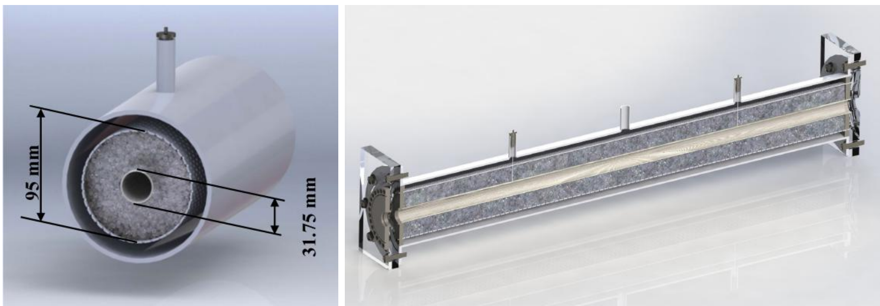

Figura 2: Description of the test section: a) main pipe dimensions, b) geometric arrangement.

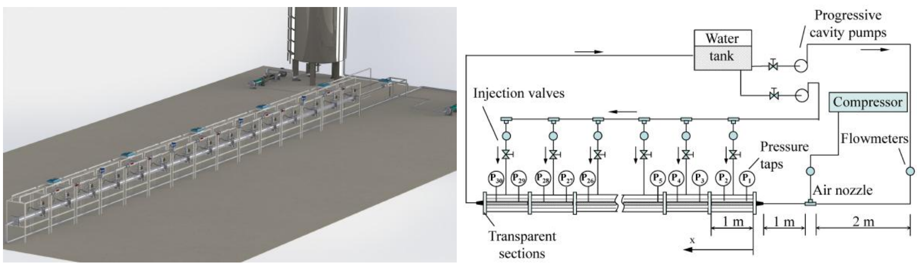

Figura 3: Schematic diagram of the flow loop and test section.

The properties of the slug flow were measured through a Dantec Shadow Sizer System. Additionally, laser diodes and photo detectors were used to measure the statistical properties of the two-phase flow along the pipe, so that changes in slug frequency, bubble velocity and lengths of the liquid slug and liquid film could be measured and spatially correlated.

For data reduction of the single phase model, the pressure losses due to flow acceleration needed to be accounted for. Pressure losses in a porous pipe with wall injection increase the momentum flux and overcome wall friction. A momentum balance on a control volume of length dx and radius R shows that the wall shear stress in given by

$$\tau_w = -\frac{1}{4}\left[\frac{dp}{d(x/D)} + \frac{d(\beta\rho U_m^2)}{d(x/D)}\right], \tag{5}$$

where β, the momentum flux factor, is the ratio of the real momentum flux through a given cross section to that based on one-dimensional flow at the mean velocity.

6. Results and discussion

The two-phase flow experiments were carried out according to the conditions shown in Table 1.

Tabela 1: Conditions for the multiphase flow experiments.

Condition	Q_l [m^{3}h^{-1}]	Q_g [m^{3}h^{-1}]	v_w^{++} (= $v_w U_m^{-1}$)
1	2.46	1	0.0010
2	2.46	2	0.0
3	2.46	2	0.0005
4	2.46	3	0.0
5	2.46	3	0.0005
6	2.46	3	0.0010
7	2.85	3	0.0010
8	2.85	4	0.0010
9	2.85	6	0.0
10	2.85	6	0.0010

The configuration of bubbles in the entrance pipe (top, Fig. 4) and test section (bottom, Fig. 4) are shown to illustrate the large degree of flow aeration provoked by the fluid injection at the wall. The large agitation provoked by turbulence breaks the large Taylor bubble into a smaller bubble surrounded by a swarm of small bubbles. Thus, the perturbations provoked by the fluid injection tend to decrease the mean size of the large bubbles and increase their frequency of passage.

To take to bottom photograph in Fig. 4 the Shadow Sizer System was positioned at a transparent window located 13 meters downstream of the inlet section. A NanoSense MKIII camera provided high resolution images (1289 x 1024 pixels) at 2000 fps.

The Shadow Sizer images were processed according with the procedure introduced in Matamoros et al. (6) for an estimation of the statistical properties of the slug flow in a pipe. Bubble reconstruction was made through the fixed window method (6).

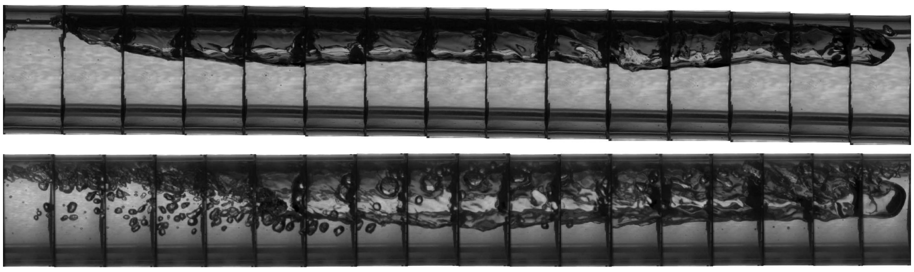

Figura 4: Bubble shape in the inlet region (top) and at a test section located 13 m downstream of the inlet (bottom, V_w^{++} = 0.001). Q_l = 2.46 m^{3}h^{-1}, Q_g = 3 m^{3}h^{-1}.

The total pressure losses are compared with predictions obtained through the models of D&H and Orell in Figs. 5 through 7.

The total pressure losses for flows without transpiration are shown in Fig. 5 for conditions 2, 4 and 9. For the lower liquid and gas flow rates the agreement between theories and experiments is within 26% in error. For the highest flow rates, Condition 9, the maximum difference reaches 38%.

The increase in pressure drop provoked by the increase in transpiration rate is seen in Fig. 6a-b for the liquid flow rate Q_l = 2.46 m^{3}h^{-1}. It is clear that for the lower gas flow rates (Conditions 1 and 3) the theoretical results for both injection rates slightly under predict the experimental data (by a maximum of 10%). For the highest gas low rate, the extended models of D&H and Orell over predict the data by 12%.

The results for the highest liquid flow rate are shown in Fig. 7. Only one injection rate was tried, v_w^{++} = 0.001. Except for the highest gas flow rate, the general agreement of both extended theories with the experimental data is very good. The over prediction of data for the higher gas flow rates is also noted.

7. Conclusions

The present work has discussed the behavior of two-phase flows in horizontal pipes with fluid injection at the wall. Ten new experimental data sets are described.

All two-phase flow experimental data are compared with extended versions of the theories of Dukler and Hubbard (2) and Orell (8). Emphasis has been placed on the prediction of pressure drop, but results on other flow properties including the translational velocity and characteristic length of the unit cell were also obtained.

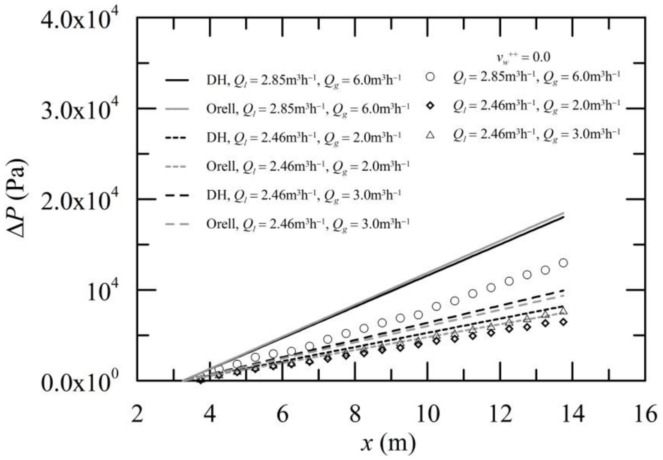

Figura 5: Pressure drop predictions for two-phase flow without wall transpiration. Flow Conditions: 2, 4 and 9.

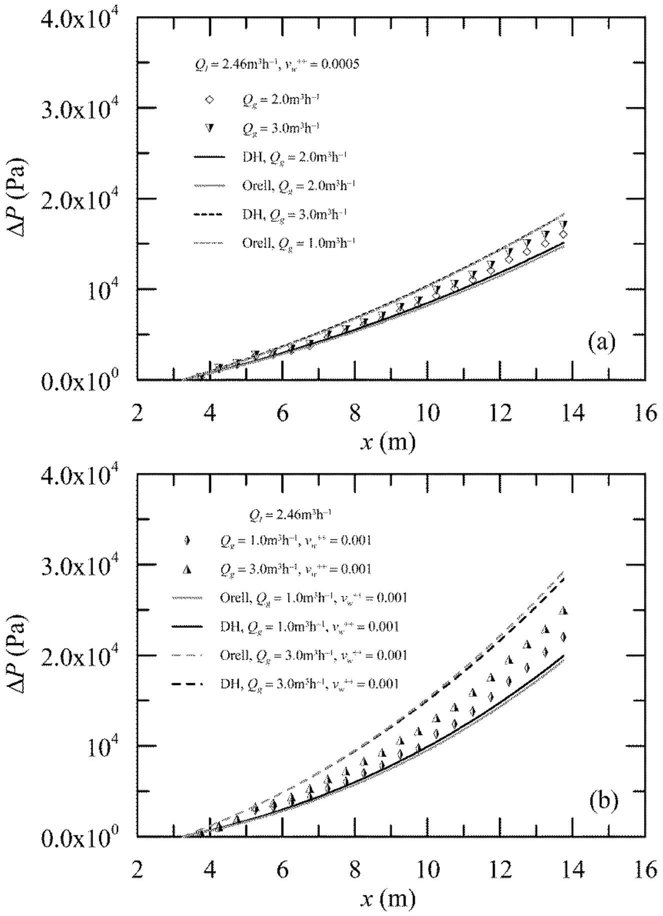

Figura 6: Pressure drop predictions for two-phase flow with wall transpiration, v_w^{++} = 0.0005 and 0.001. Flow Conditions: 3 and 5 (a), 1 and 6 (b).

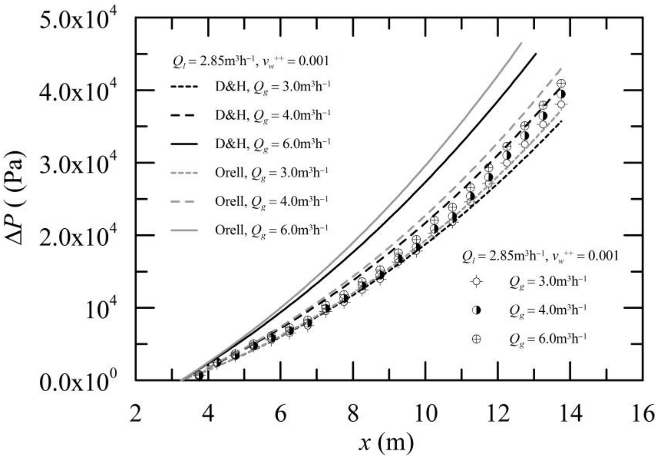

Figura 7: Pressure drop predictions for two-phase flow with wall transpiration, v_w^{++} = 0.001. Flow Conditions: 7, 8 and 10.

The transpiration and the air-bubble interaction were observed to promote near-wall turbulence, imposing considerable changes to the inlet flow. An increase in transpiration tends to push bubble noses towards the center of the permeable pipe, induce bubble break up and increase the level of aeration on the liquid piston.

Acknowledgements

In the course of the research, JBRL benefited from a CNPq Research Fellowship (Grant No 308445/2013-9) and from further financial support through Grants CNPq 458249/2014-9, FAPERJ E-26/102.212/2013 and FAPERJ E-26/010.002857/2014. APSF is grateful to the Brazilian National Research Council (CNPq) for the award of a Research Fellowship (Grant No 305338/2014-5). The work was financially supported by CNPq through Grant No 477293/2011-5 and by the Rio de Janeiro Research Foundation (FAPERJ) through Grant E-26/102.937/2011.

8. ACKNOWLEDGEMENTS

Davies, R. M., Taylor, G.I.: The mechanics of large bubbles rising through extended liquids and through liquids in tubes. Proc. Roy. Soc., **200A**, 375–390 (1950)

Dukler, A. E., Hubbard, M. G.: A model for gas-liquid slug flow in horizontal and near horizontal tubes. Ind. Eng. Chem. Fund., **14**, 337–347 (1975)

Dumitrescu, D. T.: Stromung an einer luftblase im senkrechten Rohr. Z. angew. Math. Mech., **23**, 139-149 (1943)

Fabre, J., Liné, A.: Modeling of two-phase slug flow. Ann. R. Fluid Mech., **24**, 21–46 (1992).

Loureiro, J.B.R., Silva Freire, A.P.: Slug flow in horizontal pipes with transpiration at the wall. Journal of Physics. Conference Series (Online), **318** (2011)

Matamoros, L. M. C., Loureiro, J. B. R., Silva Freire, A. P.: Length-area-volume of long bubbles in horizontal slug flow. Int. J. Multiphase Flow, **65**, 2430 (2014)

Nicklin, D.J., Wilkes, J.O., Davidson, J.F.: Two-phase flow in vertical tubes. Trans. Inst. Chem. Eng., 40, 61–68 (1962)

Orell, A.: Experimental validation of a simple model for gas-liquid slug flow in horizontal pipes. Chem. Eng. Sci., 60, 1371–1381 (2005)

Zabaras, G. B., Prediction of Slug Frequency for Gas/Liquid Flows. SPE J., **5**, 252–258 (2000)

Wallis, G.B.: One Dimensional Two-Phase Flow. McGraw-Hill (1969)

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