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Brief communication

Flow distribution of gas and liquid in parallel pipes

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1. Introduction

Two-phase flow in parallel pipes is associated with various industrial applications in which the two-phases are distributed among parallel pipes, which have common inlet and outlet manifolds. Two-phase flow in parallel pipes takes place in heat exchangers, boilers and condensers in power plants and cooling systems. One of the attractive ways for utilizing solar energy for power is to construct an array of parallel pipes that absorb solar energy. Flow in parallel conduits may take place also in oil and gas production and within the core of a nuclear reactor.

Ozawa et al. (1979, 1982, 1989) carried out experimental work on two-phase flow in capillary parallel pipes of 3.1 mm diameter. They attempted to simulate flow in boiling channels by the injection of air and water along the pipes. Reinecke et al. (1994) investigated flow reversal in vertical two-phase flow in parallel channels. Their experimental set up consists of six tubes with an inner diameter of 19.05 mm and a length of 1.3 m connecting a top and a bottom plenum. A model, based on pressure drop calculations was presented for the prediction of the reversal boundaries. Tshuva et al. (1999) investigated the distribution possibilities of air and water in a system of two parallel pipes, 2.4 cm diameter and 3 m long. Results are reported for inclination angles from horizontal to vertical. Their theoretical calculations showed that there are infinite steady state solutions to the splitting ratios, but the one seen in practice is the one that results in a minimum pressure drop.

Flow in parallel pipes is associated with splitting of the two-phase flow in various branches where the parallel pipes are connected to the inlet manifold. Most reported papers on splitting are restricted to one "branch" and one "run". Two major approaches were used for the prediction of the "route selectivity" of the gas–liquid flow in a junction: (1) based on momentum balances (Saba and Lahey, 1984; Fortuin et al., 1990; Hart et al., 1991) and (2) a "geometrical model" that tries to predict the splitting on the basis of geometrical consideration (Shoham et al., 1987, 1989).

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Azzopardi and coworkers did a considerable amount of work on splitting in branches (Azzopardi, 1993, 1994, 1999; Azzopardi and Hervieu, 1994; Azzopardi and Rea, 1999; Roberts et al., 1995, 1997). The splitting problem, even for one run and one branch is quite complicated and so far there is no reliable method to predict the splitting in a branch.

In this work the distribution of liquid and gas flowing in 4 parallel pipes with common inlet and outlet manifolds is investigated. The main objective of the present work is to observe the flow distribution of gas and liquid in 4 parallel pipes for various gas and liquid flow rates and various inclinations angles.

2. Experimental facility

A schematic diagram of the experimental facility is presented in Fig. 1. The system consists of 4 parallel pipes (spaced at 60 cm apart) with common inlet and outlet manifolds. Each pipe has a diameter of 2.6 cm and is 6 m in length. The common manifold is a pipe of 5 cm i.d. (to minimize pressure losses in the manifold). The pipes are constructed from Plexiglas to allow visual obser-

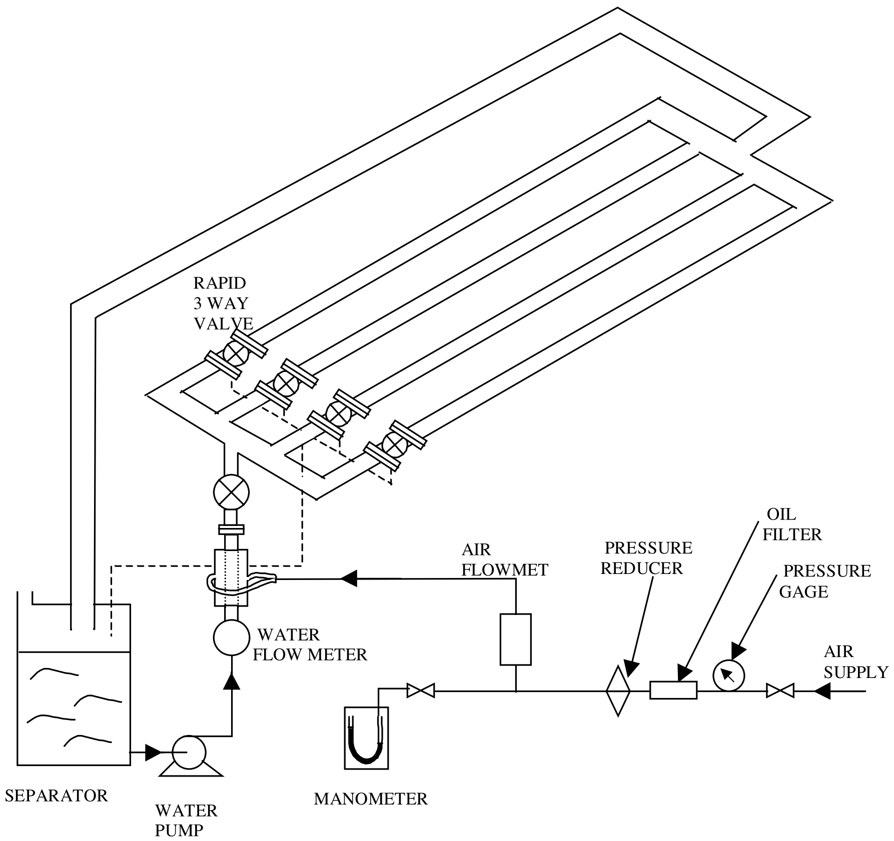

Fig. 1. Schematic flow configuration.

vations of the flow patterns in the pipes. The whole flow system can rotate upwards within the range of 0° to 15°.

Water and air are well mixed in a specially constructed inlet device before entering the common manifold. The device is an annulus with an inner pipe of 5.4 cm diameter. The inner pipe was perforated with uniformly distribution of 1200 holes, 1 mm in diameter. Water enters in the axial direction. Air is introduced into the gap of the annulus and enters the inner pipe through the perforated holes. All experiments were conducted using air and water at room temperature and atmospheric outlet pressure. The flow rates were measured only at the inlet of the manifold. Water flows in a closed loop and its flow rate into the inlet manifold is set-up by regulating the rpm of the pump using a frequency converter. Flow rates in the range of 0.05–3 l/s, are measured with an electromagnetic flow meter. Air is supplied from a compressed air line. The flow rates are in the range of 0.1–3 l/s at atmospheric pressure. The gas flow rates are measured using a turbine flow meter for the high range of flow rates and a rotameter for the low range.

3. Experimental results

Visual observation on the splitting characteristics among the 4 pipes shows an interesting phenomenon. Under certain conditions, the two phases "choose" to flow only in 1, 2 or 3 pipes (out of 4) while stagnant liquid columns are observed in the other pipes. Our objective in this experiment is to identify the number of pipes in which the flow takes place. Experiments were carried out for four inclination angles $\beta = 0°$ (horizontal), 5°, 10° and 15°. The distribution of the two-phase flow are determined visually.

For the horizontal case the flow always takes place in the four pipes and were seen to be approximately evenly split among the 4 pipes. For the case of 5°, 10° and 15° inclination, various splitting characteristics were observed depending on the liquid and gas flow rates at the inlet to the manifold. Figs. 2–4 maps the results for the splitting characteristics. For low flow rates of liquid and gas, the gas–liquid mixture "prefers" to flow through a single pipe while stagnant liquid columns partially fill the other 3 pipes. The flow in the pipe is in the form of slug flow. This type of flow configuration is marked in Figs. 2–4 by the square symbols. For increasing liquid and gas flow rates we may see gas and liquid flowing in 2 pipes while stagnant liquid columns are observed in the other 2 pipes (triangular symbol in Figs. 2–4). For a further increase of the flow rates, two phase flow is observed in 3 pipes (rhomb symbol) and finally for higher flow rates, the flow takes place in all four pipes.

4. Analysis

Since the system under consideration has common inlet and outlet manifolds the pressure drop in each of the 4 parallel pipes should be the same. The analysis starts with the calculation of the pressure drop in a single pipe as a function of the gas and liquid flow rates. Only frictional and gravitational pressure drop are considered, namely, acceleration effects are neglected. The gas and the liquid are considered incompressible and all of the properties are considered constant. The drift flux model is used to calculate the pressure drop. Since most of the time the flow in the pipes

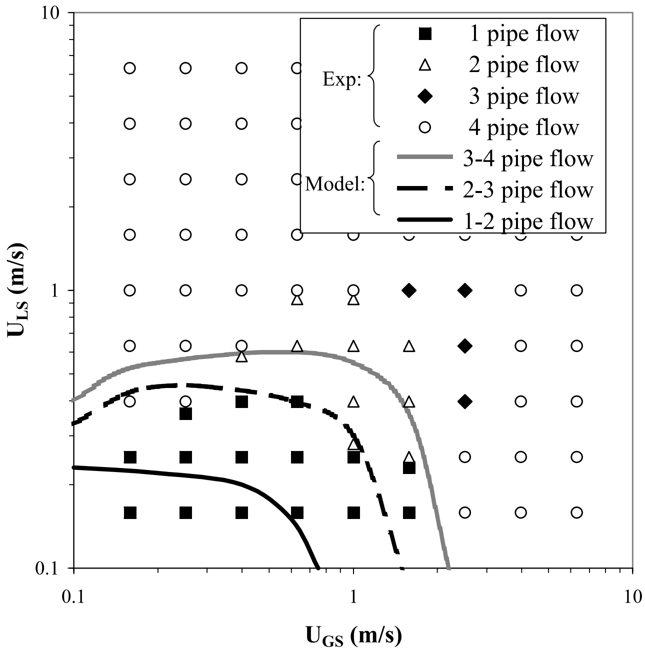

Fig. 2. Flow splitting in 4 pipe system, $D = 2.6$ cm diameter, $\beta = 5°$.

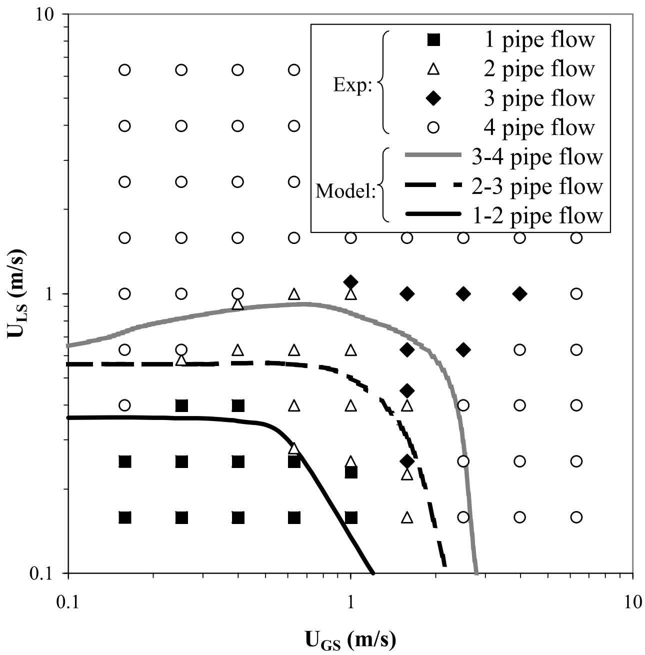

Fig. 3. Flow splitting in 4 pipe system, $D = 2.6$ cm diameter, $\beta = 10°$.

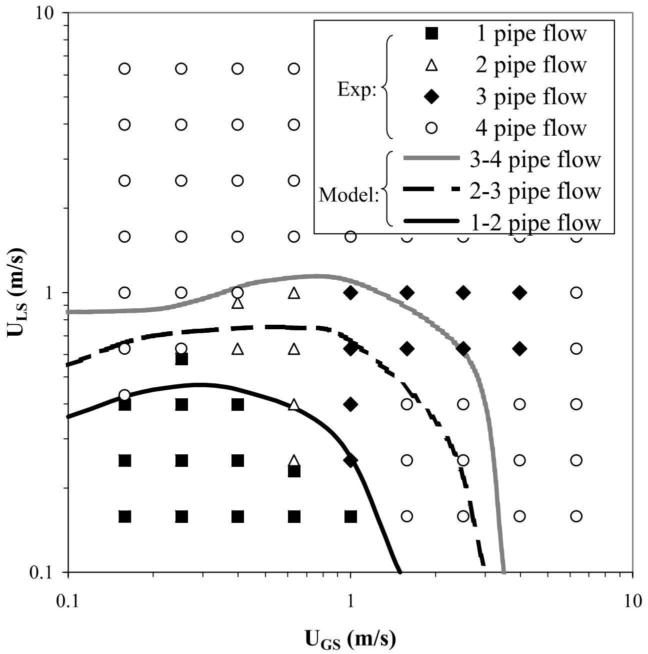

Fig. 4. Flow splitting in 4 pipe system, $D = 2.6$ cm diameter, $\beta = 15°$.

is in the form of slug flow the parameters used in the drift flux model are those for slug flow. Admittedly the use of the drift flux model is perhaps a gross approximation. Nevertheless, at this point, we would like to keep the analysis as simple as possible. Tshuva et al. (1999) also demonstrated that the drift flux model is a reasonable approximation for a wide range of gas and liquid flow rates.

The velocity of the elongated bubbles, U_G, using the drift flux model is

$$U_G = CU_S + U_d \tag{1}$$

where U_S is the mixture velocity which is equal to the sum of the superficial velocities of the gas and liquid in the pipe, $U_S = U_{GS} + U_{LS}$. The drift velocity U_d, which is the velocity of an elongated bubble in stagnant liquid, is estimated using Bendiksen (1984) proposal,

$$U_d = 0.54\sqrt{gD}\cos\beta + 0.35\sqrt{gD}\sin\beta \tag{2}$$

where D is the pipe diameter and C is the distribution parameter taken as 1.2 for turbulent flow and 2 for laminar flow (Nicklin, 1962). The average void fraction is

$$\alpha = \frac{U_{GS}}{C(U_{LS} + U_{GS}) + U_d} \tag{3}$$

The pressure drop along each pipe is calculated as follows:

$$\Delta P = \frac{2}{D} f \rho \ell (U_{LS} + U_{GS})^2 + \rho g \ell \sin\beta \tag{4}$$

where ℓ is the pipe length and ρ is the average density:

$$\rho = \alpha\rho_G + (1-\alpha)\rho_L \tag{5}$$

The friction factor, f, is calculated using Blasius type correlation, $f = cRe^{-n}$. The Reynolds number is defined in the traditional way used for the homogeneous and the drift flux models, namely

$$Re = \frac{(U_{LS} + U_{GS})D\rho}{\mu} \tag{6}$$

$c = 0.046$, $n = 0.2$ for turbulent flow and $c = 16$, $n = 1$ for laminar flow. The viscosity is calculated based on the weighted average void fraction.

$$\mu = \alpha\mu_G + (1-\alpha)\mu_L \tag{7}$$

Since for our case, $\rho_G \ll \rho_L$, $\mu_G \ll \mu_L$ and the flow is turbulent Eq. (4) reads,

$$\frac{\Delta P}{\rho_L g \ell} = \left(1 - \frac{R}{C + \frac{U_d}{U_S}}\right)\left[0.092\left(\frac{U_S}{\sqrt{gD}}\right)^{1.8}\left(\frac{D\rho_L\sqrt{Dg}}{\mu_L}\right)^{-0.2} + \sin\beta\right] \tag{8}$$

For given flow rates U_{LS} and U_{GS} one can calculate the pressure drop in a single pipe using Eqs. (4) or (8). Fig. 5 shows the results for the pressure drop vs. the total flow rate $U_S = U_{LS} + U_{GS}$ for parametric values of the gas flow rate ratio $R = U_{GS}/U_S$ where R ranges from 0 (only liquid) to 1 (only gas). Obviously we can choose infinite values of the parameter R. In Fig. 5, eleven values of R are plotted, that ranges from 0 to 1 using increments of 0.1.

The results in Fig. 5 are for air–water flow in a single pipe, 6 m long and 2.6 cm in diameter, 5° inclination and atmospheric pressure at the exit. As can be seen, for small U_S the pressure drop approaches the stagnant hydrostatic pressure of water. For the case $R = 0$ (only water) the pressure increases with the increase of the flow rate. For the case of $R > 0$ the pressure drop decreases and then increases with the flow rate. The decrease of the pressure drop results from the increase of the void fraction in the pipe and the decrease of the hydrostatic pressure.

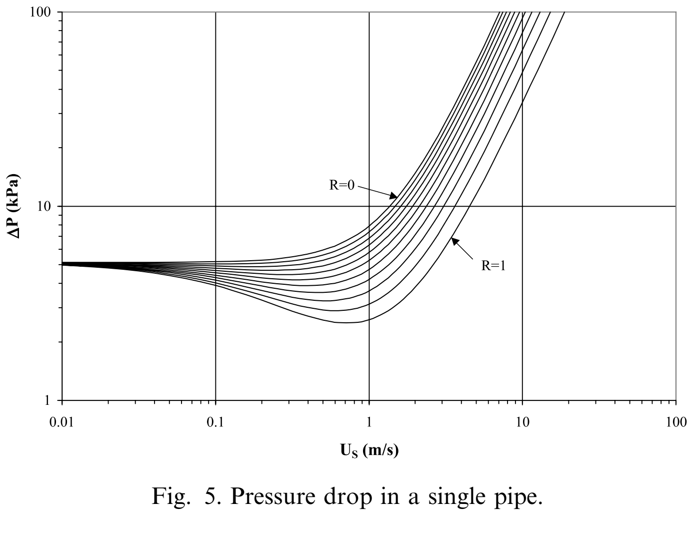

Fig. 5. Pressure drop in a single pipe.

For any given value of R for a single pipe we obtain a zero solution for U_S at low values of ΔP, two solution for U_S at intermediate values of ΔP and one solution for high values of ΔP (see Fig. 5).

Consider now a system of 4 parallel pipes. The flow rate into the common manifold, before the splitting are $U_{LS,in}$ and $U_{GS,in}$ (or $U_{S,in}$ and R_{in}). We are looking now for all possible solutions for gas and liquid distributions among the pipes that will satisfy equal pressure drop in each pipe. For each pressure drop (see Fig. 5) the solutions include all possible distributions of the phases in 4 pipes, then all possible distributions in 3 pipes (assuming stagnant liquid column in the 4th pipe) and finally all possible solutions for flow in 2 pipes.

For example, consider the case in which the flow takes place in 4 pipes. In order to find all possible solutions we sum up all combinations of gas and liquid flow rates in each pipe that will satisfy the inlet flow rates, $U_{S,in}$ and the inlet gas ratio, R_{in} (for all possible pressure drops):

$$U_{S,in} = U_{S,1} + U_{S,2} + U_{S,3} + U_{S,4} \tag{9}$$

$$R_{in} = \frac{R_1 U_{S,1} + R_2 U_{S,2} + R_3 U_{S,3} + R_4 U_{S,4}}{U_{S,in}} \tag{10}$$

where 1, 2, 3 and 4 designate the pipe number.

For N values of R ($N = 11$ in Fig. 5) one may obtain $n = 0$ up to 22 solutions of U_S and R in a single pipe, depending on the pressure drop. For n possible solutions for a single pipe one may obtain n^4 solutions for the four pipes for which the inlet conditions into the manifold is $U_{S,in}$ and R_{in}. For example, in Fig. 5, where R is subdivided into 11 values (0, 0.1, 0, 2, ... ,1) and for high-pressure drop, n equals 11, resulting in 11^4 solutions. Since however the pipe number is not distinguishable, the actual number of solutions is much less, namely:

$$\binom{n}{4} + 3\binom{n}{3} + 3\binom{n}{2} + n \tag{11}$$

thus, for example for $n = 11$ we have 1001 solutions rather than 14641 (n^4) solutions.

A solution for a given total input flow rate, $U_{S,in}$ and inlet gas ratio R_{in} at a given pressure drop can be obtained by running all possible solutions for each pipe and picking those solutions that will satisfy the input parameters calculated by Eqs. (9) and (10). If we scan now over the pressure drop from low to high-pressure drop (see Fig. 5) we can obtain all possible solutions for given input flow rates of liquid and gas.

Fig. 6 presents typical results of the calculations for the case of $U_{LS} = 0.1$ m/s and $U_{GS} = 3.9$ m/s. Scanning from low to high pressure drops, for each pressure drop all possible combinations of U_{Sj} and R_j (N was taken as 501) that results in $U_{S,in} = 4$ m/s and $R_{in} = 0.975 \pm 1\%$ were plotted in Fig. 6. The ratio of the gas flow rate in each of the 4 pipes to the total gas input into the manifold, ($U_{GSj}/U_{GS,in}$), is the value on the abscissa. Thus the collection of all points (that can generate a line) show the range of all possible solutions for U_{GSj} at each pressure drop. Note that there are enormous combinations of splitting for each pressure drop that yields the desired $U_{LS,in}$ and $U_{GS,in}$ and one cannot determine any single combination from Fig. 6. What we do see is a general tendency of the gas flow rate ratio in each pipe to range from 0 to 0.55. There is no solution above 4 kPa and below 2.9 kPa.

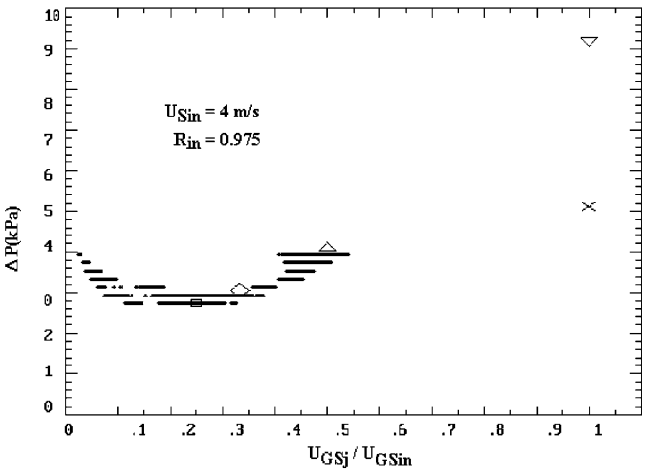

Fig. 6. Pressure drop vs. gas flow ratios for gas flow ratios: $U_{LS,in} = 0.1$ m/s, $U_{GS,in} = 3.9$ m/s, $\beta = 5°$. Solutions for even splitting: □ even splitting in 4 pipes; ◇ even splitting in 3 pipes; △ even splitting in 2 pipes; ▽ flow in 1 pipe; × stagnant liquid column; — all possible solutions for 4 pipe flow.

Since there are infinite possible solutions for gas and liquid distribution among the pipes, the question arises what is the flow distribution that will be observed in practice. We follow the assumption of Tshuva et al. (1999) that the actual physical solution is the one that results in the minimum pressure drop. Out of all the solutions in Fig. 6 the minimal pressure drop occurs for an even splitting of gas and liquid in the four pipes. This point is shown by the rectangular symbol in Fig. 6 in which case $U_{GS}/U_{GS,in}$ is 0.25 in each pipe. Note that the pressure drop at this point can be calculated directly assuming equal splitting of gas and liquid in each pipe.

Another point to check is if we may have cases in which the pressure drop is less than that obtained for the aforementioned symmetrical case. Such cases may occur when the flow takes place in one, two or three pipes while a stagnant liquid column partially fill the other pipes as was observed in the experiments under certain conditions. Thus we need to calculate all possible solutions for flow in 3 pipes assuming stagnant liquid in the 4th pipe. Again the minimum pressure drop takes place for an even splitting. Similarly we need to repeat this procedure for 2 pipes.

Since it is assumed that the practical solution is the one that yields minimum pressure drop we need to calculate only the even splitting cases. The symbols in Fig. 6 show the pressure drop for even splitting:

1. The flow is in a single pipe, $U_{GS}/U_{GS,in} = 1$ and $U_{LS}/U_{LS,in} = 1$, the pressure drop is designated as ΔP_1 and it is shown as an inverted triangle symbol on Fig. 6.
2. The flow is evenly distributed between 2 parallel pipes, $U_{GS}/U_{GS,in} = 0.5$ and $U_{LS}/U_{LS,in} = 0.5$, the pressure drop is designated as ΔP_2 and it is shown as a triangle symbol on Fig. 6.
3. The flow is evenly distributed among 3 parallel pipes, $U_{GS}/U_{GS,in} = 0.33$ and $U_{LS}/U_{LS,in} = 0.33$, the pressure drop is designated as ΔP_3 and it is shown as a rhombus symbol on Fig. 6.
4. The flow is evenly distributed among 4 parallel pipes, $U_{GS}/U_{GS,in} = 0.25$ and $U_{LS}/U_{LS,in} = 0.25$, the pressure drop is designated as ΔP_4 and it is shown as a rectangle symbol on Fig. 6 (as mentioned before).

In addition the hydrostatic pressure for an inclined pipe full of stagnant liquid is calculated, it is designated as ΔP_5 and it is plotted as an $\times$ symbol on Fig. 6.

As mentioned before the flow configuration that will take place in practice is the one that will result in a minimal pressure drop. Thus the anticipated flow that will take place is the one that satisfies the $\mathrm{Min}(\Delta P_1, \Delta P_2, \Delta P_3, \Delta P_4)$ subject to the condition that this minimum is less than the stagnant hydrostatic pressure drop ΔP_5. If, for example, the minimum pressure drop is obtained for a single pipe flow, then it is assumed that the total flow takes place in a single pipe while stagnant liquid columns take place in the other three pipes. However, this will be possible only if $\Delta P_1 < \Delta P_5$, namely, the liquid level in the stagnant 3 pipes is lower than the top level. Obviously, if ΔP_1 is larger than that of a stagnant water column then this configuration is not possible and flow in the four pipes will take place. Similarly if the minimum pressure drop is for a flow in 2 pipes (ΔP_2 is minimal) then the flow will be in 2 pipes with 2 liquid columns in the other pipes, provided that $\Delta P_2 < \Delta P_5$.

Fig. 6 shows that an even distribution among the 4 pipes occurs at the minimum pressure drop, namely lower than the pressure drop calculated for even splitting in 3, 2 or 1 pipe. Also note that the hydrostatic pressure drop for a stagnant liquid is quite high, higher than the pressure drop for a flow distribution in 4, 3, and 2 pipes, but lower than the pressure drop for the flow in a single pipe.

The possibility to get a minimum pressure drop in a single, 2 or 3 pipes rather then for flow in 4 pipes is due to the effect of gravity on the pressure drop. A flow in a single pipe (for example) results in high flow rates of liquid and gas in which case the slip is negligible and the void fraction is relatively high (see Eq. (5)). As a result the hydrostatic pressure contribution is low. Obviously for the case of horizontal flow the minimum pressure drop is always obtained when the flow is evenly split among the 4 pipes.

The lines in Figs. 2–4 present the results for the flow configuration as obtained by the present analysis. The lines demarcate between regions where the total gas and liquid flow rates take place in 1, 2, 3 and 4 pipes. For example the line 1–2 is the transition line between the region of flow in 1 pipe to flow in 2 pipes.

Comparing the calculated lines with the experimental data shows that this simple theory predicts the general trend of the transition of the flow configuration fairly well although one cannot claim good agreement under all conditions.

5. Summary and conclusions

Flow splitting of gas and liquid in 4 parallel pips was investigated. Experimental results were obtained for 0°, 5°, 10° and 15° inclinations. For the horizontal case the flow takes place in all of the 4 pipes, usually with an even splitting. For the inclined pipes various flow configuration could take place. For low liquid and gas flow rates the two-phase mixture prefers to flow in a single pipe while stagnant liquid fills part of the other three pipes. As the flow rates of liquid and gas increase, flow in two, three and eventually in four pipes takes place.

The number of pipes in which flow takes place and the number of pipes in which stagnant liquid columns are presented is fairly well predicted using steady state solutions and assuming that the flow configuration will be the one that results in a minimum pressure drop. The pressure drop is calculated using the drift flux model. Although more accurate methods for the calculation of the pressure drop can be applied, we consider the drift flux model as advantageous to other methods due to its simplicity and ease of calculation while it is still fairly adequate to simulate the basic physical phenomenon.

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