PERGAMON

International Journal of Multiphase Flow 25 (1999) 1491–1503

International Journal of Multiphase Flow

www.elsevier.com/locate/ijmulflow

Two-phase flow in inclined parallel pipes

M. Tshuva, D. Barnea, Y. Taitel*

Department of Fluid Mechanics and Heat Transfer, Faculty of Engineering, Tel-Aviv University, Ramat-Aviv, 69978, Israel

Received 2 November 1998; received in revised form 14 January 1999

It is a pleasure to dedicate this paper to Professor Gad Hetsroni towards his 65th birthday. Gad should be credited for advancing the area of multiphase flow as a scientific discipline both by his own work and by the outstanding *International Journal of Multiphase Flow* which he founded and serves as a principle editor. Through his leadership, persistence and devotion the Journal that was founded in 1973 soon became a leading journal and a vehicle for new scientific and engineering progress related to multiphase flow. We wish Gad many years of productive work and hope to celebrate together many more birthdays.

Abstract

Two-phase flow in parallel pipes is associated with the application of Direct Steam Generation by solar heating. In this process boiling water is fed into many parallel pipes from a common manifold. Instability and non-uniformity of the flow in this case can be a major operational problem. In this work the gas and liquid distribution in two parallel pipes is mapped experimentally. It is found that the flow distribution can be either symmetric or asymmetric depending on the flow conditions and pipe inclination. A model that explains the observed phenomena is proposed. © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Two-phase flow; Parallel pipes; Steam generation; Solar energy

1. Introduction

The study of two-phase flow in parallel pipes where the feed is from a common manifold is an interesting problem as the two phases may split unevenly when entering the parallel piping. The main motivation for this work is related to the processes that take place in the application

* Corresponding author. Tel.: +972-3-640-8220; fax: +972-3-640-7334.
E-mail address: taitel@eng.tau.ac.il (Y. Taitel)

PII: S0301-9322(99)00048-8

of direct steam generation (DSG) by solar heating. Such flows can develop instability and/or uneven distribution of the flow rates in the parallel pipes which is usually an undesirable phenomenon.

Pederson and May (1982) and Murphy and May (1982) studied two-phase flow instabilities which may arise during the operation of parallel pipes that absorb focused solar energy and produce steam directly in the collectors. They investigated the hydrodynamic transient behavior of a two-phase boiling system. Five flow instabilities were identified as potentially harmful to the operation of a DSG system, and generalized maps were drawn which estimate the stability of a parallel-channel solar system.

Jovic et al. (1994) investigated experimentally the onset of pressure drop oscillations in three parallel channel flow. It was shown that the inter channel interaction can lead to unstable two phase flow regime.

Experimental work has been done by Ozawa et al. (1979, 1982, 1989). Their work is on two-phase flow systems 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. Their conclusion is that the injection of air has a destabilizing effect on the pressure drop oscillations. On the other hand, the injection of liquid has a stabilizing effect, but induces a small-amplitude oscillation in the liquid flow rates.

No work has been carried out on parallel two-phase flow in inclined pipes. The work of Reinecke et al. (1994), however, is similar to the approach used in this work. Their work focuses on flow reversal in vertical two-phase flow in parallel channels that is related to loss of coolant accident (LOCA) or to loss of pumping power accident (LOPP) in nuclear plants. 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. The two-phase mixture was fed into the bottom plenum and experiments were carried out to determine the boundaries of the reversal state. A model, based on pressure drop calculations was presented for the prediction of the reversal boundaries. The boundaries for reversal two-phase flow in a multiple tube array are determined when the hydrostatic pressure drop exceeds the system pressure.

The principle objective of the present work is to find the operational conditions under which instability and/or uneven flow distribution may exist in parallel pipe systems.

2. Experimental apparatus

A schematic diagram of the experimental system is shown in Fig. 1. The experimental apparatus consists of two parallel pipes in which parallel flow is established and a third control pipe. Each pipe has a diameter of 2.4 cm and 3 m in length. The pipes are constructed of Plexiglas which allows to observe the flow patterns in the pipes. The system has controlled water and air supplies. The whole flow system can rotate within the range of 0 to 90°. The pipes are equipped with fast closing valves, activated simultaneously, for the measurement of the liquid holdup in each pipe. These valves are used to assess the symmetry of flow in the two pipes.

The superficial gas velocities are in the range of 0.15–5.60 m/s. The superficial liquid

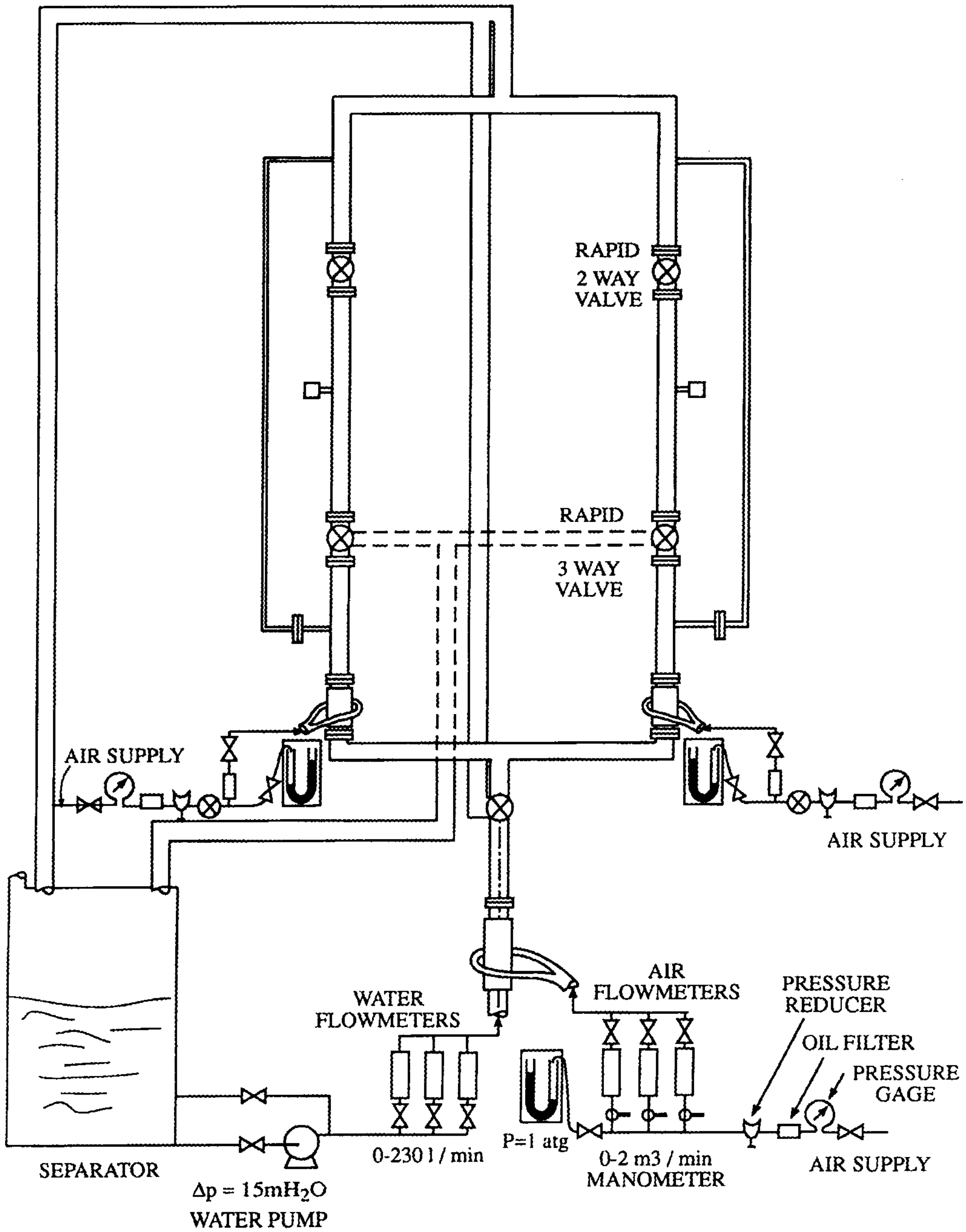


Fig. 1. Experimental apparatus.

velocities are in the range of 0.02–3.03 m/s. The input section guaranties perfect mixing of the two fluids at the inlet before the splitting takes place.

Pressures drop is measured using differential pressure transducer DP-15 of Validyne. The test is performed for ten angles of inclination 0°, 5°, 10°, 20°, 30°, 45°, 60°, 70°, 80°, and 90°. The output pressure is always atmospheric.

3. Experimental results

For the case of horizontal flow, the flow conditions in the two parallel pipes are identical. The flow pattern in the pipes is elongated bubble flow or slug flow. The holdup in the two pipes as well as the pressure difference is identical and the flow is symmetric for the whole range of flow rates.

For the case of upward inclined flow, asymmetric flow is observed in a certain range of gas and liquid flow rates. Figs. 2–7 map the experimental symmetry conditions for the inclination angles of 5°, 10°, 20°, 45°, 70° and 90° plotted as a function of the total liquid and gas input. Two types of flow distribution are observed. For high liquid and/or gas flow rates the flow is symmetric as for the case of horizontal flow (the square symbols in Figs. 2–7). For low flow rates of gas and liquid the flow is asymmetric (the circular symbols in Figs. 2–7). The

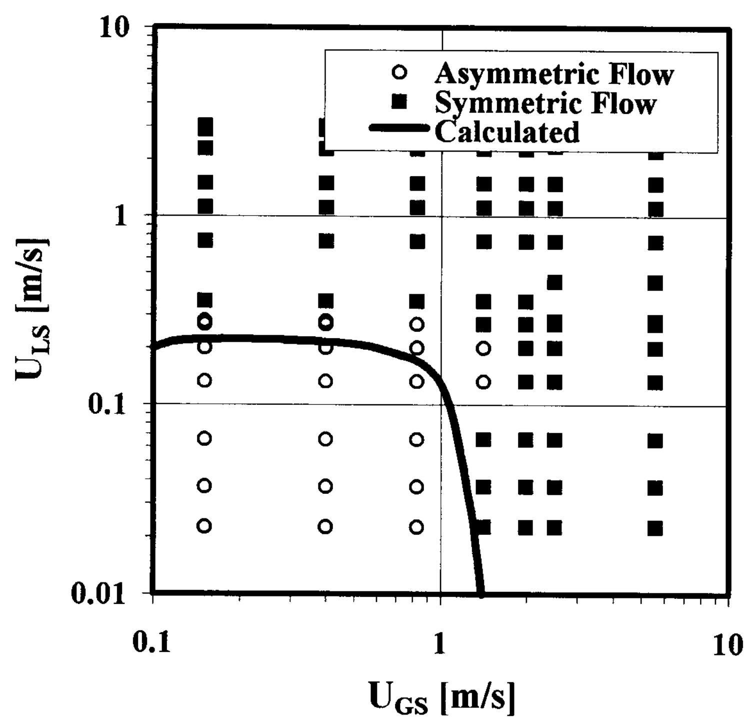


Fig. 2. Flow distribution — upward inclination angle 5°.

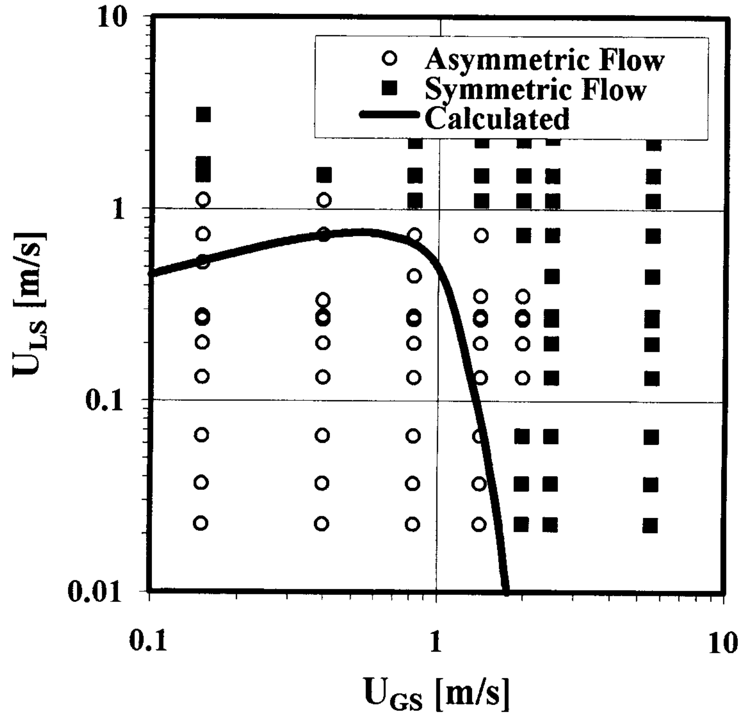


Fig. 3. Flow distribution — upward inclination angle 10°.

asymmetrical flow observed in our experiments takes the following form: the total flow of gas and liquid is directed to one pipe while the other pipe is partially filled with a *stagnant liquid.* The height of this liquid column is determined by the pressure gradient that exists in the other pipe (see Fig. 8). Observations of the flow regimes show that the flow always starts out as symmetric flow, and only after a short time the flow may become asymmetric. The region of asymmetrical flow distribution increases as the inclination angle increases.

The flow distribution appears to be quite stable. A pulse disturbance of air injection that is introduced in one of the two pipes does not alter the symmetry characteristics of the flow. For the case of asymmetric flow a pulse in the stagnant liquid column causes an interchange of the flow conditions in the two pipes, that is, the flow now is through the pipe that was the 'stagnant pipe' while the other pipe contains now the stagnant liquid.

4. Analysis

In the analysis, we try to find all possible steady state solutions for any given total input of liquid flow rate, U_{LS}, and gas flow rate, U_{GS}.

The liquid and the gas enter the two parallel pipes via a common manifold. The flow of the

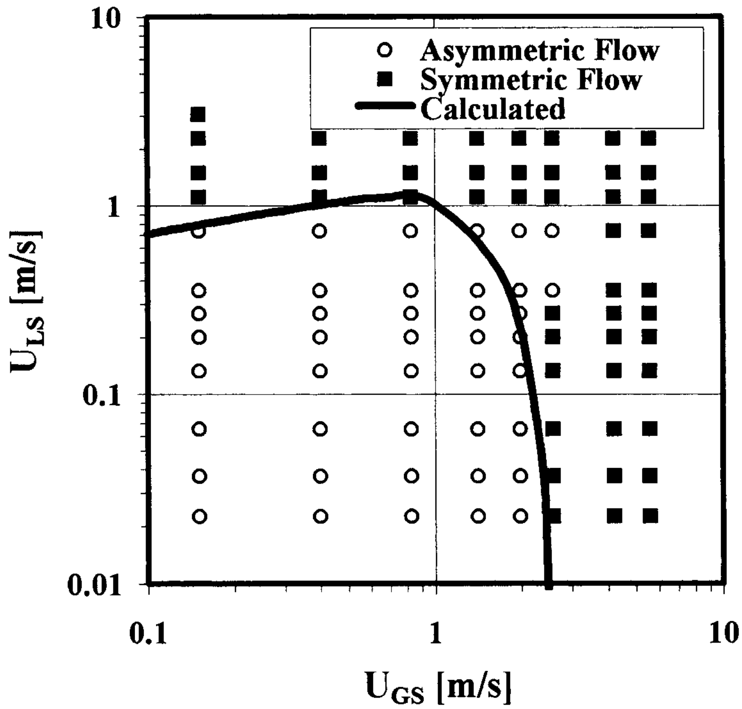


Fig. 4. Flow distribution — upward inclination angle 20°.

gas and the liquid is then split into the two pipes. U_{LS1} and U_{GS1} are the liquid and the gas flow rates (per unit area) that enter pipe no. 1. The flow rates in pipe no. 2 will then be $U_{LS2} = U_{LS} - U_{LS1}$ for the liquid and $U_{GS2} = U_{GS} - U_{GS1}$ for the gas. A possible steady state solution is the one for which the split between the two pipes results in an equal pressure difference for the two pipes.

The calculation of the pressure drop is performed using physical models. At first the flow pattern is determined using Barnea (1987) unified flow pattern model. Once the flow pattern is predicted the pressure drop for the specific flow pattern obtained is determined by physical models that simulate very closely the hydrodynamics of the flow (Taitel and Dukler, 1976; Taitel and Barnea, 1990).

The solution procedure starts by determining the gas flow rate in pipe no. 1, U_{GS1}, and then scan all possible liquid flow rates, U_{LS1}, that will yield the same pressure difference in the two pipes. Figs. 9 and 10 show all possible steady state solutions where the pressure difference in the two pipes is equal for the case of a total gas flow rate of $U_{GS} = 1$ m/s and three values of the total liquid flow rates, $U_{LS} = 0.2$, 0.3 and 0.5 m/s. The upward inclination angle is 5° in Fig. 9 and 10° in Fig. 10. The steady state solutions for the relative liquid flow rate U_{LS1}/U_{LS} as a function of the relative gas flow rate U_{GS1}/U_{GS} are presented in Figs. 9a and 10a. Figs. 9b and 10b show the pressure difference that is associated with each solution. Thus, for example,

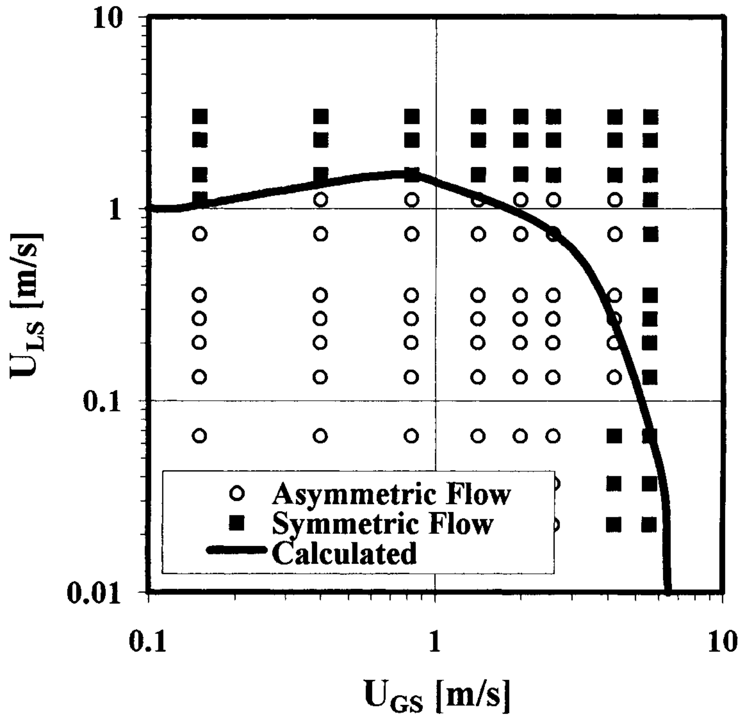


Fig. 5. Flow distribution — upward inclination angle 45°.

for 5° inclination, $U_{GS1}/U_{GS} = 0.20$, $U_{LS1}/U_{LS} = 0.4$ and for $U_{GS1}/U_{GS} = 0.80$, $U_{LS1}/U_{LS} = 0.60$ m/s, the pressure difference in the two pipes is equal and it is $\Delta P = 2800$ Pa.

In addition to the infinite number of theoretically possible steady states mentioned above, a solution for which the whole flow is via one pipe is also possible, provided the pressure difference for this pipe is less than the hydrostatic pressure created by a stagnant liquid in the other pipe. This solution is presented in Figs. 9b and 10b by the squares symbols plotted at $U_{GS1}/U_{GS} = 100\%$. In Fig. 9b the experimental results of the pressure difference for the case of the total liquid flow rate, $U_{LS} = 0.3$ are also presented.

As can be seen, there is (theoretically) an infinite number of solutions that satisfies equal pressure difference for each total input of liquid and gas flow rates. In addition, another steady state solution may be possible in which the total flow of liquid and gas takes place in one pipe while the other pipe contains a stagnant liquid column, as shown in Fig. 8. This solution is possible provided the pressure drop of the two phase flow in the pipe is less than the hydrostatic pressure exerted by the liquid when it fills the pipe.

Out of all these solutions the question is what will be the physical case that will also match our experimental data. We postulate that the physical solution will be the one in which the

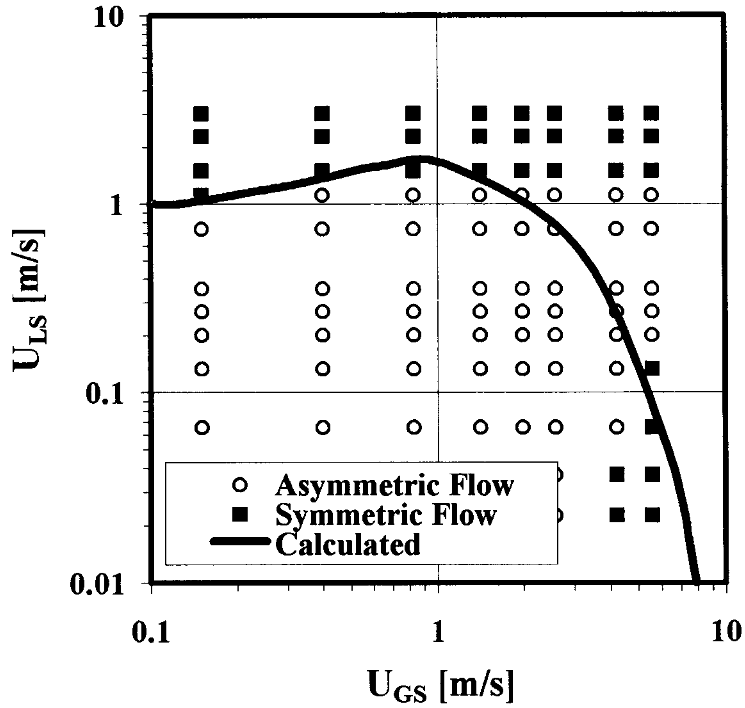


Fig. 6. Flow distribution — upward inclination angle 70°.

pressure drop is minimal. This condition is associated with the minimum energy needed to maintain the flow for a given total liquid and gas flow rate.

Observation of Figs. 9 and 10 shows that the symmetric distribution of the two phases in the pipes yields a pressure drop which is always less than the pressure drop obtained for all other combinations of gas and liquid distributions. Thus, we expect that the solutions for the non-symmetric distributions of the phases in the pipes are not physical. However, as aforementioned, when a 'single pipe' flow solution exists, and the pressure drop associated with this solution is less than the minimal pressure drop associated with the symmetric solution than this solution will take place in practice. For example, the conditions presented in Fig. 9 predict symmetric distribution. On the other hand, Fig. 10 shows that the physical solution for the cases of $U_{LS} = 0.2$ and 0.3 m/s are that of a 'single pipe' flow.

The aforementioned analysis enable to map the zones of symmetric flow distribution and asymmetric flow where the total flow is directed into a single pipe. The lines that demarcate these zones are shown in Figs. 2–7. The agreement between the experimental results and the analytical results is usually satisfactory. Note that the theoretical calculation of the pressure drop still suffers from a limited accuracy (see comparison with the experimental pressure drop data in Fig. 9). Still the trend that shows a minimum pressure drop in the symmetrical

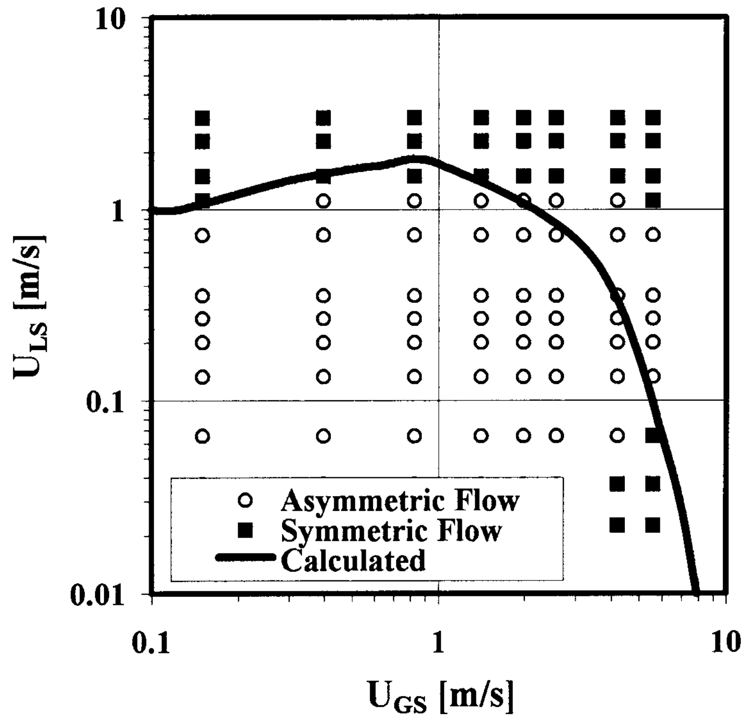


Fig. 7. Flow distribution — upward inclination angle 90°.

distribution is clearly observed also by the experimental data. This lack of accuracy influences also the accuracy of the calculated demarcating boundaries in Figs. 2–7.

5. Summary and conclusions

The distribution of gas–liquid two phase flow in two parallel pipes with common inlet and outlet manifolds is studied for a wide range of gas and liquid flow rates and for various upward pipe inclinations.

It is observed that two possible configurations can take place: (1) symmetric distribution of liquid and gas in the two pipes and (2) asymmetric flow in which the two phases flow in one single pipe and a stagnant liquid column is present in the other pipe. The non-symmetric configuration is observed in upward inclined parallel pipes at low gas and liquid flow rates. The region of asymmetric flow increases with the angle of inclination. For the horizontal case the flow is symmetric for all flow conditions.

A theoretical analysis shows that essentially infinite number of steady state flow distribution exists satisfying equal pressure difference in the two pipes. It is postulated that the flow configuration that will take place in reality will be the one that results in a minimal pressure drop.

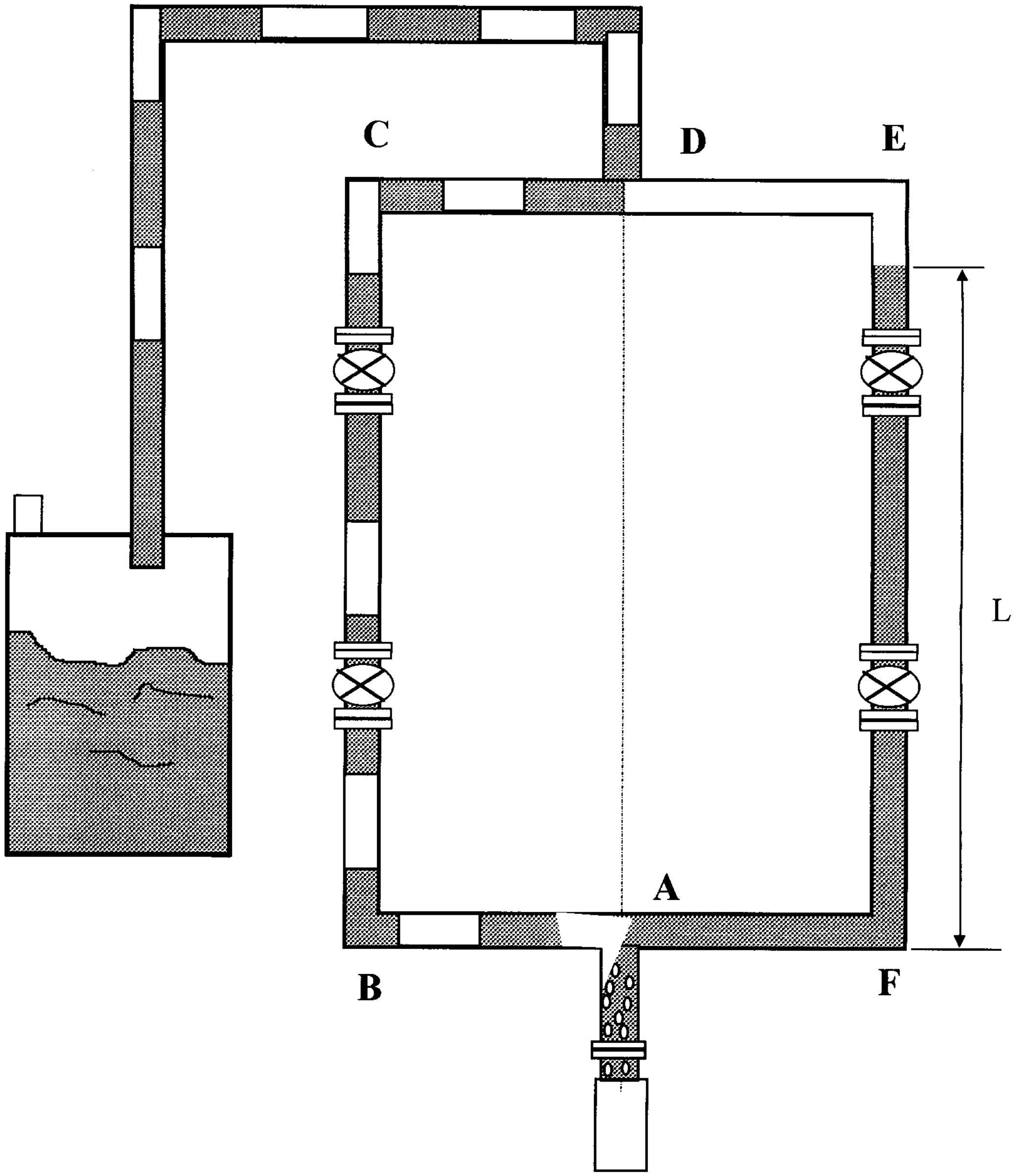
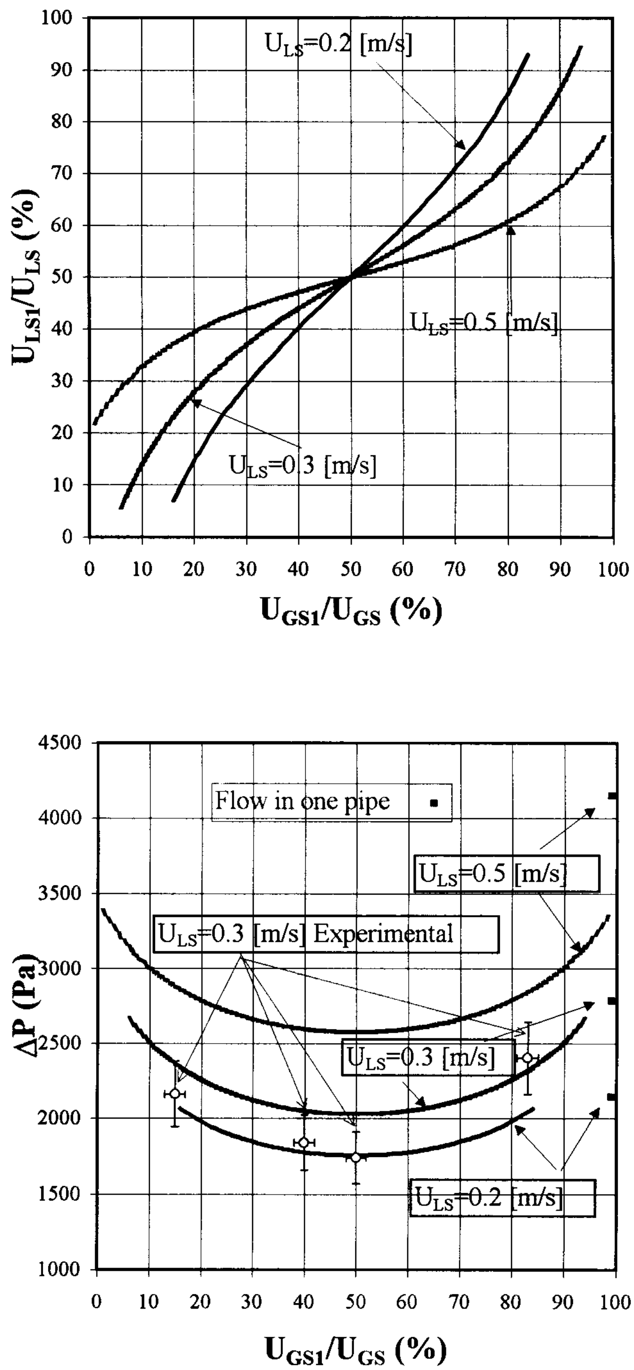


Fig. 8. Schematic presentation of the asymmetric case.

(a)



(b)

Fig. 9. (a) Calculated steady states, (b) Pressure difference associated with the steady state solution. $U_{GS} = 1$ m/s, upward inclination angle 5°.

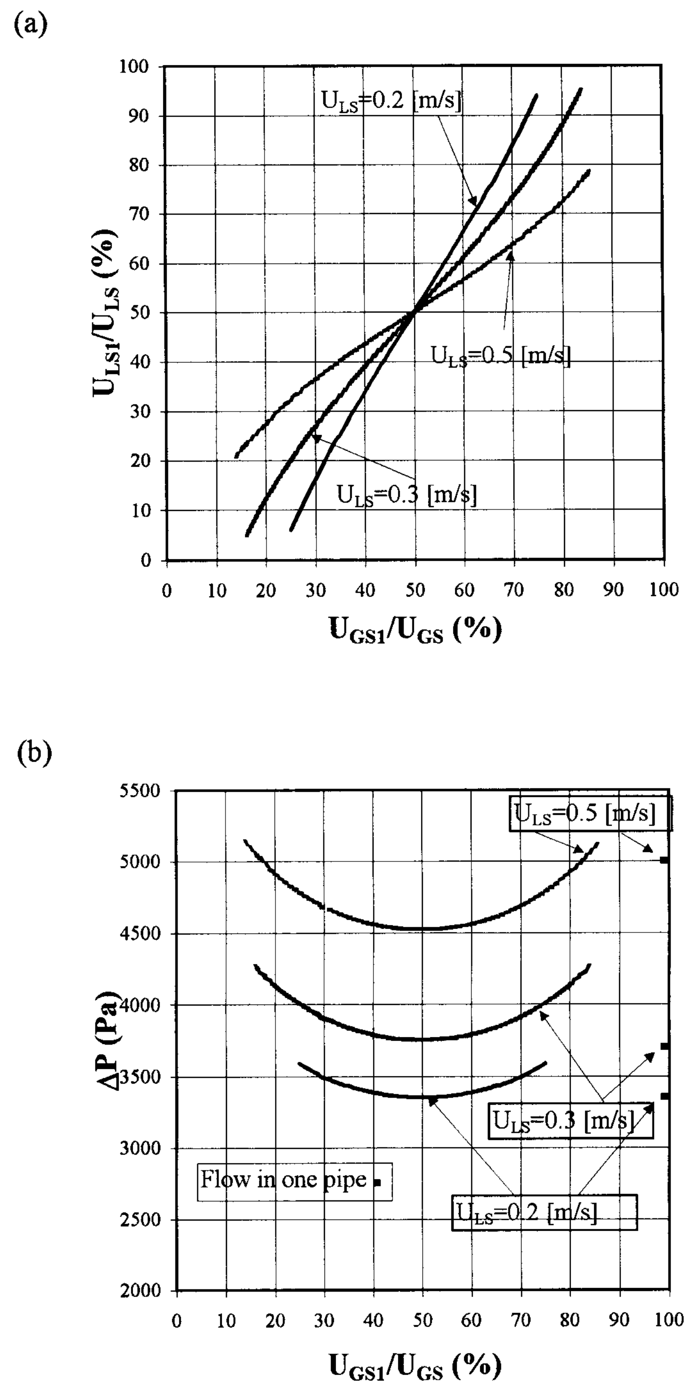


Fig. 10. (a) Calculated steady states, (b) Pressure difference associated with the steady state solution. $U_{GS} = 1$ m/s, upward inclination angle 10°.

Maps of superficial liquid velocities versus superficial gas velocities can be prepared for various operating conditions (length and diameter of the pipe, upward inclination angle, liquid and gas physical properties), which allow to determine the transition from the symmetric to asymmetric flow distribution.

References

Barnea, D., 1987. A unified model for prediction flow pattern transitions in the whole range of pipe inclination. Int. J. Multiphase Flow 13, 1–12.

Jovic, V., Afgan, N., Jovic, L., Spasojevic, D., 1994. An experimental study of the pressure drop oscillations in three parallel channel two phase flow. In: Hewitt, G.F. (Ed.), Proceedings of the Internationa Heat Transfer Conference, Brighton, UK, pp. 193–198 Paper 14-TP-9.

Murphy, L.M., May, E.K., 1982. Steam generation in line-focus solar collectors: a comparative assessment of thermal performance, operating stability, and cost issues, SERI/TR- 632-1311, Golden, CO, Solar Energy Research Institute.

Ozawa, M., Akagawa, K., Sakaguchi, T., Tsukahara, T., Fujii, T., 1979. Oscillatory flow instabilities in air–water two-phase flow systems — first report, pressure drop oscillation. Bull. JSME 22, 1763–1770.

Ozawa, M., Akagawa, K., Sakaguchi, T., Suezawa, T., 1982. Oscillatory flow instabilities in a gas–liquid two-phase flow system, heat transfer in nuclear reactor safety. Hemisphere, Washington, DC, pp. 379–390.

Ozawa, M., Akagawa, K., Sakaguchi, T., 1989. Flow instabilities in parallel-channel flow systems of gas–liquid two-phase mixtures. Int. J. Multiphase Flow 15, 639–657.

Pederson, R.J., May, E.K., 1982. Flow instability during DSG in a line-focus solar collector system, SERI/TR- 632-1354. Golden, CO, Solar Energy Research Institute.

Reinecke, N., Griffith, P., Mewes, D., 1994. Flow-reversal in vertical, two-phase, two-component flow in parallel channels. In: 32nd Meeting of the European Two-Phase Flow Group.

Taitel, Y., Dukler, A.E., 1976. A model for prediction flow regime transitions in horizontal and near horizontal gas–liquid flow. AIChE J. 22, 47–55.

Taitel, Y., Barnea, D., 1990. Two phase slug flow. In: Hartnett, J.P., Irvine Jr., T.F. (Eds.), Advances in Heat Transfer, 20. Academic Press, New York, pp. 83–132.