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A COMPARISON OF EXISTING FLOW-PATTERN PREDICTIONS DURING FORCED-CONVECTIVE TWO-PHASE FLOW UNDER MICROGRAVITY CONDITIONS

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Abstract—The utilization of pumped two-phase flow loops in space-based thermal-power systems has been the subject of considerable attention from researchers in the past few years. Because of their ability to meet high-power-level demands over extended space structures, two-phase flow loops are favored over the conventional single-phase systems. Predictions of the influence of reducing gravity on the flow patterns (and their transitions) in two-phase flow are essential, since changes in the heat-transfer coefficients and the pressure drop are strongly coupled to changes that take place in flow patterns. This study summarizes the work that was done to date in this area and examines the now available flow-pattern maps for microgravity conditions with recommendations for future investigations.

Key Words: microgravity, flow patterns, two-phase flow

INTRODUCTION

Studies related to the subject of two-phase flow in a microgravity environment have been emerging rapidly in the past few years. Due to the anticipated high-power-level demands for thermal management in future spacecraft and aboard the Space Station Freedom, active methods of transporting heat along a spacecraft were pursued. A two-phase system was considered an excellent alternative to the conventional single-phase system in providing large energy levels at uniform temperature, regardless of variations in the heat loads. Many studies in this area at earth gravity have shown that the heat-transfer coefficients and frictional pressure-drop during the flow of a liquid and a gas (or vapor) depend to a large extent on how the two phases arrange themselves in the conduit. Expecting the same dependency at 0-*g*, a non-ambiguous knowledge of the flow patterns in a microgravity environment is essential to the study of heat transfer in two-phase flow in such an environment. Different approaches have been taken in order to study the influence of gravity on the two-phase flow patterns. These approaches can be divided into two main groups: ground-based research; and flight experiments. Ground-based research included testing the two-phase system behavior when the orientation of the test section was changed from horizontal (where the influence of gravity is profound) to inclined. Others performed theoretical studies in order to extend the available correlations for transition lines on the 1-*g* flow-pattern maps to 0-*g*. A third group carried out experimental work using an equi-density, liquid–liquid system (thus eliminating the influence of buoyancy forces) in an effort to simulate the microgravity conditions on the ground.

On the other hand, flight experiments included flow-pattern observations and high-speed photography in an actual reduced-gravity environment aboard test aircraft and also in drop towers using single-component (boiling) and two-component, two-phase flow systems. These studies are summarized in the following two sections, with emphasis on the most significant results obtained in each case.

GROUND-BASED RESEARCH

Fowle (1981) performed ground-based tests in order to verify the functional capabilities of a pumped two-phase thermal-transport system which was proposed for use in space applications. The laboratory apparatus was a closed-loop two-phase system using Freon-11 as the working fluid. It consisted of an evaporator and a condenser separated by a length of adiabatic tubing mounted on a table top. Flow-pattern observations were made downstream of the evaporator and condenser. A series of tests were made by fixing the liquid flow rate and gradually increasing the power supply to the evaporator until the quality of its discharge reached 100%. Flow observations of the behavior of the system were also made when the apparatus was tilted and also when the section of Tygon tubing was lifted to a higher elevation from the table top. Unfortunately, none of the heat-transfer data and flow observations were reported in that work. The author reported, however, that although local-flow patterns and pressure drop changed with the mentioned alterations, the system continued to serve its heat-transport functions.

Eastman *et al.* (1984) carried out a theoretical study in order to investigate the effects of various forces on the fluid-flow patterns and heat-transfer mechanisms as a first step in the study of the influence of gravity on these parameters. An improved explanation of the forces causing separation from a heated surface indicated conditions under which pool boiling and forced-convective boiling may be possible in a weightless environment. The authors suggested that the flow-pattern transitions in different gravity fields can be reasonably predicted using the criteria of Weisman *et al.* (1979; Weisman & Kang 1981) with the exception of extremely small gravity fields and very small tubes. The equations describing the transition from intermittent to annular flow and from annular to dispersed flow are, respectively, as follows:

$$G = B\left(\frac{1}{x}\right)\left(\frac{x}{1-x}\right)^{0.2232} g^{0.4107} \quad [1]$$

and

$$G = C(1-x)^{-1} g^{0.25}, \quad [2]$$

where G is the total mass velocity (kg/m^2 s) for both phases, x is the quality and B and C are functions of the tube size, surface tension, friction factor and the densities of both phases [see Eastman *et al.* (1984) for these expressions].

When the above boundaries were plotted for Freon-11 at 21°C and gravities of 1-g and 0.008-g levels, the results showed a shift in both boundaries to lower mass velocities with the reduction of gravity. Eastman *et al.* (1984) concluded their study by saying that pool boiling may be possible at 0-g for fluids with a low surface tension in a subcooled-liquid condition. Forced-convection effects will aid the boiling process and reduce any difference between 1-g and 0-g performance.

Karri & Mathur (1987), in an attempt to simulate the microgravity conditions at 1-g, used a unique approach to study the flow patterns of vapor–liquid flows. Two immiscible liquids of equal density were used to obtain flow-pattern data in a horizontal glass tube of 2.54 cm i.d. Water simulated the vapor phase, while selected oils (e.g. Dow Corning 200 silicone oil + CCl_4), being the more viscous liquid, simulated the liquid phase. A series of flow patterns were observed during those runs and were reported in terms of bubble, slug and annular flows. The authors defined these basic flow patterns in a conventional way with, for example, observations of slug flow described as Taylor bubbles separated by "liquid"-phase flow that completely filled the tube cross-section. A simulated microgravity flow-pattern map for horizontal flow based on their observations was proposed in that study; this is shown in figure 1.

It is worth mentioning here that this method of simulation was implemented earlier by Lovell (1985), who used water and polypropylene glycol (which simulated the liquid phase). His experimental results suggested certain flow patterns which have not often been observed at 1-g. An example of such flow patterns is what was called "inverse annular", where "liquid" was observed to flow in the core of the pipe and "vapor" flowed around the perimeter. These uncommon observations, being the first attempt at this method of simulation, were attributed to inappropriate surface-tension effects.

Also, Karri & Mathur (1988) extrapolated the 1-g models of Taitel *et al.* (1980; Taitel & Dukler 1976) and Weismen *et al.* (1979; Weisman & Kang 1981) for horizontal and vertical flows to microgravity levels. The authors plotted the flow-pattern maps, based on these models, for 0.01-g and 10^{-5}-g microgravity levels. With horizontal flow, the comparisons showed that the three boundaries: stratified–intermittent, intermittent–dispersed bubble and stratified–annular/mist all moved toward lower superficial velocities of both phases as the gravity level was reduced. At very

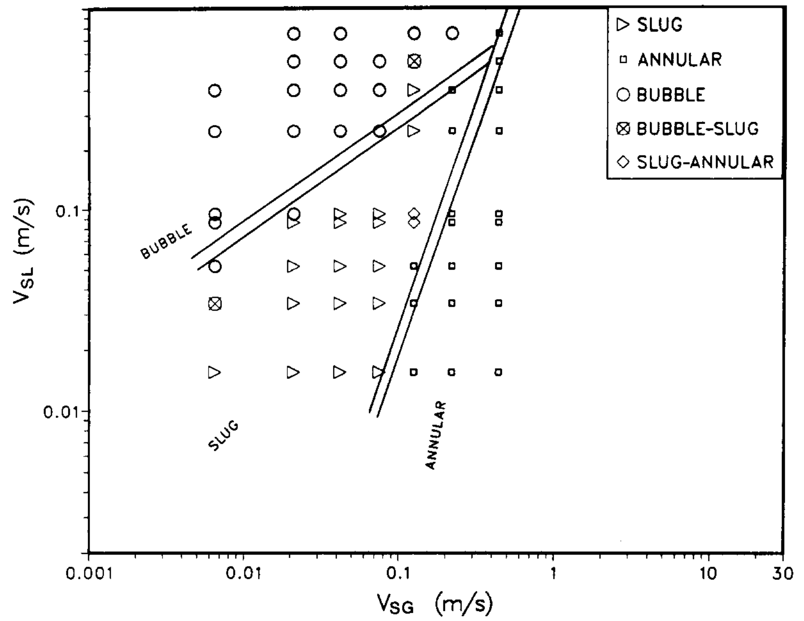

Figure 1. Simulated microgravity flow-pattern map of Karri & Mathur (1987).

low gravitational accelerations, both models showed that stratified flow would not exist. With vertical flow at 0.01-g, both models also predicted a shift in the boundaries toward lower superficial velocities of both phases. At a gravitational acceleration of 10^{-5}-g, the maps showed that bubble flow would not exist. Also at this gravity level, the study showed that the flow-pattern maps for horizontal and vertical flows using the Weisman *et al.* (1979; Weisman & Kang 1981) models were almost identical with essentially three flow patterns; namely, dispersed bubble, intermittent and annular/mist.

FLIGHT EXPERIMENTS

The first comprehensive set of pressure-drop data and flow-pattern observations during actual 0-g experiments were taken by Heppner *et al.* (1975). Experiments were performed first on the ground to collect a data base at 1-g, and then at reduced-gravity aboard the NASA KC-135 aircraft using a water–air (two-component) system. Data were also collected during the 2-g pull-out period of the aircraft. Quandt's (1965) approach was modified with other considerations to predict the location of the separating boundaries between three basic types of flow. These flow patterns were classified as segregated (stratified, wave, annular), intermittent (plug, slug) and distributed (dispersed, bubble and any other flow where one phase is continuous). The boundary between distributed and segregated flows was shown to be a function of Fr and the total mass velocity G. The correlation which predicts this boundary was given as follows:

$$G = \left[\left(\frac{2}{f_{\mathrm{TP}}}\right) gD\rho_{\mathrm{L}}\bar{\rho}\right]^{0.5}, \qquad [3]$$

where f_{TP} is the two-phase friction factor and $\bar{\rho}$ is the average density of the two-phase mixture, calculated from

$$\bar{\rho} = \frac{\rho_{\mathrm{L}}\rho_{\mathrm{G}}}{\rho_{\mathrm{L}}x + (1-x)\rho_{\mathrm{G}}}. \qquad [4]$$

The boundary between segregated and intermittent flow was given by

$$G = \left[\left(\frac{2}{f_{\mathrm{TP}}}\right) gD\bar{\rho}^{2}\right]^{0.5}. \qquad [5]$$

These two transition boundaries were plotted for the conditions of 1-g and 0.01-g, as shown in

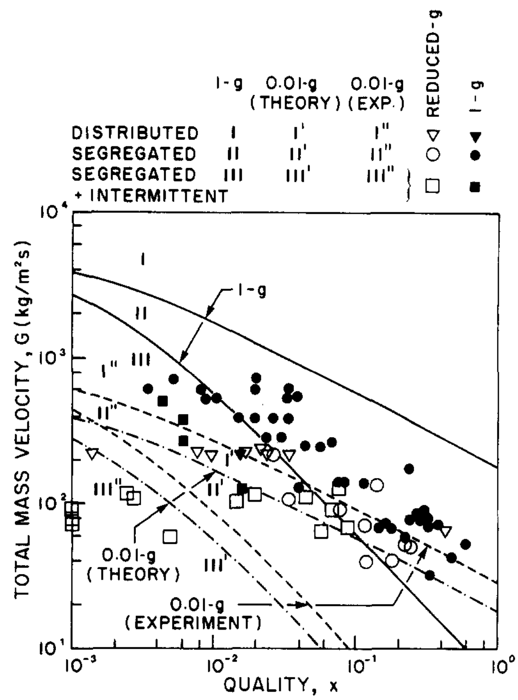

Figure 2. Flow-pattern observations of Heppner *et al.* (1975) at reduced and 1-*g* conditions on Quandt's (1965) flow-pattern map.

figure 2. The theory indicated a shift in the boundaries at low-*g* with the intermittent and segregated flows restricted to narrower ranges of quality and total mass velocities. Experimental data, also shown in figure 2, indicated shifts in the same direction but with smaller magnitudes. Another set of flight tests produced shifts close to the predicted ones with the latter still underpredicting the transition lines. One possible reason for this discrepancy is that the criteria of Quandt (1965) for the prediction of the transition boundaries were evaluated using a constant value of the two-phase friction factor ($f_{TP} = 0.02$). Using different values for f_{TP} would shift the boundaries closer to the experimental lines. Further investigation of the interfacial friction factor under microgravity conditions is therefore needed. It should be also noted here that the shifts, as predicted by [3] and [5], are in the same direction as those given by Eastman *et al.* (1984). However, the shift in the annular–intermittent boundary, as predicted from [1], is somewhat larger than that obtained from [5].

Another set of experimental data (Hill *et al.* 1987) was taken aboard the NASA KC-135 aircraft flying a total of 54 parabolae during 2 days of testing. The two-phase flow test loop employed the Sunstrand (Bland *et al.* 1984) Two-phase Thermal Management System Concept (TPTMS). A two-phase (liquid–vapor) mixture of Refrigerant-114 was produced by pumping nearly saturated liquid through an evaporator and adding heat via electric heaters. The quality of the two-phase flow was varied by changing the evaporator heat load. Pressure-drop and flow-pattern data were obtained at 1-*g* before and after the flight tests. The authors summarized the main flow-pattern observations as matching those given by Dukler *et al.* (1987); namely bubble, slug, annular and mist flow. They reported that only two out of these four main flow patterns were observed during the reduced-gravity testing for the range of qualities from 5 to 86%. These observations were as follows: at qualities < 10%, continuous liquid slugs were interspersed with classical "Taylor"-shaped bubbles of high vapor void fractions. Above 15% quality, an annular film was observed with no bridging in the tube. In the transition region, between 10 and 15% quality, they reported that the liquid surface seemed to have an increased roughness and occasional areas of droplet mist similar to the churn flow observed in vertical upflow, except flow reversal was not observed in that case. At the highest qualities, annular/mist flow was observed. Moreover, the research group aboard the KC-135 observed a fifth flow pattern which was given the name "frothy annular". They described this flow as annular flow with an "enriched", thicker annular liquid film when compared to ground testing (the ratio was approx. 2:1). They also indicated that the liquid film in that case appeared to contain a significant vapor-phase content.

Dukler *et al.* (1987), in a preliminary study, developed a microgravity flow-pattern map and tested it against a comparatively large set of water–air flow-pattern observations taken during drop-tower experiments (9.5 mm i.d. and 0.457 m long test section) and Learjet (12.7 mm i.d. and 1.06 m long test section) trajectories. The transition from bubble to slug flow was believed to take place due to bubble coalescence as the bubble concentration and size increased. From examination of the flow-pattern observations recorded on high-speed film, it was noted that the dispersed bubbles in a slug flow were moving at a velocity equal to that of the front of a slug. This indicates that a no-slip condition exists in a microgravity environment. It was also argued that this transition will take place at a void-fraction value of approx. 0.45; the equation representing the transition is given by

$$V_{SL} = 1.22\, V_{SG}. \qquad [6]$$

Similarly, the transition from slug to annular flow was speculated to take place when the void fraction, as dictated by two models for each flow pattern, becomes equal. These two models for slug and annular flows were developed from the physical concepts of each flow and are, respectively, given below:

$$\frac{V_{SG}}{(V_{SL} + V_{SG})} = 1.2\,\langle\epsilon\rangle, \qquad [7]$$

where $\langle\epsilon\rangle$ is the average void fraction during slug flow; and

$$\frac{\epsilon^{5/2}}{(1-\epsilon)^2} = \left(\frac{f_i}{f_w}\right)\left(\frac{\rho_G}{\rho_L}\right)\left(\frac{V_{SG}}{V_{SL}}\right)^2, \qquad [8]$$

where ϵ the void fraction for annular flow and f_i and f_w are the interfacial and the wall friction factors, respectively. These transition lines are shown in figure 3 together with the flow-pattern observations under microgravity conditions.

Lee *et al.* (1987) developed a theoretical two-phase flow-pattern transition map for a microgravity environment based on the physical concepts of four basic flow patterns. These flow patterns were dispersed flow, slug flow, stratified flow and annular flow. In their analysis, they considered

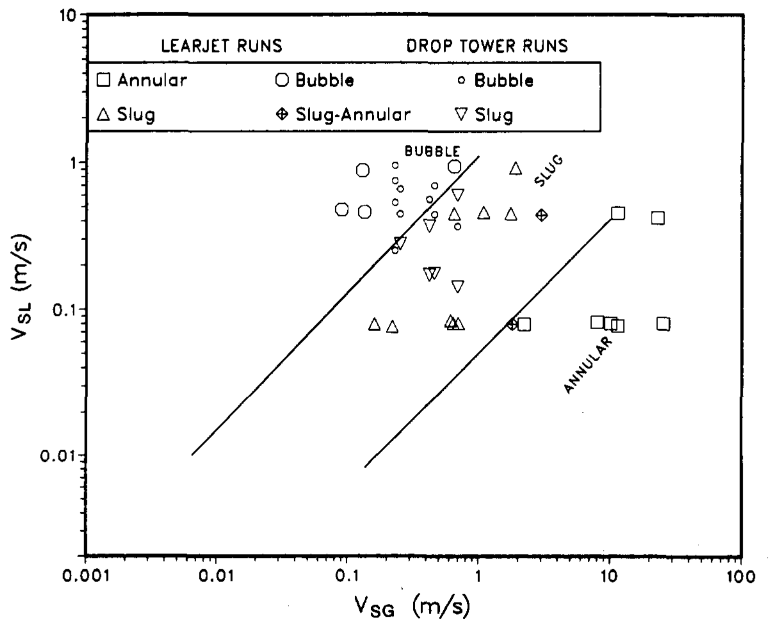

Figure 3. Microgravity flow-pattern map and experimental data of Dukler *et al.* (1987).

the different forces acting on the mixture for each flow pattern and showed that transition between any two basic flow patterns would take place when the balance between these forces is interrupted. According to their analysis, stratified flow will occur when the body forces become larger than the surface-tension forces. The transition from slug to bubble flow will take place when the force from eddy turbulent fluctuations is strong enough to overcome the surface-tension forces, and the transition from slug to annular flow will take place as the gas inertia increases and becomes large enough to overcome the surface-tension forces. Three dimensionless parameters A, B and C were developed to describe the transition boundaries between the different flow patterns. These parameters, and the corresponding transition boundaries are:

$$A = \frac{\sigma}{(\rho_L - \rho_G)gD^2} = \frac{1}{8\pi}\left(\frac{4\pi}{3}\right)^{1/3}(A''_G)^{2/3}(D)^{4/3}, \qquad [9]$$

which represents the transition boundary between stratified flow and the other flows;

$$B = \frac{\rho_L^{0.8} V_{SL}^{1.8} D^{0.8} \mu_L^{0.2}}{\sigma} = \frac{4}{0.023\sqrt{\pi}} \frac{h_l'^{0.2}}{V_L' \sqrt{A''_G}}, \qquad [10]$$

which represents the transition boundary between slug and dispersed flow; and

$$C = \frac{\rho_G V_{SG}^2 D}{\sigma} = \frac{2\sqrt{\pi}}{V_G'^2 \sqrt{A''_G}}, \qquad [11]$$

which represents the transition boundary between slug and annular flow; where

$$A''_G = \frac{A_G}{D^2}, \quad h_l' = \frac{h_l}{D}, \quad V_L' = \frac{V_L}{V_{SL}} \quad \text{and} \quad V_G' = \frac{V_G}{V_{SG}}. \qquad [12]$$

These dimensionless parameters were used with the Martinelli parameter X as coordinates to develop a microgravity two-phase flow-pattern map, shown in figure 4. Experimental data at 0.01-g were taken aboard the KC-135 aircraft and were used to examine the theoretical transition boundaries discussed above. This comparison is shown in figure 5 with the coordinates being the superficial liquid and gas velocities. It is clear from figure 5 that no stratified flow was observed during the flight tests.

Another set of flow-pattern observations, in addition to pressure-drop measurements, were taken (Kachnik *et al.* 1987) using water as the working fluid in order to further examine the flow transition boundaries of Lee *et al.* (1987) and generate a body of data under microgravity conditions. Void fractions were also measured during that set of flight tests and high-speed photography recorded the flow patterns. Bubbly, annular and slug flow patterns were observed in the test section at reduced-gravity conditions. Some of these observations were plotted on a flow-pattern map based on Quandt's (1965) approach, this is shown in figure 6.

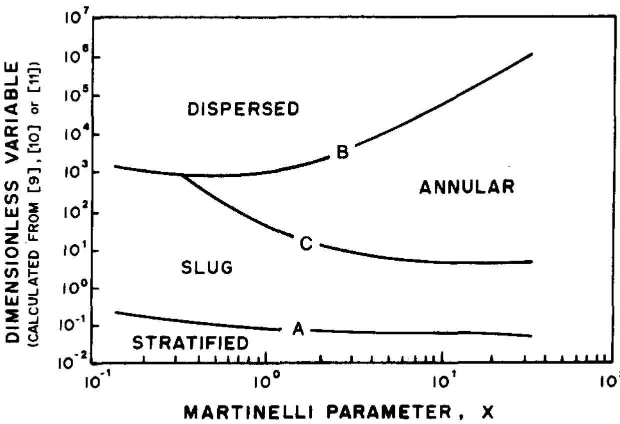

Figure 4. Microgravity flow-pattern map (I) of Lee *et al.* (1987).

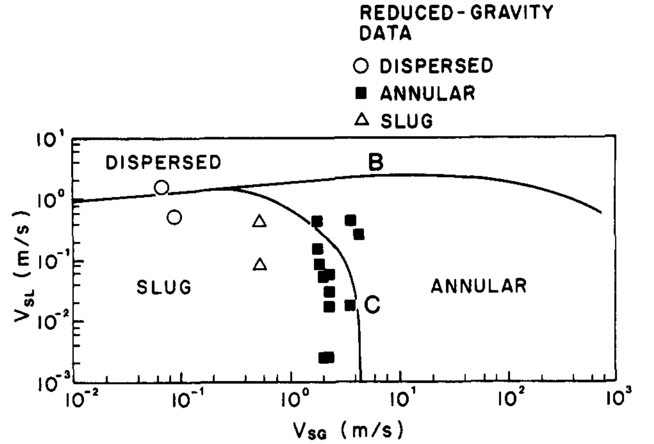

Figure 5. Microgravity flow-pattern map (II) of Lee *et al.* (1987).

The map shows, as reported by the authors, that gas–liquid flows which were stratified under 1-*g* and 2-*g* conditions were observed as slug flow under reduced-gravity conditions. This transition to slug flow was observed to take place immediately upon reaching the microgravity zone during the parabola. It can be seen from figure 6 that, except for bubble flow, the theoretical transition boundaries underpredicted the microgravity data. It is interesting at this point to compare the shifts in the flow-pattern boundaries obtained here with those reported by Heppner *et al.* (1975). Comparing figure 6 with the experimental results of Heppner *et al.* (1975), shown in figure 2, indicates that the shifts are in the same direction but with a larger magnitude (approximately twice) for the first case.

COMPARISONS AND DISCUSSION

A summary of the previous survey is given in table 1. In this table, single-component (boiling) studies were grouped separately from those with two-component (liquid–gas or liquid–liquid) systems.

With regard to identification of the flow patterns, there are two basic groups among the investigators. The first group (Heppner *et al.* 1975; Kachnik *et al.* 1987) matched their observations to those for horizontal flow at 1-g, as classified by Baker (1954) or later by Quandt (1965). The second group (Dukler *et al.* 1987; Hill *et al.* 1987; Karri & Mathur 1987) matched their observations

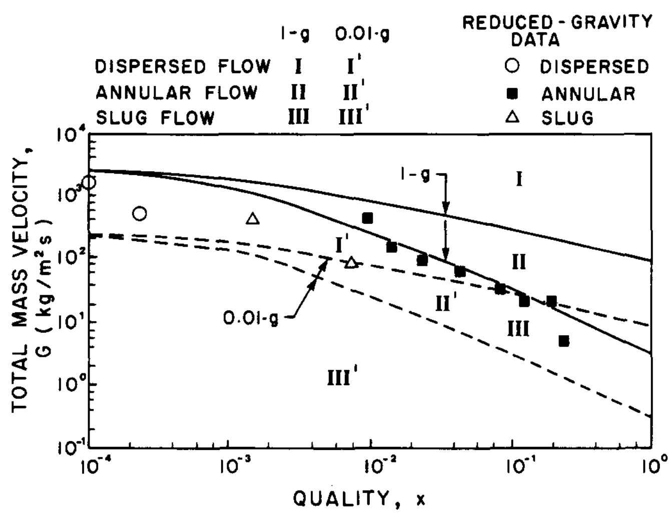

Figure 6. Flow-pattern map showing the microgravity data of Kachnik *et al.* (1987).

Table 1. Summary of microgravity flow-pattern studies

Investigator(s)	System	Test-section	Reduced-gravity facility	Gravity level	Duration of reduced gravity (s)	Flow-pattern observ.	Developed flow-pattern map
Heppner *et al.* (1975)	Water–air	Clear plastic $D = 2.54$ cm $L/D = 20$	KC-135	0.01-*g*	20	Yes	Yes
Dukler *et al.* (1987)	Water–air	(1) Clear tube $D = 9.52$ mm $L = 0.457$ m	30 m Drop tower	$\leqslant 0.02$-*g*	2.2	Yes	Yes
		(2) Clear tube $D = 12.7$ mm $L = 1.06$ m	Learjet	$\leqslant 0.02$-*g*	12–22	Yes	Yes
Karri & Mathur (1987)	Selected oils–water	Glass tube $D = 2.54$ cm	—	—	—	Yes	Yes
Hill *et al.* (1987)	Freon-114 (boiling)	Clear tube $D = 1.58$ cm $L = 1.83$ m	KC-135	$\leqslant 0.1$-*g*	25 per parabola (54 in total)	Yes	No
Kachnik *et al.* (1987)	Water	Boiler, quartz and stainless steel $D = 8$ mm Condenser, glass-in-glass $D = 6$ and 10 mm $L = 1.5$ m	KC-135	± 0.01-*g*	25 per parabola (300 in total)	Yes	No
Lee *et al.* (1987)	—	Theoretical study		± 0.01-*g*		—	Yes
Eastman *et al.* (1984)	Freon-11	Theoretical study		0.008-*g*		No	Yes

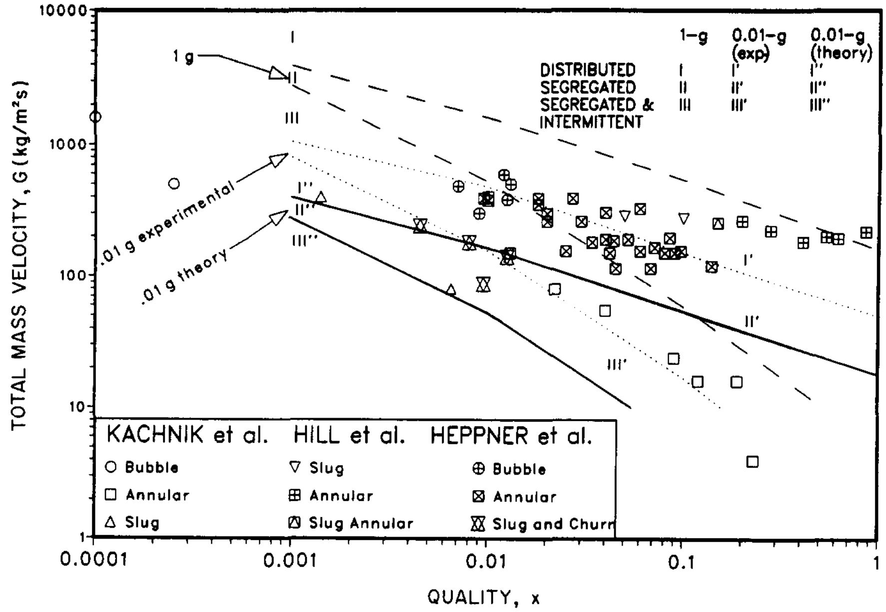

Figure 7. Comparison of the data with the experimental and predicted microgravity transitions of Heppner *et al.* (1975).

to those for vertical upward flow. Also, the microgravity flow-pattern maps followed the same classification as described above. The maps developed with flow patterns matching those for horizontal flow were tested with similar flow-pattern observation data points, with the addition of Hill *et al.*'s (1987) data. The latter observations, though originally matched to those observed with vertical flow, were shown (by the original authors) to fit well on horizontal-flow maps. These comparisons are discussed in the following section.

The comparison between the microgravity transition boundaries of Heppner *et al.* (1975) and the experimental data is shown in figure 7. It should be noted that in this comparison, as well as in all the others, only the first set of flow-pattern observations taken by Heppner *et al.* (1975) was used. The authors obtained a second set of observations during another low-*g* run with results generally similar to those used in the comparisons here. As mentioned earlier, the shift in the transition boundaries at 0.01-*g* is in the same direction as with the predicted lines but of a smaller magnitude. It can be seen from figure 7 that the entire data set of Hill *et al.* (1987) fell outside both the experimental and predicted low-*g* transition lines. These rather large discrepancies could be partially attributed to the fact that the physical properties of Freon-114 are quite different from those of the water–air system (e.g. the density ratio in the first case is approx. 30 times less than that for the water–air system). The data of Kachnik *et al.* (1987) fits the experimental transition lines (except for one point in each of the bubble and annular flows). The data of Heppner *et al.* (1975), except for some points in dispersed and segregated flow, fits the experimental lines well.

Figure 8 shows the theoretical transition lines, as proposed by Eastman *et al.* (1984), for Freon-11 at 21°C and gravity levels of 1-*g* and 0.008-*g*. As shown in this figure, the shift in the boundaries at low-*g* is in the same direction as that of Heppner *et al.* (1975). However, as mentioned before, the shift in the annular–intermittent boundary, as predicted from [1], is somewhat larger than that obtained from [5]. Moreover, the annular flow region with the transitions proposed by Eastman *et al.* (1984) occupies a wider range of flow qualities and total mass-flow rates, and this was still the case when the gravity was lowered to 0.008-*g*. It is obvious from figure 8 that the agreement between the data and the predictions is very poor. Except for some slug and annular data, the theoretical lines overpredicted the transition boundaries.

The third comparison was made with the transition boundaries proposed by Lee *et al.* (1987). As shown in figure 9, the boundary between slug and annular flow could be improved to fit the data better if shifted slightly to the left (thus, to lower values of V_{SG} at the same values of V_{SL}). The slug data points fit well on the graph, but the few bubble flow data points of Heppner *et al.* (1975) are poorly predicted by those boundaries.

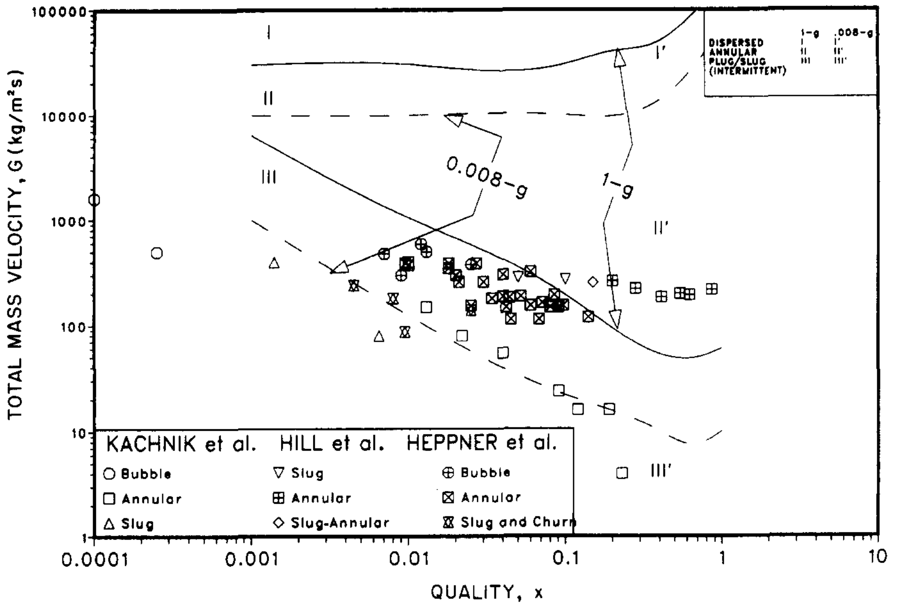

Figure 8. Comparison between the microgravity flow-pattern observations and the theoretical lines proposed by Eastman *et al.* (1984).

The flow-pattern map of Karri & Mathur (1987) is shown in figure 10 with five sets of microgravity flow-pattern data imposed on it. The bubble–slug boundary predicts well the experimental data, while the slug–annular boundary seems to be considerably shifted to the left (when all the data sets are considered). The annular flow region, as predicted by their map, appears to include most of the slug data of the other investigators in addition to slug–annular flow, and also some dispersed flow. This suggests that with the equi-density system, annular flow appears earlier (in terms of lower V_{SG} values at the same V_{SL}) than with a normal liquid–vapor system. Although the value of the interfacial tension of the silicone oil–water system (47 dyn/cm) is very comparable to some common liquid–air systems, it is speculated here that this early appearance of annular flow could be attributed to different mechanisms of interfacial tension and shear forces.

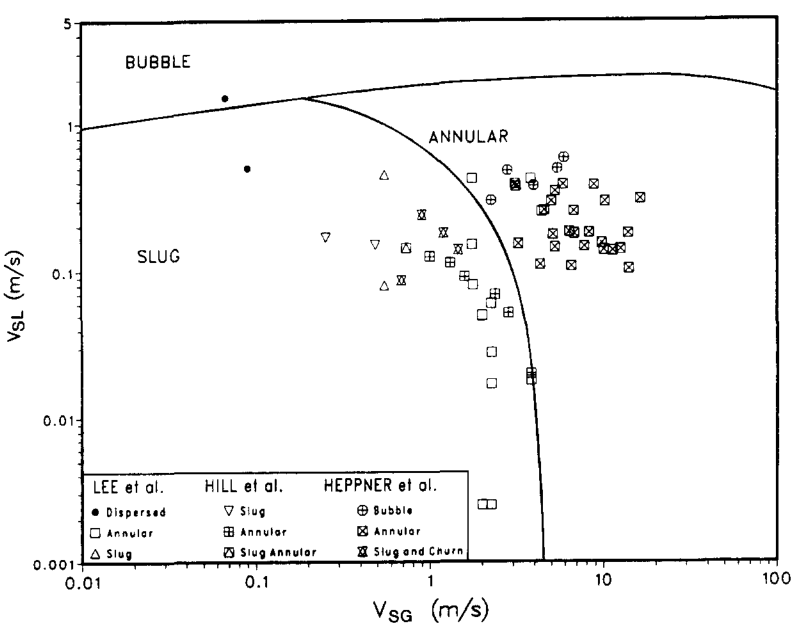

Figure 9. Comparison between the microgravity observations and the theoretical lines of Lee *et al.* (1987).

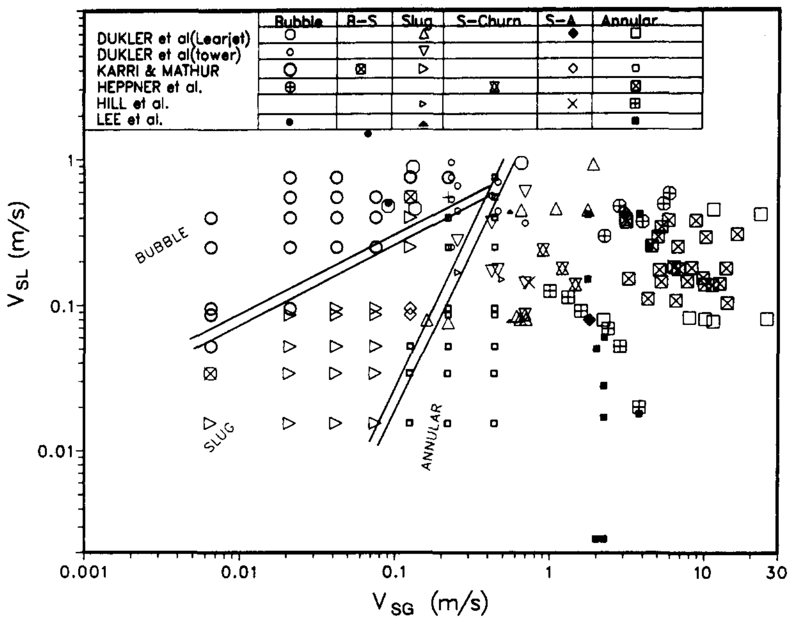

Figure 10. Simulated and actual microgravity observations on the flow-pattern map of Karri & Mathur. (1987).

More studies are needed to explain these results and examine the validity of this method of simulation.

The models of Taitel & Dukler (1976) and Weisman *et al.* (1979) for horizontal flow at a gravitational acceleration of 0.01-g were tested with the microgravity experimental data of Kachnik *et al.* (1987), Hill *et al.* (1987) and Heppner *et al.* (1975). These observations, in addition to the fact that they were matched to those for horizontal flow at 1-g, were taken at gravity levels of approx. 0.01-g; and thus are very appropriate for use in testing these models. The model of Taitel & Dukler (1976) correlated the data considerably well. As shown in figure 11, except for some of

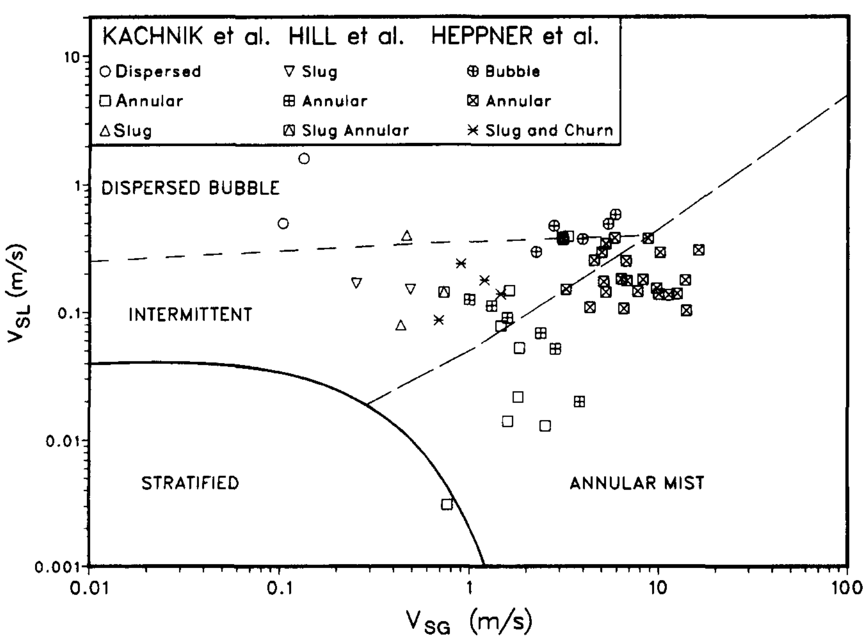

Figure 11. Comparison of the data with the model of Taitel & Dukler (1976) for horizontal flow at 0.01-g.

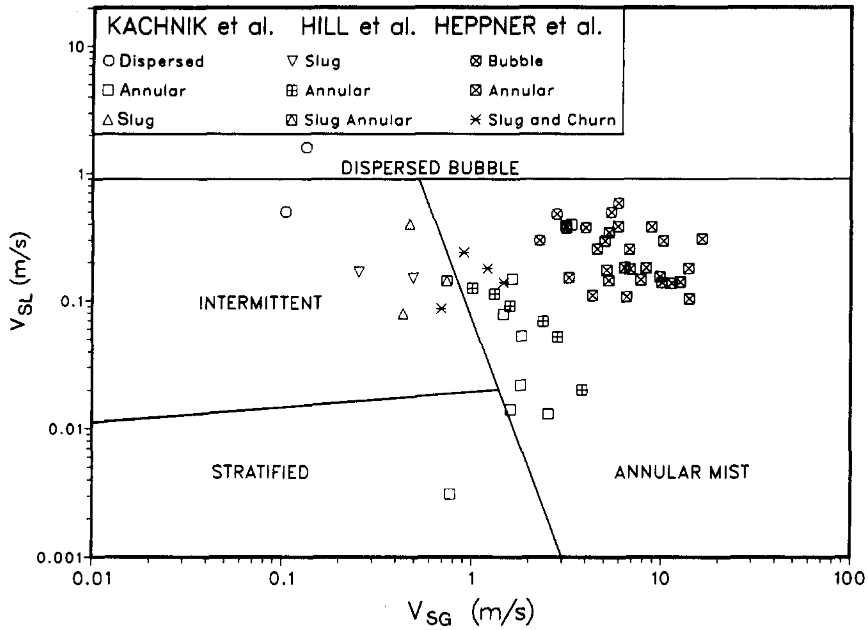

Figure 12. Comparison of the data with the model of Weisman *et al.* (1979) for horizontal flow at 0.01-*g*.

the annular data of Hill *et al.* (1987) and Heppner *et al.* (1975), the transition boundaries seem to separate the data very well. It should be noted that the annular data occupy the region which is called annular/mist by Taitel & Dukler (1976). This is also the case with the next three comparisons, shown in figures 12–14. The Weisman *et al.* (1979) model, shown in figure 12, also appears to be in good agreement with the data but not as successful. Their bubble–intermittent boundary overpredicts the bubble and slug data. Also, the intermittent–annular/mist boundary seems to be shifted to the left on the map.

For vertical flow, the models of Taitel *et al.* (1980) and Weisman & Kang (1981) were tested with the data of Dukler *et al.* (1987), Lee *et al.* (1987) and Karri & Mathur (1987). The comparisons

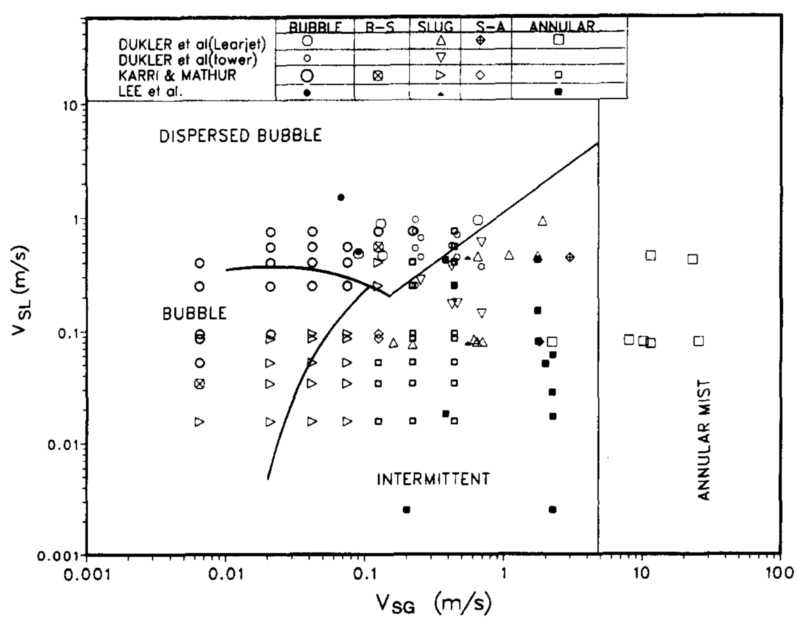

Figure 13. Comparison of the data with the model of Taitel *et al.* (1980) for vertical flow at 0.01-*g*.

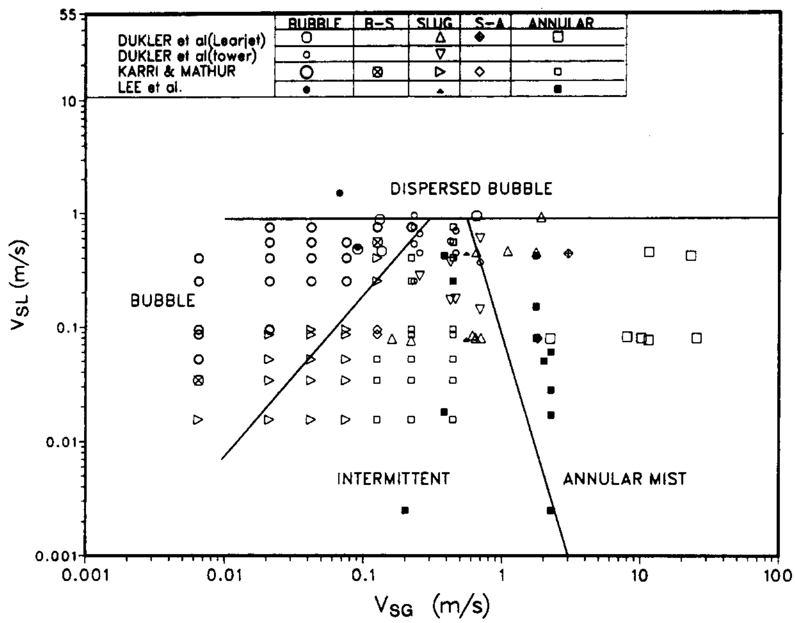

Figure 14. Comparison of the data with the model of Weisman & Kang (1981) for vertical flow at 0.01-*g*.

with these two maps are shown in figures 13 and 14 for Taitel *et al.* (1980) and Weisman & Kang (1981), respectively. In the first case, the model predicted well the data of Dukler *et al.* (1987); however, this was not the case with the data of Lee *et al.* (1987) where all the annular flow data points fell in the intermittent region on the map. Also, the annular data of the equi-density system appears in the slug region on the map, while the bubble data are distributed over a wide range of the bubble and dispersed-bubble regions. There is no obvious reason for the difference in predictions between this model and the one for horizontal flow, when both models were extrapolated to 0.01-*g*. More microgravity observations are needed for comparison before any definitive statements can be made. As in the case with horizontal flow, the model of Weisman & Kang (1981) appears to correlate the data reasonably well, but with less predictive capabilities than those of Taitel *et al.* (1980; Taitel & Dukler 1976).

Finally, a comparison with the flow-pattern map of Dukler *et al.* (1987) was made and the results are shown in figure 15. As indicated earlier, this map was developed theoretically by suggesting models which were based on a critical void fraction for both transitions; namely from bubble to slug and from slug to annular. Except for some of Karri & Mathur's (1987) and Heppner *et al.*'s (1975) data, the bubble–slug transition seems to correlate the microgravity data very well. As should be expected, the annular flow data of Karri & Mathur (1987) occupied the slug region on the map.

In developing the equations for the slug–annular transition, Dukler *et al.* (1987) used an average value equal to 1.2 for the parameter C_0 (the ratio of the Taylor-bubble velocity, V_b, to the total superficial velocities of both phases). This empirical value was chosen based on actual measurements of V_b from the films taken during microgravity tests. As reported by Dukler *et al.* (1987), measurements indicated that C_0 varied between 1.15 and 1.35. They also argued that since no physical models existed at that time for slug flow under microgravity conditions, by which the parameter C_0 could be estimated for different fluid properties and pipe sizes, a tentative average value of 1.2 seemed reasonable. Also shown in figure 15 is the transition line for $C_0 = 1.06$, as used by Hill *et al.* (1987) for a Freon-114, liquid–vapor system. In general, the slug–annular boundary correlated most of the slug and annular data points of Heppner *et al.* (1975), Hill *et al.* (1987) and Kachnik *et al.* (1987).

In all the previous comparisons, only the mapping coordinates given by the original authors were used. The majority of the microgravity data and flow-pattern maps were given using coordinates in terms of the liquid and gas superficial velocities. A search was done in the literature in order

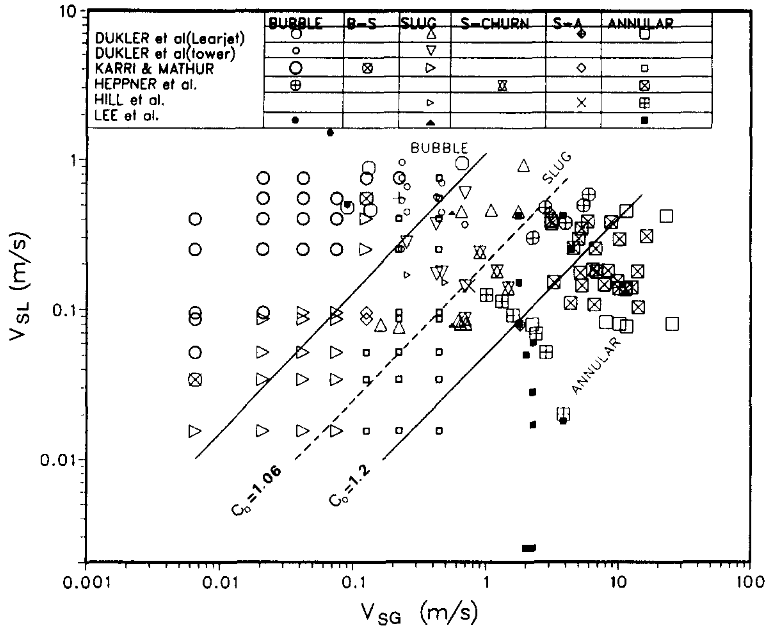

Figure 15. Simulated and actual microgravity observations on the microgravity flow-pattern map of Dukler *et al.* (1987).

to find other mapping coordinates which could be perhaps more appropriate for making a general comparison of the data and the transition lines. The coordinate system of Oshinowo & Charles (1974) was developed based on flow-pattern observations in a 2.54 cm vertical upriser and a downcomer using different liquid–gas combinations which covered a wide range of fluid properties and mass-flow rates.

This coordinate system is in terms of the volumetric ratio ($\sqrt{Q_L/Q_G}$) and $Fr_{TP}/\sqrt{\Lambda}$, where Fr_{TP} is a two-phase Froude number ($Fr_{TP} = (V_{SL} + V_{SG})^2/gD$) and Λ is a liquid property group given by

$$\Lambda = \frac{\mu_s}{(S_L \sigma_s^3)^{0.25}}, \qquad [13]$$

where μ_s, S_L and σ_s are specific viscosity, specific density and specific surface tension, respectively, of the liquid with reference to water. It is believed that using these coordinates in comparing the actual and simulated microgravity data will reduce the differences due to the wide range of fluid properties covered by those data sets, and will also accomodate the different gravity levels and tube sizes which were used in the experiments.

The results of this comparison are shown in figure 16 on a log–log scale. The simulated microgravity data of Karri & Mathur (1987) occupied the lower left corner of the graph, while the rest of the data formed one band at higher values of V_{SL} and V_{SG}. Since the properties of the equi-density system are well taken into account through the use of the liquid property group Λ, and the gravity level and tube size are accommodated in the dimensionless group Fr_{TP}; then for data points to fit within the same band of actual microgravity observations, it is expected that higher superficial "vapor" velocities should be associated with them. This means that, for example, bubble flow with the equi-density system would occur at higher V_{SG} (or perhaps both V_{SL} and V_{SG}) values than those obtained with the actual microgravity data.

The area designated by Heppner *et al.* (1975) as dispersed flow included only some of their bubble data, while the segregated flow region included most of the annular data points. The intermittent region included, in addition to slug and churn flow, most of the annular data points of Lee *et al.* (1987). The bubble–slug transition of Lee *et al.* (1987) was not successful in separating these two flow patterns. However, better predictions were obtained with their slug–annular boundary. The bubble–slug boundary of Dukler *et al.* (1987) separated the two flow patterns very well [except for the bubble data points of Heppner *et al.* (1975)], while the slug–annular transition (with $C_0 = 1.2$)

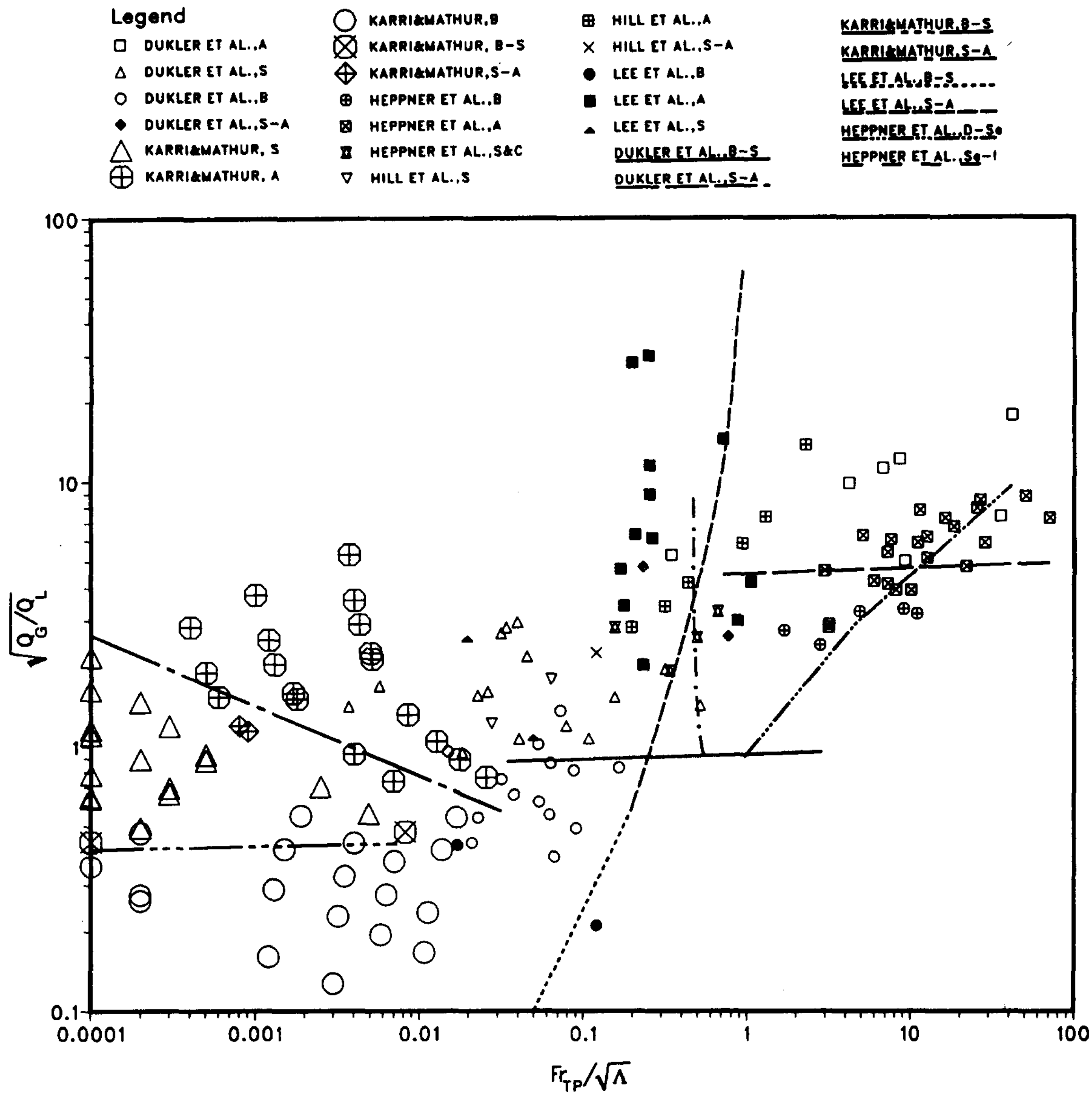

Figure 16. Comparison between the microgravity data and flow-pattern transitions using the mapping coordinates of Oshinowo & Charles (1974).

was less successful in that the area noted as slug flow included annular data points from all the other experiments. This, as discussed earlier, could be attributed to a different C_0 value, and hence a shift in the slug–annular boundary, for each liquid and gas combination and tube size.

SUMMARY AND CONCLUSIONS

It is clear from this study that research work related to flow patterns in forced-convective two-phase flow systems under microgravity conditions is still in the formative stage. Flow-pattern maps were developed both theoretically and empirically. Theoretical approaches included analysis of the different forces that could affect the formation of a certain flow pattern at 0-g. Another group used a critical-void-fraction method, which was based on flow models for bubble and slug flows and flow-pattern observations at microgravity. Other theoretical approaches included extending the correlations for flow-pattern transitions at 1-g to the microgravity situation. Empirical transition lines were developed using single-component (boiling water or Freon–114) and two-component (basically water–air) systems and also using an equi-density, liquid–liquid system. From the results of the comparisons done in this work, the following conclusions and recommendations can be made:

1. Using the terminology and definitions of flow patterns in two-phase horizontal flow, observations based on these definitions appear to have a reasonable agreement with the experimental transition lines obtained by Heppner *et al.* (1975) for 0.01-*g* conditions and a very good agreement with the Taitel & Dukler (1976) model for horizontal flow (when the latter was extrapolated to 0.01-*g*).
2. The transition boundaries proposed by Karri & Mathur (1987), using an equi-density system, appear to predict well the bubble–slug transition. However, very large discrepancies exist with the slug–annular transition. A study on the interfacial tension and shear forces associated with such a liquid–liquid system is needed in order to explain some of these discrepancies and assess this method of simulation.
3. Considering the total data set, the microgravity flow-pattern map of Dukler *et al.* (1987) seems to have the best predictive capabilities. More data covering a wide range of fluid properties and mass flow rates of both phases are needed to critically examine its validity for overall predictions.
4. The method of using the existing flow-transition correlations at 1-*g* to predict the flow patterns at reduced values of earth gravity appears to be successful. However, due to the fact that forces acting on the flow at 1-*g* (and to what extent each one influence a particular flow pattern) vary considerably at 0-*g*, this simple approach needs to be substantiated with a critical examination of the influence of changing gravity on the forces acting on the flow at reduced-gravity conditions.
5. Since gravitational forces are very significant in horizontal two-phase flows at 1-*g*, and since they do not exist at 0-*g*, matching the microgravity flow observations to those observed with horizontal flow at 1-*g* seems inconsistent. A more realistic analogy would be with those definitions associated with vertical upward flow, where the contribution of the gravitational force compared to other forces exerted by, for example, the pressure gradient and friction could be very small (depending, of course, on the range of liquid and gas flow rates).

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