Two-Phase Flow

Mapping and Transition

Under Microgravity Conditions

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Abstract

In this paper, recent microgravity two-phase flow data for air-water, air-water-glycerin, and air-water-Zonyl FSP mixtures are analyzed for transition from bubbly to slug and from slug to annular flow. It is found that Weber number-based maps are inadequate to predict flow-pattern transition, especially over a wide range of liquid flow rates. It is further shown that slug to annular flow transition is dependent on liquid phase Reynolds number at high liquid flow rates. This effect may be attributed to growing importance of liquid phase inertia in the dynamics of the phase flow and distribution. As a result a new form of scaling is introduced to present data using liquid Weber number based on vapor and liquid superficial velocities and Reynolds number based on liquid superficial velocity. This new combination of the dimensionless parameters seem to be more appropriate for the presentation of the microgravity data and provides a better flow pattern prediction and should be considered for evaluation with data obtained in the future.

Similarly, the analysis of bubble to slug flow transition indicates a strong dependence on both liquid inertia and turbulence fluctuations which seem to play a significant role on this transition at high values of liquid velocity. A revised mapping of data using a new group of dimensionless parameters show a better and more consistent description of flow transition over a wide range of liquid flow rates. Further evaluation of the proposed flow transition mapping will have to be made after a wider range of microgravity data become available.

Introduction

Two-phase flows under microgravity condition appear in a large number of important applications in fluid handling and storage, and in spacecraft thermal management. The physics of this ubiquitous flow is however very complex and not well understood. Over the last decade, available microgravity experimental data base has grown several folds but still remains substantially incomplete in several important ranges of flow parameters.

An important research activity in this area has been the mapping of two-phase flow pattern transition under microgravity conditions. An accurate map of flow pattern transition is critical in prediction of phase distribution in two-phase flows, calculation of friction, and heat transfer effects. It plays a key role in the design of two-phase flow systems, determination of pumping requirements, and estimation of effective convection heat transfer rates in fluid transport, storage, and heat exchange equipment. Most investigators agree that under microgravity conditions there are only three flow patterns in tube flows: bubbly, slug, and annular flow.

The majority of the experimental data have been collected during parabolic flights. Most of the microgravity experiments have been performed with air and liquid water due to convenience in their use aboard aircraft and issues related to experimental safety and flexibility. The data collected in these flights include pressure drop, volumetric gas and liquid flow rates, void fraction, and visual identification of flow pattern transition from bubbly to slug flow and from slug to annular flow. The flow diameter for all available data varies from approximately 6 mm to 40 mm. The superficial gas flow velocity range is from approximately 0.09 m/s to 30 m/s and liquid superficial velocity from 0.05 m/s to 3.5 m/s. The other parameters that are varied include kinematic viscosity (by a factor of 6) and surface tension coefficient (by a factor of 21.) More important consideration is the range of dimensionless parameters. The two-phase flow data considered in this paper is limited to two values of Pr (.5 and 40), and a range of 200 to 20,000 for Reynolds number based on superficial liquid velocity. The range of Weber number is approximately from 0.01 to 1000 based on superficial gas velocity and from 10 to 1000 for superficial liquid velocity. It is important to note that the range of Weber number has been principally achieved by changing flow velocity and not by varying fluid property.

In general, available data remain insufficient to provide reasonably general models or provide complete and satisfactory mapping of flow transition under microgravity conditions. As a result the mapping of flow transition remains limited to the available data with important gaps in the range of key variables. The paucity of microgravity data also makes it difficult to search and identify satisfactorily all dimensionless parameters that may play important roles in the flow transition under microgravity conditions.

Early studies[1] in the development of criteria for transition flow patterns and mapping used small number of microgravity data in dimensional maps. These maps were initially developed for use in normal gravity conditions. Others[2] used modified Weber and Froude numbers with limited success to establish transition regions. In these studies air-water mixture was used and the flow diameter was not varied. The main conclusion was that gravity influences flow pattern and the flow pattern influences flow parameters such as pressure drop, phase distribution and, by inference, heat transfer.

In several more recent investigations[3,4] microgravity experiments were used to develop Quandt maps (mass flow vs. quality) for flow pattern transition. It was observed that while bubbly flow is rather easily predicted, slug and annular flow transitions are difficult to predict accurately. In another study[5] several dimensionless flow variables were used to discuss the transition between four flow patterns: dispersed, stratified, slug, and annular flows. The parameters, which are in terms of the ratio of surface tension, gravity, friction and turbulence fluctuations, were intended to predict microgravity flow transition. It was observed that the results did not agree well with available data.

In a review[6], available microgravity data (up to 1989) on transition and flow pattern mapping were used to verify several analytical models and gravity-based transition maps. While each map seemed to have some advantage and agreed with data within a particular range, no single map provided a general framework for the prediction of flow pattern transitions. In a recent study[7] four flow patterns (bubble, slug, slug-annular, annular) were observed in KC 135 experiments with air-water. Maximum liquid and gas superficial velocities were 3.73 m/s and 29.9 m/s, respectively. Froude and Weber numbers were calculated and the latter, based on superficial gas velocity, was suggested to be the only key dimensionless number for predicting the transition from bubbly to slug and slug to annular patterns. The results, however, seem to suggest that other factors may play an important role as demonstrated by the failure of Weber number maps to predict transition at high liquid phase velocity.

In a series of studies by Dukler and colleagues transition models between bubbly and slug flow were developed and discussed on dimensional maps using superficial gas velocities[8-10]. The bubble-size measurements showed much larger coalescence in microgravity than under normal gravity condition and seemed to depend on tube diameter. A series of complimentary experiments were reported with liquid mixtures of water, glycerin, and Zonyl FSP[11]. In this study fluid mixtures were used with two coefficient of viscosity values (different by a factor of 6) and two values of surface tension coefficients (different by a factor of 21). The results show some success in comparison with the previous prediction of flow pattern transition using Weber number. However, this prediction again is seen to be accurate only for the lower range of liquid phase velocity.

The present paper deals with a new approach to the flow transition map. The suggested transition maps, which are similar to Weber-number maps, are based on different dimensionless parameters. It is intended to show here that the proposed maps are more general than the simpler Weber-based maps and are able to resolve the shortcomings of Weber-based maps at high liquid phase velocity. While all available data can be used to discuss and verify new transition maps suggested in this study, it was found convenient to use and present the data from the microgravity experiments in Reference 11.

Analysis

The two common flow pattern transition maps suggested for microgravity air-water two-phase flows are void fraction-based criterion[8] and Weber number-based criterion. A recent discussion of the void fraction transition map and the related unsolved issues and problems can be found in Ref. 12. The problems with this map formulation is the dimensional nature of coordinates and the related lack of generality associated with it. The advantage of the map is the simplicity associated with the delineation lines. However the simplicity and success associated with the transition lines are, in part, due to factors that are themselves derived from the experimental data[10].

The Weber number criteria for mapping has also simple and useful features as shown in Fig. 1. The map is essentially a statement on the importance of only one variable, i.e., Weber number based on superficial gas velocity, We_G. As a result, the map suggests that only two forces are important in the determination of the transition: inertia and surface tension in gas flow. This implies that the liquid flow plays a little or no role. Also, the laminar or turbulent nature of the two-phase flow plays no role in the pattern transition. The Weber number-based mapping seems to be an inaccurate representation of transition at high liquid-based Weber number ($We_L>100$). The transition pattern is shown to be dependent on the liquid flow rate[12].

The Weber number transition map can be reconstituted based on actual velocities of gas and liquid instead of the superficial velocities[13]. The result is shown in Fig. 2. As it is observed the bubbly-slug transition data still show deviation from a horizontal (predicted constant We_G) line. The deviation becomes more obvious if only the transition data (e.g., Bubbly-slug flow data) are presented. The deviation from a horizontal line is attributed to error in the data. However the trend of the transition data clearly show dependence on the liquid phase Weber number even when they are calculated based on the actual velocities. The reconstituted map does not include the corresponding slug-annular transition data.

The complex and dissimilar physics in flow patterns as widely different as bubbly, slug or annular flows seem to make it unlikely that the same force balance is maintained throughout the three flow patterns. This is even less likely when laminar and turbulent features are present in each or both phases of these two-phase flows.

Bubbly -Slug Transition

In this transition, several features are observed in various reported experiments. For example, it is observed that increase in diameter tends to affect transition in air-water mixture (AW) but does not affect significantly the air-water-glycerin (AWG) or air-water-Zonyl FSP (AWZ) flows. The

Reynolds number based on the liquid superficial velocity is generally large in these cases. However, in the case of air-water flow, the smaller viscosity implies larger (and possibly near turbulent) values of Reynolds number. Table 1 shows the range of Re_L for the two tube diameters and three mixtures that were used in experiments and reported in Ref. 11. It is observed that the median AW Re_L values for the 12.7 mm and 25.4 mm-diameter tube flows are 6105 and 10,870, respectively. The median values of the Reynolds number for the AWG (1042 and 2889) and AWZ (2485 and 4521) are however smaller as observed in Table 1. The effect of changing diameter on AWZ flow was observed to be minimal. One way to explain this phenomenon is that the transition depends on both Weber and Reynolds numbers. In this way the increase in the diameter is compensated by the change in surface tension due to the addition of Zonyl FSP. It is therefore suggested that the transition is not only scaled by We_G, as suggested by earlier studies, but it may also be inversely affected by increase in Re_L.

The viscosity coefficient was changed in the experiments by a factor of 6. This change did not seem to affect the transition for the air-water, and air-water-glycerin systems for the 12.7 mm diameter tube. The same change seems to affect somewhat the transition in flows through the 25.4 mm tubes. Apparently the relative small increase in the viscosity coefficient begins to show some effect on flow transition only in combination with an increase in diameter (larger range of Re_L). This implies that while the transition depends on Re_L, the effect is more pronounced at higher values of Re_L.

Finally, the comparison of AW and AWZ indicates that decrease in the surface tension has direct effect on the transition. This suggest that Weber number plays a direct role in the transition and the surface tension force is an important player in the dynamics of force balance in all two-phase flow data obtained in these experiments. It seems that in the bubbly to slug flow transition, the friction force is also an important player in the dynamics of the flow. This observation is even more valid at high liquid flow rates. This means that the primary balance may be found between friction, inertia and surface tension forces. As a result the right group of dimensionless parameters is We_G/Re_L and not We_G which indicates a simple gas inertia and surface tension balance with no role assigned to liquid flow inertia and friction. The rather large friction expected to be present in the bubbly flows may suggest that a more appropriate scale will be a $We_G/(Re_L)^{1.8}$ which takes into account the friction in a turbulent liquid phase flow regime.

These general observations hold true for the reported experiments[11]. There are general agreements, with some notable discrepancies, between the results of this study and other similar microgravity experiments[10]. For example in a study[14] using air-water two-phase flows in 9.525 mm, the results agree well with the results of 12.7 mm AW flow presented here. However, there are some differences between the two results which include the question of how strongly the transition depends on gas velocity. In yet other investigations[7], air-water flow in 9.525 mm tubes show different bubble-slug transition. These discrepancies imply the need for further collection of data and a wider range of parameters so that a definitive conclusion can be reached.

Table 1

The Range (and Median Values) of Reynolds Number Based on the Liquid Superficial Velocity

Two-Phase Flow System	12.7 mm Diameter		25.4 mm Diameter	
	Bubbly-Slug	Slug-Annular	Bubbly-Slug	Slug-Annular
Air-Water (AW)	1,280 -10, 930 (6,105)	220 - 1600 (910)	8, 636 -13,106 (10,870)	3,100 -15,824 (9,462)
Air-Water-Glycerin (AWG)	502 - 2,080 (1,042)	153 - 1,186 (670)	1,435 - 4,343 (2,889)	545 - 4,252 (2,399)
Air-Water Zonyl FSP (AWZ)	1,270 - 3,700 (2, 485)	850 - 6,451 (3651)	2,565 - 6,477 (4,521)	1,231 - 6,997 (4114)

Slug-Annular Flow Transition

In the slug-annular transition region the friction force does not seem to be important. This may be due to the relative low liquid Reynolds number in most cases. As observed in Table 1, and with one exception, the median values of Re_L is observed to be lower in all slug-annular transition data when compared with bubbly-slug transition data. The relative large void fraction in slug and annular flows and the negligible relative velocities between the two phases that are observed in all microgravity experiments, suggest that wall and interfacial friction may not be a significant force when compared with liquid and gas inertia. As a result it is expected that the dimensionless group of parameters that are important in the transition is We_G/Re_L where a laminar liquid phase flow and a dominant dynamic balance between the liquid and gas inertia is assumed for the transition from slug to annular flow pattern.

Experiments seem to confirm the above observations. For example, the change in tube diameter (a factor of two) had little effect in the transition for all three fluid systems. The reason, of course, is that the We_G/Re_L is independent of the tube diameter. The viscosity coefficient change by the addition of glycerin also fails to show any important effect in slug-annular transition. This indicates that in the range of the Re_L considered in experiments reported in Ref. 11, friction remains unimportant relative to inertia even after viscosity coefficient is increased. Similarly the change in surface tension is seen to have no effect in this transition as reported in the same study. This also implies that the dominant balance is between the gas and liquid inertia at least within the limited change of the surface tension coefficient considered in these experiments.

The slug-annular transition observed for air-water flow in 9.525 mm in Ref. 14 compares well with the 12.7 mm-diameter air-water flow experiments in Ref. 11. Also, the results reported in Ref. 7 for slug-annular transition in 9.525 mm-diameter tube flow are in substantial agreement with the results reported in Ref. 11.

Results

The experimental data in Ref. 11 were used to calculate Weber number for both air and liquid phase flows. For clarity in the graphs, only the transition data indicated as bubbly -slug (B-S) and slug-annular (S-A) are selected for developing a transition map. For air-water flow a We_G vs. We_L map is shown in Fig. 3 for both bubbly-slug and slug-annular transitions. As observed and reported by others, the trend indicates that in both cases transition is dependent on liquid Weber number at high liquid flow rates. Fig. 4 and Fig. 5 are similar transition mapping for air-water-glycerin and air-water-Zonyl flows in 12.7 mm tube flow under microgravity conditions. In all cases the slope is clearly observed to be different from zero. In fact, for bubble-slug transition, the dependence on liquid inertia (or We_L in this case) is significant. A change of two orders of magnitude in We_L produces a similar order of magnitude change in We_G.

For <u>slug to annular</u> flow transition, liquid inertia is apparently an important force in the dynamics of the phase separation. The reason may be sought in liquid inertia overcoming the surface tension and adversely affecting the transition to annular flow for a given gas inertia effect. In fact if one modifies Weber number for gas flow through dividing it by liquid Reynolds number, the effect of liquid inertia can be removed. This is shown on Fig. 6 where a plot of modified gas Weber number, We_G/Re_L, is presented as a function of liquid Weber number, We_L, for 12.7 mm-tube air-water flow data. Similarly, when the data for 25.4 mm tube is presented in terms of We_G/Re_L vs. We_L, the increasing dependence on We_L at high liquid velocity is eliminated. The 25.4 mm tube flow data is also included in Fig. 6.

For <u>bubbly to slug</u> flow transition, the liquid inertia is even more important. At relatively high liquid inertia the coalescence of the bubbles and formation of Taylor bubbles is achieved at higher gas velocities (higher We_G.) The opposite effect is observed at low liquid inertia. For the range of liquid Reynolds number in these experiments, the turbulence fluctuations may be an important contributing effect in overcoming surface tension. For this purpose, the ratio of gas Weber number to liquid Reynolds number was further modified by a normalized turbulent shear effect. The turbulence shear normalized with laminar friction in pipe flow scales with $(Re_L)^{0.8}$.

Modifying the previous ratio of liquid Weber to Reynolds numbers with the normalized turbulent shear, the suggested right group of parameter that needs to be plotted as a function of We_L becomes $We_G/(Re_L)^{1.8}$. The results for air-water flow through 12.7 and 25.4 mm tubes are presented in Fig. 7. This ratio in the figures is shown as We_G/Re_{LT} for convenience. The results show that while the transition from bubbly to slug flow involves inertia, surface tension and turbulence shear, the dominant balance seem to be between the turbulent fluctuations and gas inertia over the entire range of experimental data available from Ref. 11.

The data for air-water-glycerin transition from bubbly to slug and from slug to annular flows are presented together in Fig. 8. The results for each pattern transition includes both the 12.7 mm and 25.4 mm tube flows. The data spread is associated with the nature of observation and the visual estimation of the transition. Finally, the results for air-water-Zonyl solution are presented in Fig. 9 for both bubbly-slug and slug-annular transitions and the two tube diameters used in the experiments. The data for both diameters are combined to show that the transition criteria is independent of change in the flow diameter.

The transition data for all fluids and flow rates and the two diameters are combined and are presented in Fig. 10. It is evident in these figures that the flow pattern transition depends only on We_G/Re_L or $We_G/(Re_L)^{1.8}$ for slug-annular and bubbly-slug transitions, respectively. A mean value for this combination of parameters can be estimated in each case. It is observed that the transition from bubbly to slug flow occurs at

$$We_G/(Re_L)^{1.8} \sim 5 \times 10^{-8}$$

and the transition from slug to annular flow occurs at

$$We_G/Re_L \sim 10^{-3}$$

Conclusion

The Weber number-based transition mapping for two-phase flow was modified to account for the dependence of gas Weber number on liquid phase inertia. It is observed that for slug-annular transition, the liquid Reynolds number does play an important role in the dynamics of the flow. The transition from slug to annular flow seems to depend on a balance between liquid and gas inertia and the correct scaling is found to be We_G/Re_L. The experimental data for the three types of two-phase flow systems which were considered indicate that the transition occur approximately around $We_G/Re_L \sim 10^{3}$. The bubbly to slug transition is seen to depend on a balance between turbulent shear and gas inertia and the correct scaling is seen to be $We_G/(Re_L)^{1.8}$. The experimental data suggest that this transition occur approximately around $We_G/(Re_L)^{1.8} \sim 5 \times 10^{-8}$.

10^{-3}

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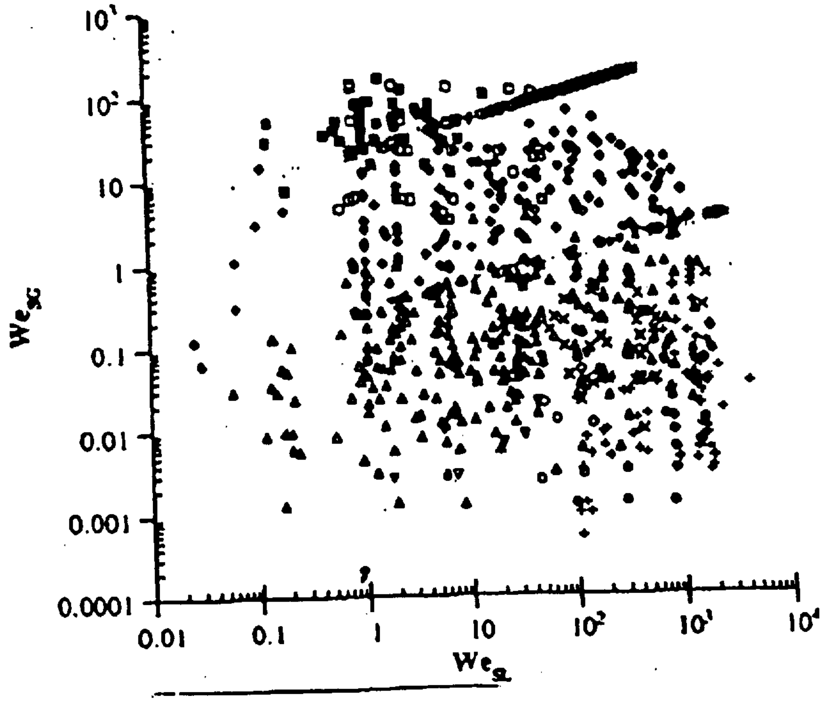
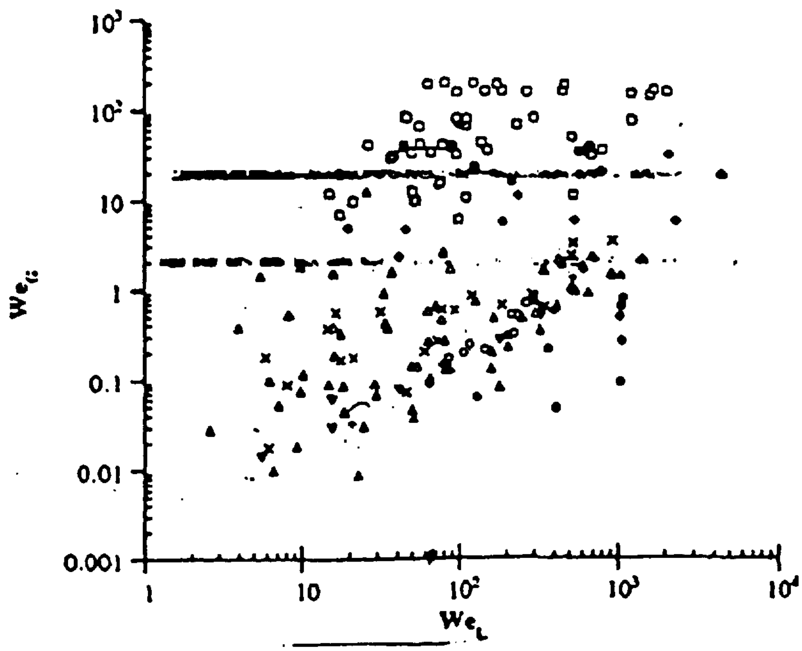

We_{SG}
We_{SL}
0.0001
0.001
0.01
0.1
1
10
0.01
0.1
1
10

FIG 1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We_L
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0.01
0.1
1
10
1
10

FIG 2

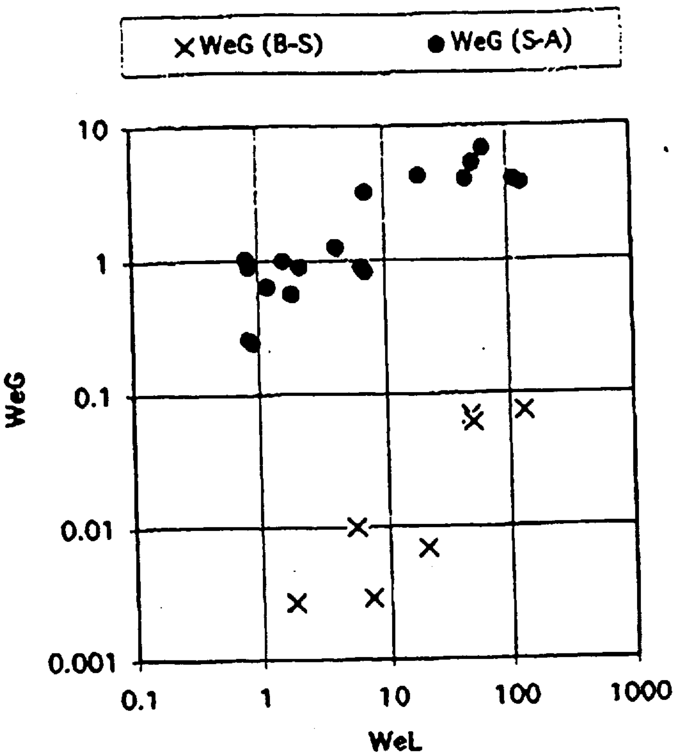

FIG 3

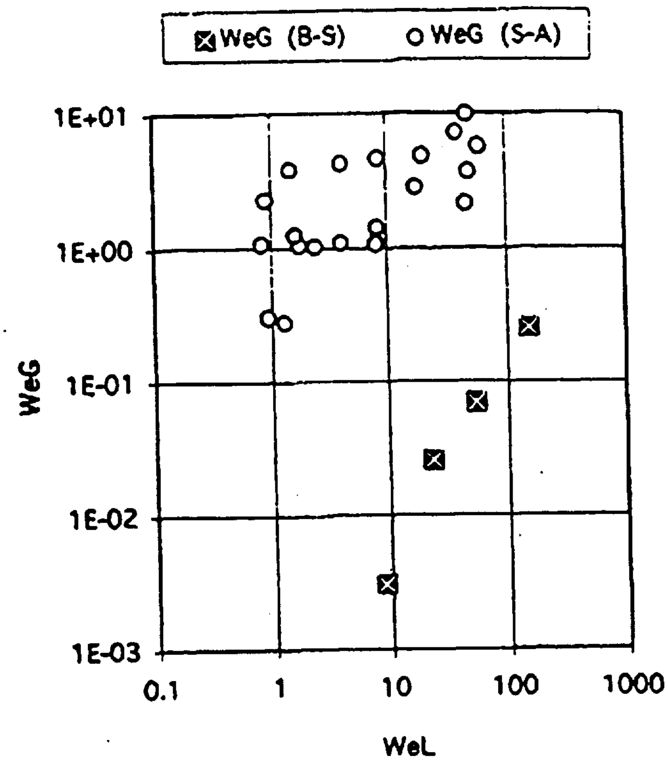

FIG 4

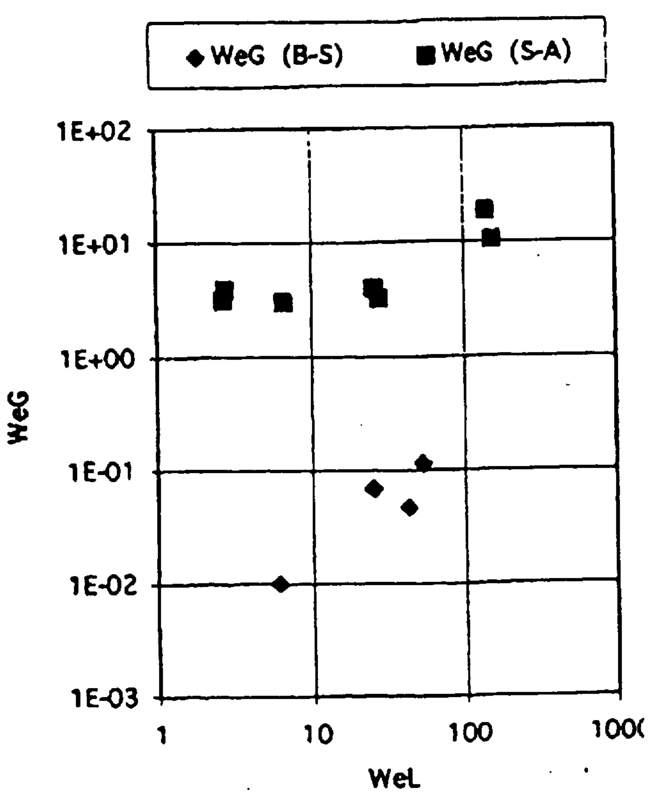

FIG 5

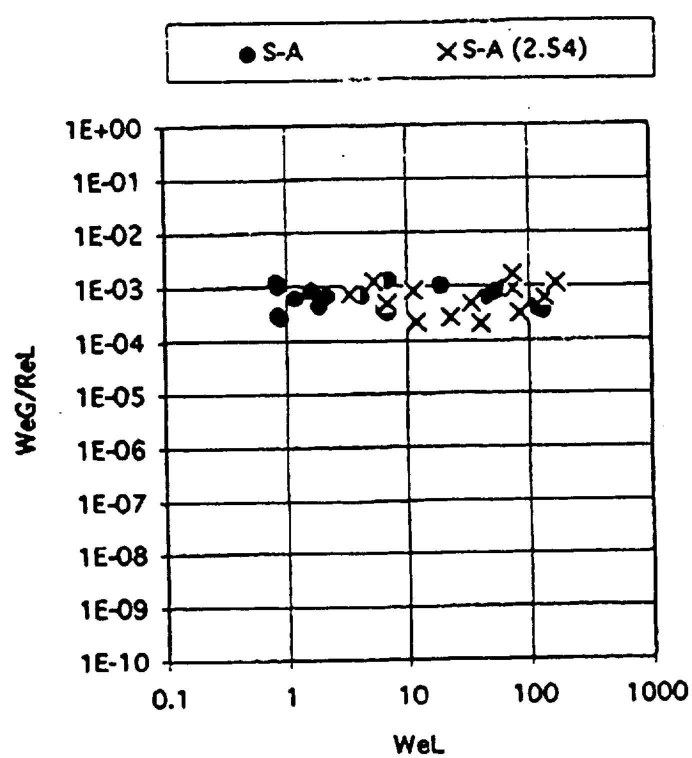

FIG 6

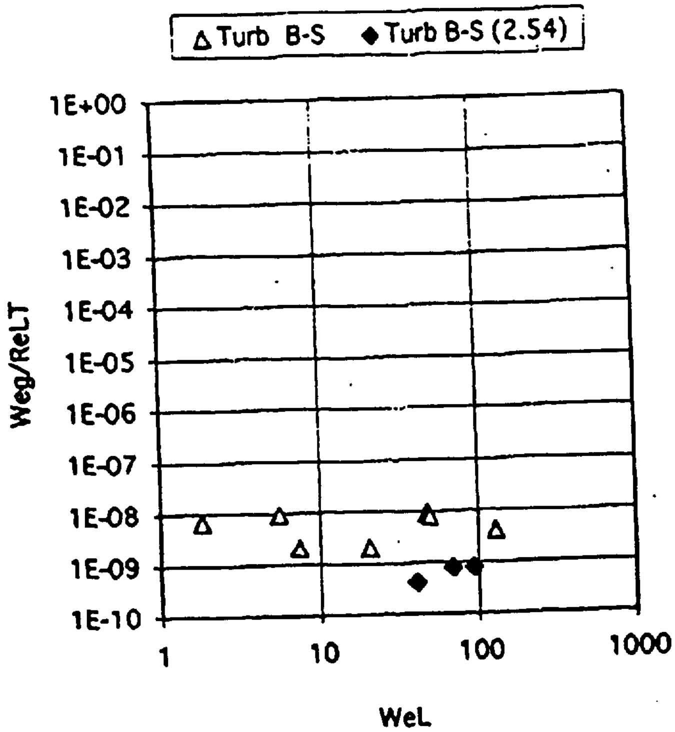

FIG 7

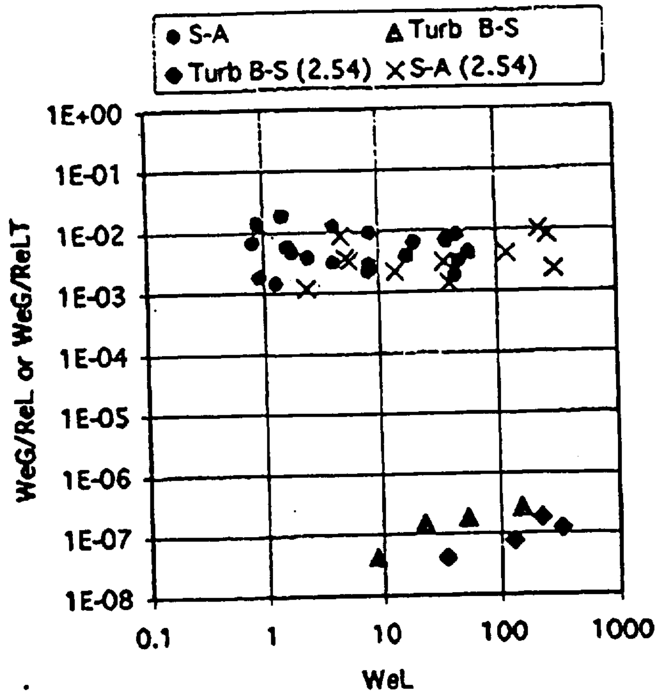

FIG 8

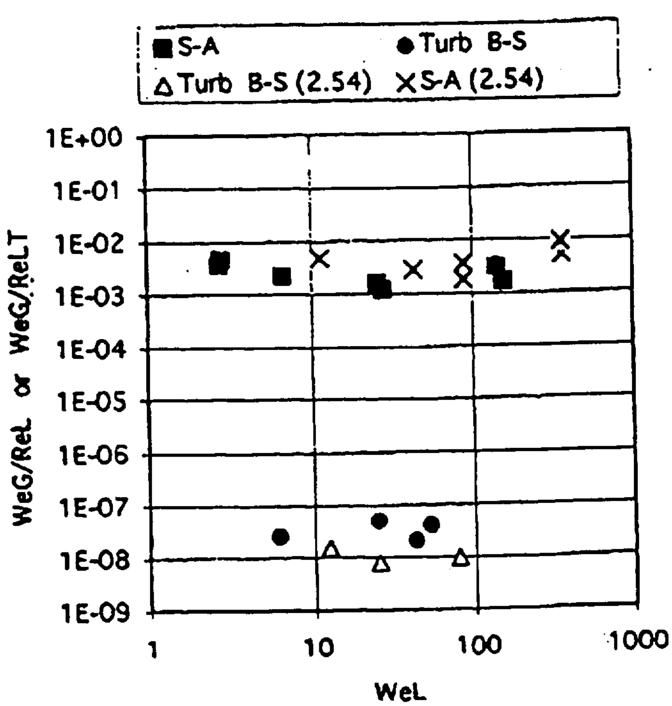

FIG9

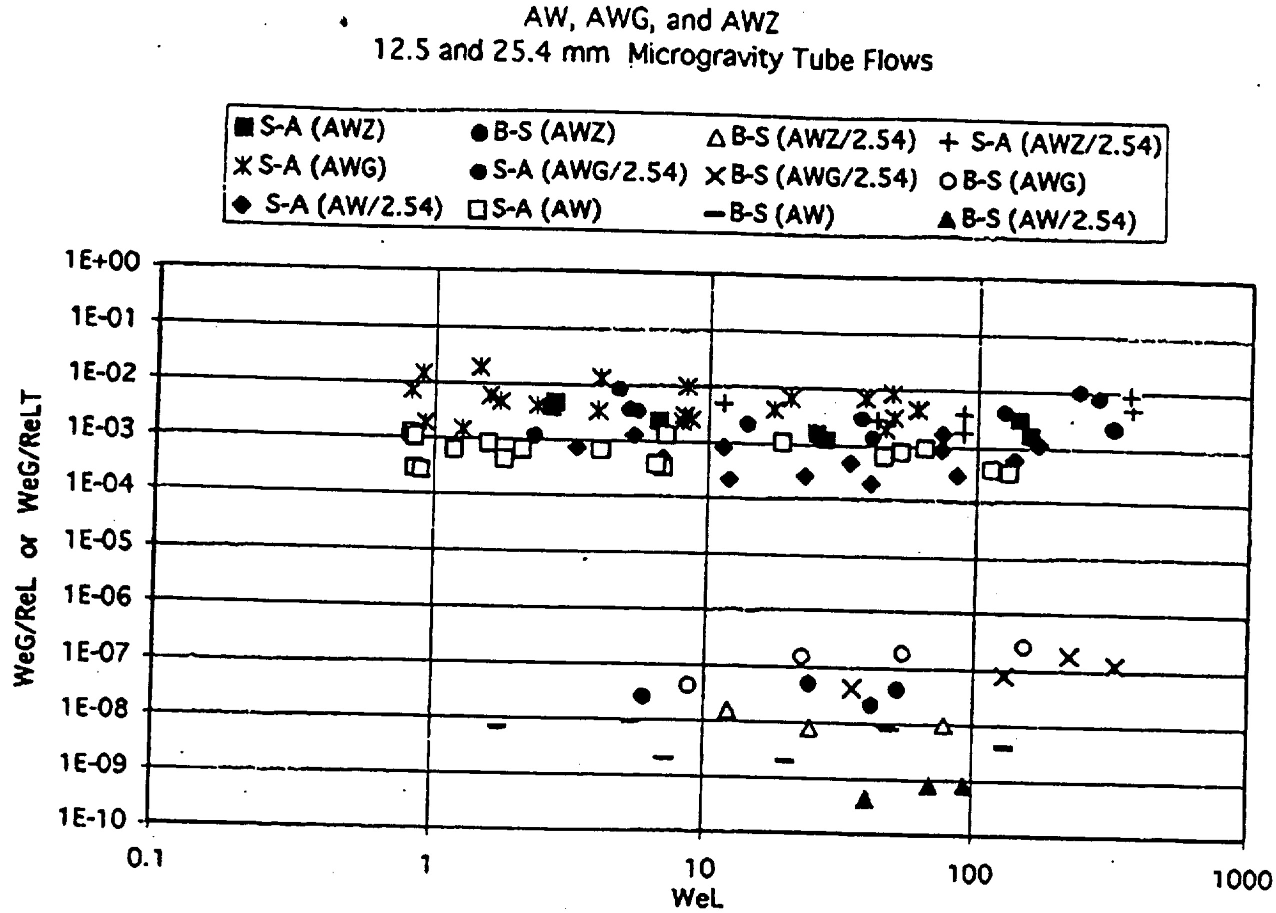
AW, AWG, and AWZ
12.5 and 25.4 mm Microgravity Tube Flows
S-A (AWZ)
B-S (AWZ)
B-S (AWZ/2.54)
S-A (AWZ/2.54)
S-A (AWG)
S-A (AWG/2.54)
B-S (AWG/2.54)
B-S (AWG)
S-A (AW/2.54)
S-A (AW)
B-S (AW)
B-S (AW/2.54)
1E+00
1E-01
1E-02
1E-03
1E-04
1E-05
1E-06
1E-07
1E-08
1E-09
1E-10
0.1
1
10
100
1000
WeL
WeG/ReL or WeG/ReLT

Fig 10

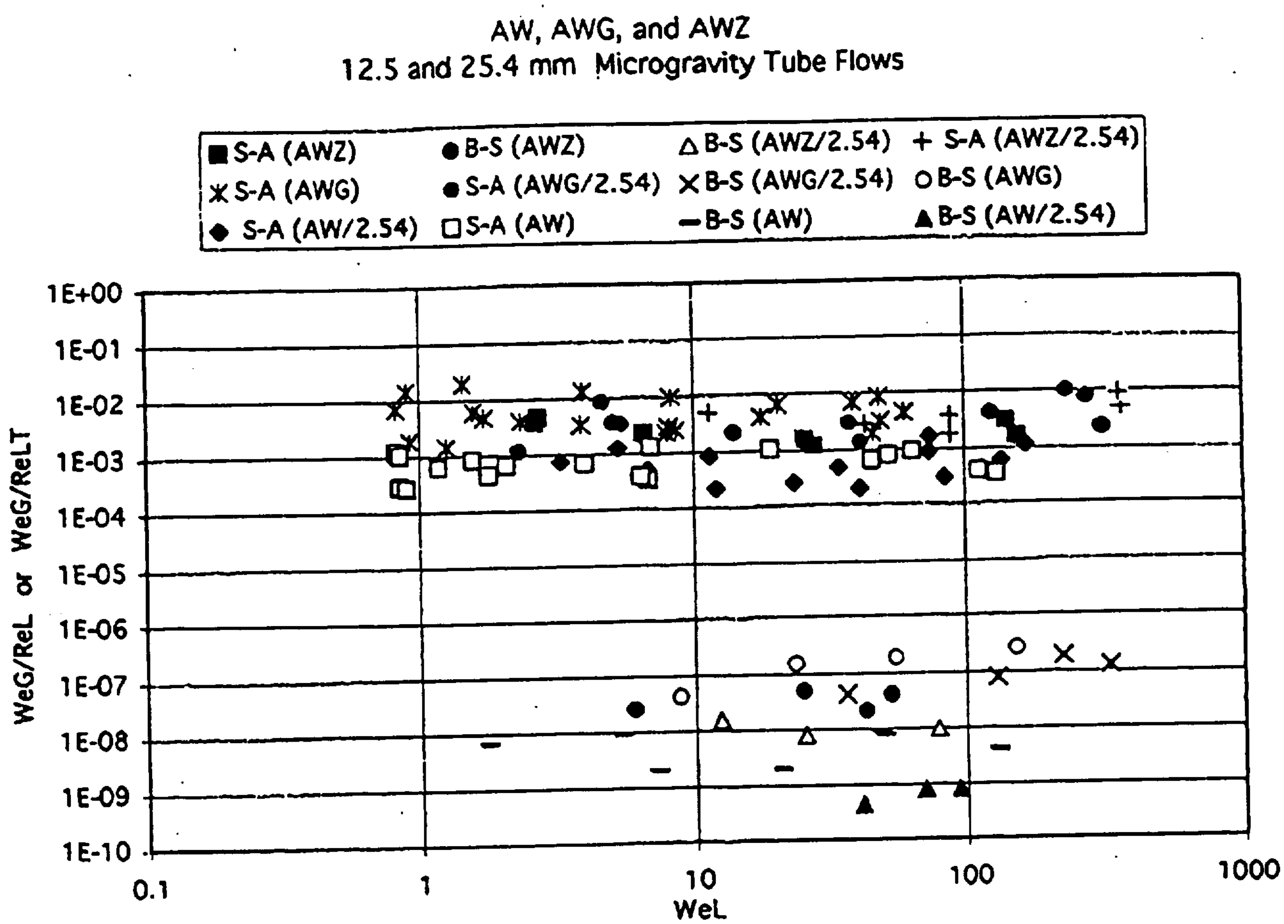
AW, AWG, and AWZ
12.5 and 25.4 mm Microgravity Tube Flows
S-A (AWZ)
B-S (AWZ)
B-S (AWZ/2.54)
S-A (AWZ/2.54)
S-A (AWG)
S-A (AWG/2.54)
B-S (AWG/2.54)
B-S (AWG)
S-A (AW/2.54)
S-A (AW)
B-S (AW)
B-S (AW/2.54)
1E+00
1E-01
1E-02
1E-03
1E-04
1E-05
1E-06
1E-07
1E-08
1E-09
1E-10
WeG/ReL or WeG/ReLT
0.1
1
10
100
1000
WeL

Fig 10