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BRIEF COMMUNICATION

WEBER NUMBER BASED FLOW-PATTERN MAPS FOR LIQUID–GAS FLOWS AT MICROGRAVITY

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1. INTRODUCTION

It has been shown earlier, Rezkallah (1995) and Zhao & Rezkallah (1993), that the two-phase flow patterns at a microgravity environment ($g = 0.0981$ m/s^2; on average) can be basically grouped into three main regions; namely a surface tension dominated region (bubble and slug flows), an inertia dominated region (annular flow), and a transitional region (frothy slug–annular flow). Furthermore, the transition lines between these three regions were estimated using constant values of the Weber number, based on the gas phase superficial velocity (We_{SG}). The transition from the surface tension dominated region (bubble/slug flows) to transitional flows was hypothesized to occur at a $We_{SG} = 1.0$, and that from transitional flows to inertia dominated region (annual flow) at $We_{SG} = 20$; these boundaries are shown in figure 1. The map was tested against the microgravity flow pattern observations available at that time, and showed reasonable agreement with the boundaries mentioned above.

Since the publication of our map in 1993, more experimental data and flow pattern observations appeared in the literature. These include the data sets of Rezkallah & Zhao (1995) for water–air, Rite & Rezkallah (1994) for glycerine/water (50, 60, and 65%, by weight)–air mixtures, Colin & Fabré (1995) water–air data; taken in a wide range of tube sizes (6–40 mm, i.d.), and the water–air and glycerine/water (50% by weight)–air data of Bousman (1995); taken in 12.7 and 25.4 mm (i.d.) tubes.

The data set of Rezkallah & Zhao (1995) was taken in a 9.525 mm (i.d.) tube for water–air and three glycerine/water mixtures (the mixture dynamic viscosity ranged from 5 to 11 times that of water at room temperature), with air as the gas phase. Experiments were conducted onboard the NASA KC-135 zero gravity aircraft. Pressure-drop and heat-transfer measurements were simultaneously taken in all cases. In addition, during a more recent flight (Febuary 1994), volumetric void-fraction measurements were also taken using a non-intrusive capacitance sensor placed immediately before the observation test section. During all flight and ground experiments, flow pattern observations were recorded at 500 or 1000 f.p.s., using a high speed video system (NAC-HSV1000). The liquid superficial velocity ranged from 0.015 to 3.5 m/s, while the gas superficial velocity ranged from 0.09 to 29.9 m/s, covering a very wide range of flow regimes from bubbly to fully-developed annular flows. The water–air flow pattern observations from those flights are plotted in terms of the Weber numbers of the liquid and gas phases (based on the superficial velocities); this is shown in figure 2. As can be seen, the transition boundaries based on the superficial Weber numbers under-predict the experimental data at high gas void fractions.

The glycerine/water–air data (Rite & Rezkallah 1994) for the three mixtures tested are shown in figure 3. The data are mostly in the slug and transitional regimes, and they cover limited ranges of the liquid and gas superficial velocities; i.e. $0.7 < V_{SL} < 2.0$ m/s, and $0.6 < V_{SG} < 12$ m/s. The transition boundary from slug flow to transitional flow occurred at a We_{SG} value, based on the superficial gas velocity, of almost 2. As seen in figure 3, this transition has an upward slope similar to the one seen earlier with water–air data.

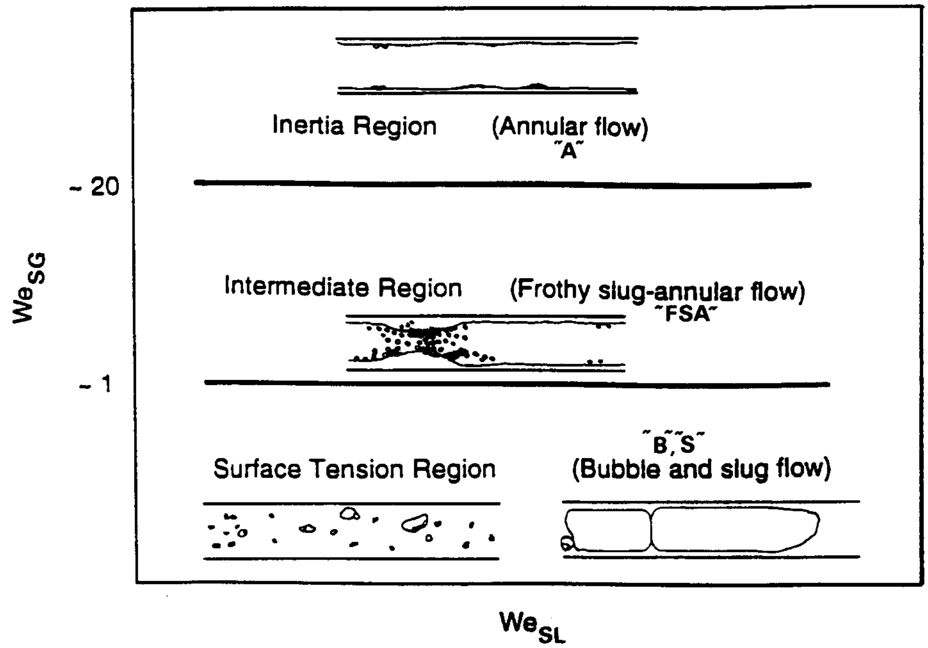


Figure 1. Micrograviry two-phase flow pattern map based on the superficial Weber numbers, Zhao & Rezkallah (1993).

The water–air data of Colin & Fabré (1995) were taken in several tube diameters (6, 10, 19, and 40 mm, i.d.) on-board the French zero-gravity aircraft (Caravelle). Bubble, slug and frothy slug-annular transitional flows were reported for those flights. It was shown in that work that the transition from bubble/slug type flows to frothy slug-annular flow occurs at $We_{SG} = 2.0$ (instead of 1.0, as originally suggested by Zhao & Rezkallah 1993). This was particularly true for the data taken in the tube diameter range of 6–19 mm.

Finally, the data of Bousman (1995) were reported for water–air and a glycerine/water (50% by weight)–air mixture in 12.7 and 25.4 mm (i.d.) tubes. Another data set was reported for

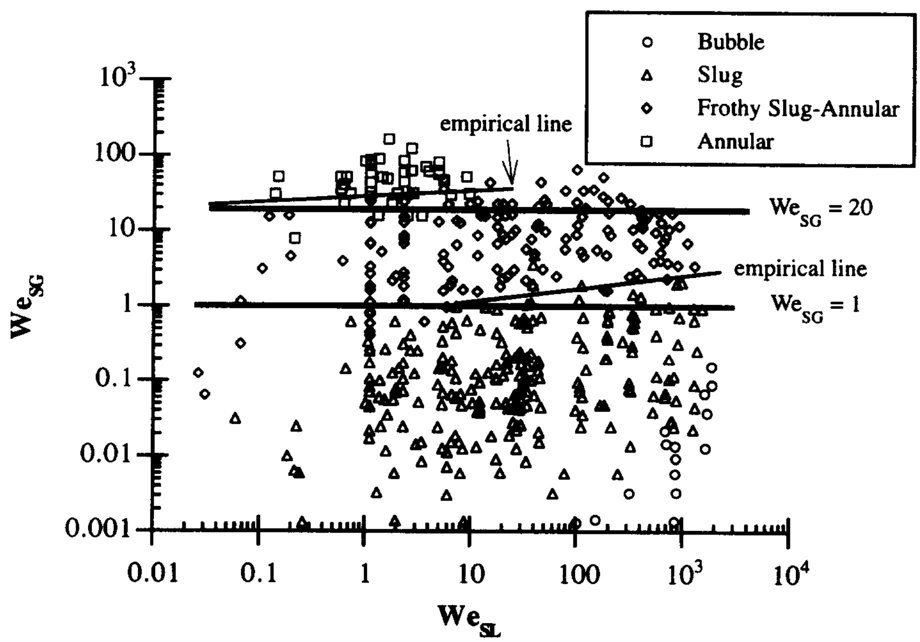


Figure 2. Comparisons of microgravity flow pattern map with water–air data of Rezkallah & Zhao (1995).

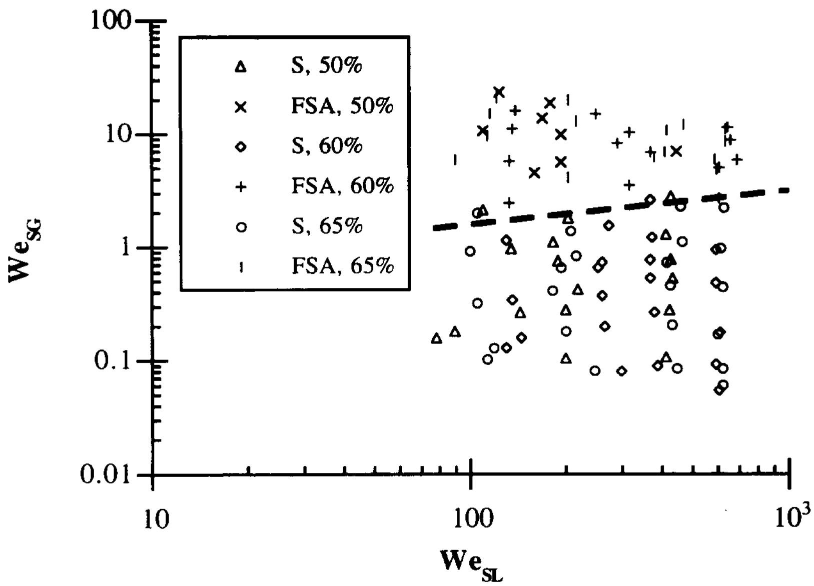


Figure 3. Glycerine/water–air data of Rite & Rezkallah (1994); S = slug, FSA = frothy slug–annular.

air–water with a surfactant (Zonyl FSP) added to water to reduce its static surface tension. Bubble, slug, annular, and transitional flows were reported for all three liquid–gas data sets. Considering the entire data set, the liquid superficial velocity was in the range 0.08–0.9 m/s, and the gas superficial velocity was in the range of 0.22–25 m/s, approximately. When Bousman (1995) plotted his data sets on the flow pattern map (in terms of We_{SG} vs We_{SL}), the transitions from bubble/slug type flows to transitional flow (frothy slug–annular), and from transitional flows to annular flow showed an upward positive slope similar to the one seen earlier in figures 2 and 3.

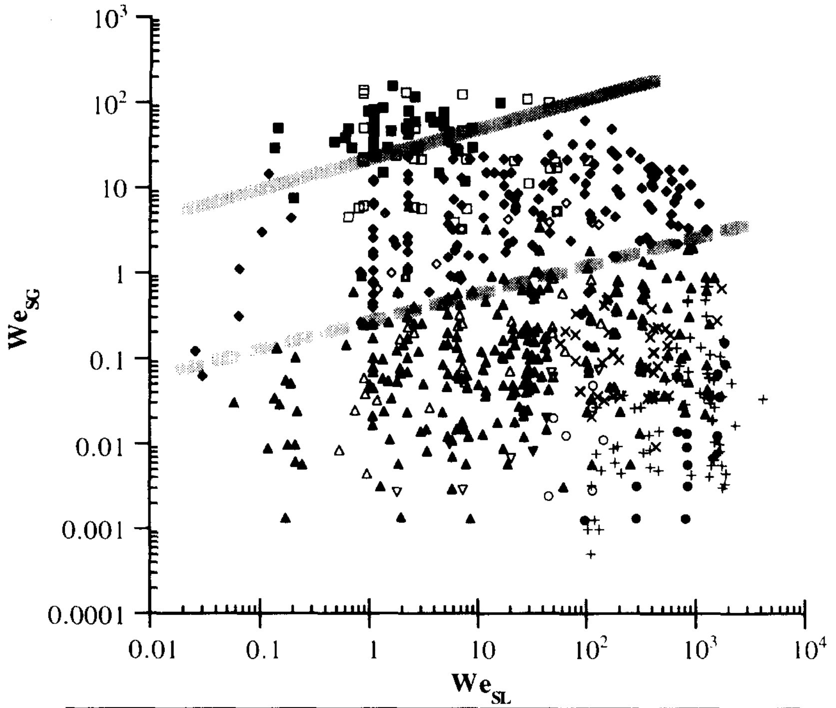
The water–air data obtained from the flight experiments listed above are plotted on the Zhao & Rezkallah (1993) flow regime map (in terms of We_{SL} vs We_{SG}), and the results of the comparison are shown in figure 4. As can be seen from the figure, the data fit extremely well within the three regions of the map. The transition lines from bubble/slug to slug flows, and from transitional flows to fully-developed annular flow have a positive slope of 1:4, approximately.

2. DISCUSSION OF RESULTS

Based on the findings from the recently performed experiments listed above, with the upward positive slope being repeatedly obvious as more data appear in the literature, the author attempted to plot the data in terms of the Weber number based on the *actual* gas and liquid velocities instead of the superficial velocities. The gas-phase velocity could be either obtained from actual *in situ* velocity measurements at microgravity (which are very sparse at this time), or it could be inferred using *in situ* measurements of the gas void-fractions at microgravity. The latter has been done in recent years, and the results are now available for the water–air data set of Elkow & Rezkallah (1995), and for the water–air and glycerine/water–air data sets of Bousman (1995).

When the above three sets of data were plotted in terms of We_L and We_G (instead of We_{SL} and We_{SG}), the transition lines appeared, as has been originally hypothesized, at constant values of We_G; being 2 for the transition from bubbly/slug type flows to transitional flows, and 20 for the transition from frothy slug-annular flow to annular flow. These comparisons are shown in figure 5. As can be seen from that figure, except for some of the water–air data points of Bousman (identified as annular flow) appearing in the transitional flow region, the transition lines seem to predict the flow regimes very well.

Since the transition from slug to annular flow in microgravity, as opposed to 1–G condition, occurs over a much wider range of gas volumetric void fractions (or gas qualities), data points near this transition could be easily mistaken as annular flow. From our own experience with thousands of video images taken at high speed rates, if the viewer is not particularly careful to go over the



○	B: Bousman	□	A: Bousman	◆	FSA: Rezkallah
▽	BS: Bousman	●	B: Rezkallah	■	A: Rezkallah
△	S: Bousman	▼	BS: Rezkallah	+	B: Colin
◇	FSA: Bousman	▲	S: Rezkallah	×	S: Colin

Figure 4. Comparisons of microgravity flow pattern map with water–air data of Rezkallah & Zhao (1995), Bousman (1995), and Colin & Fabré (1995); B = bubble, BS = bubble–slug transition, S = slug, FSA = frothy slug–annular, A = annular.

entire set of frames in a particular microgravity duration "or parabola" (at a frame speed of 500 fps, this could be sometimes in excess of 10,000 frames), there is a good chance that at some time into the parabola the liquid phase will once again "bridge" the tube. If this is the case, a very conservative approach by our Microgravity Research Group will label the flow "transitional forthy slug–annular", rather than annular. If the bridging occurs only once over the entire duration of the microgravity parabola (on average, this lasts for 20–22 s), this will disqualify the set point from being considered as a "fully-developed" annular flow. Such a conservative approach to the definition of fully developed annular flow could be not strictly followed by other researchers in reporting their data sets. Another reason could be due to motion-induced camera blur when a mechanical shutter is used. This could perhaps explain some of the discrepancies seen with the Bousman's data near the transition line, $We_G = 20$.

3. CONCLUSIONS

Recent experimental flow regime data for liquid–gas flows at microgravity conditions were used to assess the validity of a previously published flow pattern map using the Weber numbers of both liquid and gas phases as the mapping parameters. The comparisons showed that the experimental data can be better predicted using the mapping coordinates; We_L, and We_G, which are based on the *actual* gas and liquid velocities rather than the superficial ones. The experimental data included adiabatic two-phase water–air and glycerine/water mixtures of different viscosities (ranging from 5 to 11 times that of water at room temperature), with air as the gas phase. The water–air data were taken in circular tubes, with the inside diameter ranging from as low as 6 mm to as high as

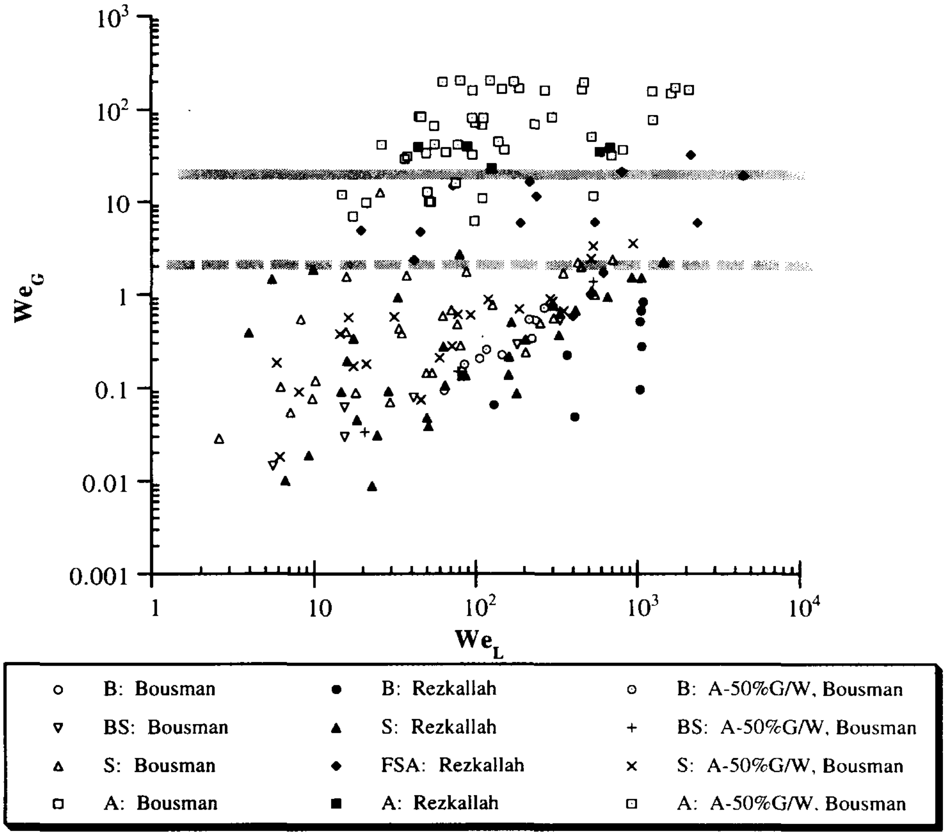


Figure 5. Comparisons with the microgravity flow-pattern map in terms of Weber numbers based on actual liquid and gas velocities; B = bubble, BS = bubble-slug transition, S = slug, FSA = frothy slug–annular, A = annular.

40 mm. Thus, the effect fo tube diameter on the flow regimes is well accounted for through the use of the Weber number dimensionless groups.

The transition from bubble/slug type flows to transitional flow was shown to occur at a constant value of We_G (based on the actual gas velocity) of about 2, while the transition from frothy slug–annular type flows to fully-developed annular flow was shown to take place at $We_G = 20$. Changing the viscosity of the liquid (through the use of glycerine/water mixtures) seems to have a minimum or no effect on the flow transitions. This is again a confirmation that the parameters included in the dimensionless groups of We_L and We_G are the most appropriate mapping coordinates for microgravity conditions.

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