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PRESSURE DROP IN GAS–LIQUID FLOW AT MICROGRAVITY CONDITIONS

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Abstract—A new set of experimental pressure drop air–water flow data at microgravity conditions obtained aboard the NASA KC-135 aircraft is reported. Comparisons between pressure drop values at $\mu - g$ and $1 - g$ vertical upward flow suggest that the forced convection two-phase flow frictional pressure drop at microgravity is of the same order of magnitude as that at normal gravity for otherwise the same tube geometry and flow conditions. The main reason seems to be that the flow is mainly inertia dominated over the range of liquid and gas flow rates tested. The experimental data were compared with several widely used empirical models, e.g. homogeneous model, Lockhart–Martinelli method and Friedel's model. All models gave reasonable predictions.

Key Words: two-phase flow, pressure drop, microgravity

INTRODUCTION

The determination of frictional pressure loss in two-phase flows is essential to the design of a variety of industrial heat-transport systems and also in chemical and petroleum processes. A large number of investigations have been carried out on the ground in the past five decades. Many correlations and models have been proposed for the prediction of the two-phase flow pressure drop at the Earth's gravity (e.g. Lockhart & Martinelli 1949; Dukler *et al.* 1964 a, b; Chisholm 1967; Friedel 1979). In comparison, very little research was done for conditions of reduced gravity due to the limited access to such environment, and the high costs associated with it. The development of space thermal transport and power acquisition systems has triggered research in two-phase flow at microgravity conditions. Two-phase flow could meet the escalating power requirements in future thermal management and thermal control systems in spacecraft, communication and Earth observation satellites and space stations. It is also essential for the analysis of the potential use of space nuclear reactors, and also in material processing and life support systems at reduced gravity. Understanding the hydrodynamic characteristics of two-phase flow under reduced gravity is essential to the designers of such systems.

Most of the existing pressure drop correlations are empirically or semi-empirically derived from terrestrial test data. These provide a good starting point for the study of two-phase flow pressure drop at microgravity conditions. When gravitational forces are reduced, the behavior of the flow is different in that the phase distribution is more symmetrical, and the gas slip ratio is very small (Dukler *et al.* 1988; Zhao & Rezkallah 1993). The differences and similarities between two-phase flow pressure drop at microgravity and at normal gravity should be studied. The correlations for predicting two-phase flow pressure drop, which were derived at normal gravity, have to be re-examined for microgravity conditions before they can be used with confidence.

The first experimental work on reduced gravity gas–liquid forced flow pressure drop and flow pattern was conducted by Heppner *et al.* (1975). The test section was a 25.4 mm i.d. hole bored in a clear plastic rectangular block. The length-to-diameter ratio was very short (about 20). Flow pattern and pressure drop data were collected during experiments with air and water aboard the NASA KC-135 aircraft flying parabolic trajectories and also on the ground with the test section placed in a horizontal orientation. The results suggested that pressure drop at microgravity was higher than that at normal gravity with horizontal orientation. While the interpretation of the results is somewhat questionable due to the short test section used ($L/D = 20$), and the fact that duplicate tests gave different results, the data gave some qualitative measures of possible reduced gravity effects.

Chen *et al.* (1991) presented experimental data of a two-phase flow pressure drop using saturated Refrigerant-114 as the working fluid under normal and microgravity conditions. The test section was a 1.58 cm diameter tube, and it was also mounted horizontally. Tests were performed aboard the NASA KC-135 aircraft, and pressure drop data were collected while the vapour quality x increased from 0.05 to 0.90 (V_{SL} from 0.02 to 0.16 m/s). Slug flow was observed over the quality range from 5 to 10%, and annular flow was found to exist for a quality range from 15 to 90%. The pressure drop results at microgravity were compared with those at normal gravity obtained with a horizontal orientation. At the same gas quality, the pressure drop at microgravity was found to be higher than that at normal gravity. Several two-phase pressure drop models for the $1-g$ condition were compared with the test data. The homogeneous model appeared to correlate the pressure drop well at microgravity in the slug flow regime. An annular flow model, using an empirical interfacial friction factor based on their microgravity data, was found to adequately correlate the pressure drop data in that flow regime.

An experimental study was also conducted by Colin *et al.* (1991) during a series of parabolic trajectories. Void fraction, flow pattern and pressure drop data were reported for air–water flow in a 4 cm i.d. conduit (mainly in the bubble and slug flow regimes). The measurements suggested that pressure drop under microgravity conditions in the bubble and slug flow regimes can be reasonably predicted using a homogeneous model.

Almost all of the previous studies on two-phase flow pressure drop were conducted in a horizontal channel; where stratification of the two phases occurs during tests on the ground. The difference of two-phase flow pressure drop on the ground may be several hundred percent when the flow orientation is changed from horizontal to vertical (Spedding *et al.* 1982). There appears to be no comparisons of the pressure drop results at microgravity with those obtained at normal gravity in a vertical upward flow, where the flow structure is somewhat similar. The purpose of the present study is to provide a new set of experimental pressure drop data at microgravity conditions, and to compare them with those obtained at normal gravity in a vertical upward flow. Widely used models and correlations based on terrestrial test data are also examined using the microgravity experimental data.

EXPERIMENTAL METHODS

Experimental apparatus

The test facility, shown schematically in figure 1, was used for conducting the microgravity experiments on the NASA KC-135 aircraft, as well as at normal gravity. The test apparatus consists of a 9.525 mm i.d. test section, a liquid flow loop, a gas-flow loop, a pump/separator unit, a mixer, a data acquisition system and flow-pattern recording cameras.

Water and air were used as the working fluids. Water was pumped in a closed loop from the pump/separator unit to the experimental test section and back to the pump/separator. Water flow rate was varied by adjusting the rotational speed of the pump and a set of flow control venturis. It was measured using two turbine flowmeters, with velocity ranges of 0.07–2.1 m/s (0.3–9 l/min) and 0.1–3.5 m/s (0.5–15 l/min) for the first and second meters, respectively. The accuracy was 1% of readings for both flowmeters. When liquid velocities were lower than 1.0 m/s, the first was used, otherwise the second meter was used. Air was supplied from a compressed air tank attached to the apparatus. The air flow rate was controlled and measured using mass flow controllers. The controllers had ranges of 0–20 and 0–100 SLM (standard liters per minute), and an accuracy of 1% of full scale. All turbine meters and mass flow controllers were calibrated prior to and after each flight.

The two-phase flow was supplied through a mixer. The mixer was designed such that the gas enters it from several small holes on the wall, and is mixed with the liquid which flows axially in the mixing chamber. The vertical test section, which is 0.9525 cm i.d., has a total length of 1.5 m. The observation section is located 80 cm from the mixer and is 12.7 cm long. The observation section was set into a "light-path-corrector" to reduce distortion near the wall due to the curvature

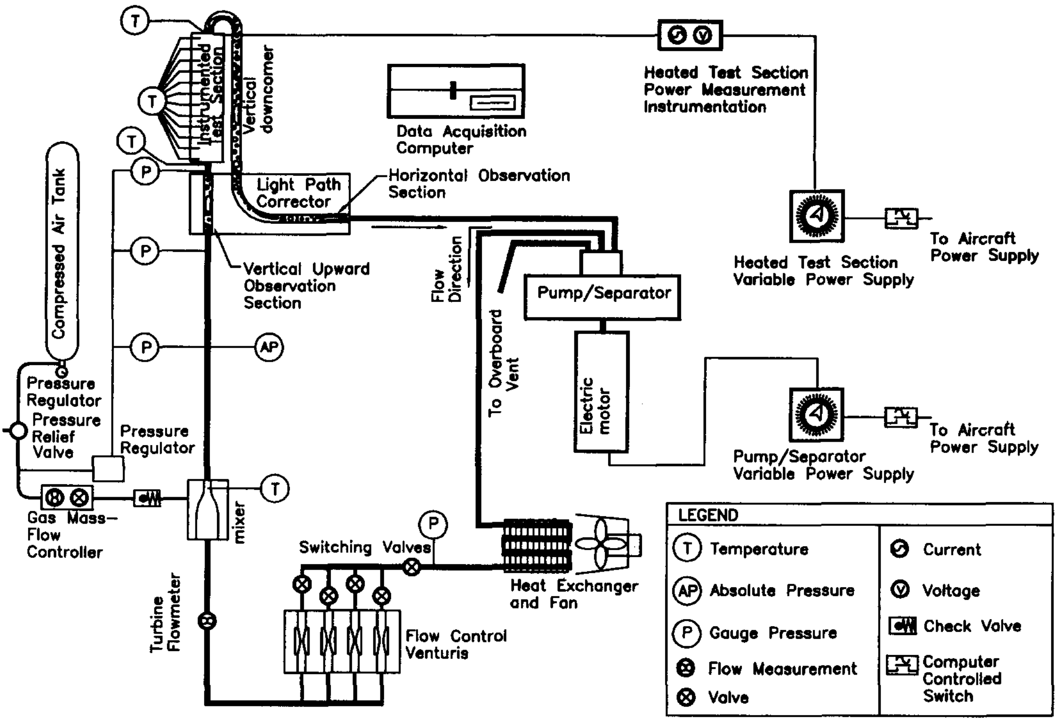

Figure 1. A schematic of the experimental facility.

of the tube. The light-path-corrector is an acrylic box filled with glycol, which has nearly the same index of refraction as the acrylic tube. The observation section is followed by a vertical heated test section having the same inside diameter and 36 cm long.

Absolute pressures and gauge pressures were measured at a distance of 25.7 cm from the mixer outlet. Two additional gauge pressure measurements were taken at 30.5 and 69 cm down stream from the bottom transducer. All of the pressure readings were taken using Validyne pressure transducers with accuracy of 0.25% of full scale. The absolute pressure transducer is a sealed unit with a range of 0–410 kPa (0–60 psia). The range for the middle transducer is 0–14 kPa (0–2 psi), and the ranges for the top and bottom transducers are 0–21 kPa (0–3 psi). The other sides of the three gauge pressure transducers were connected to a Null Matic pressure regulator. The regulator was used to set the reading of the middle transducer to zero at all times. All of the transducers were carefully calibrated before the flight campaign.

An accelerometer, operated in a central unit by the Canadian Space Agency, was used to record the actual g-level in the x, y and z directions. All the data were acquired using a 486/66 MHz computer. Two-phase flow patterns were recorded on a NAC high speed color video camera (1000 fps).

Before the flight test, a study of the frequency response of pressure drop fluctuations was conducted on the ground to determine the required sampling frequency. Water–air flow was run in the flight apparatus covering the range of flows that would be tested during flight. The signals from the three gauge transducers were recorded on a TEAC data recorder at a tape speed of 19 cm/s, which resulted in a bandwidth of DC to 5000 Hz. The data were digitized later using a D/A system at 2048 samples per second. A fast Fourier Transform was performed for these data points. It was found that the maximum observed frequency is approximately 30 Hz, and the smallest frequency is approximately 15 Hz. It was decided that a sampling rate of about 70 Hz is adequate, and this was used during the experiments.

Processing of pressure drop data

From the readings of the three gauge pressure transducers, two pressure gradients may be obtained: from bottom to top (69.0 cm) and from bottom to middle (30.5 cm). Since the accuracy

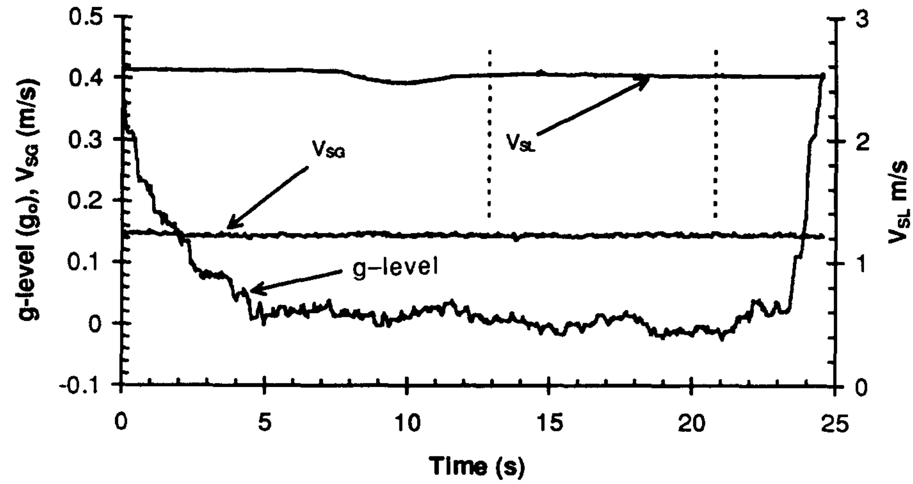

Figure 2. A typical microgravity period.

of the transducers is 0.25% of full scale, the uncertainties associated with the measurement of pressure gradient are 106 Pa/m for values obtained over the 69.0 cm length, and 204 Pa/m for values obtained over the 30.5 cm length. Due to the relatively large range of the transducers (this is necessary to accommodate pressure fluctuations and high pressure values during the hypergravity periods), and relatively short lengths over which the pressure drops were measured, small pressure gradients could not be measured accurately using this setup. It was decided that pressure drop values less than 2 kPa/m must be discarded. For the rest of the data, the uncertainty in the measurement of pressure gradients due to the pressure transducers is 5% for bottom to top reading (69.0 cm length), and 10% for bottom to middle reading (30.5 cm length).

Pressure drop and flow-pattern data were collected during the flight campaign of February 1994, and also on the ground. During each parabola, the absolute pressure, three gauge pressures, temperatures, liquid and gas volumetric flow rates and g-levels were collected at a sampling rate of about 70 points per second for each point using the 486/66 MHz computer. Final data were obtained by averaging of at least 500 data points.

Data selection was based on duration of the microgravity period where changes in the acceleration levels and liquid and gas flow rates were minimum about an average. A typical g-level before, during and after a microgravity period is shown in figure 2. The variation of liquid and gas superficial velocities V_{SL} and V_{SG} are also plotted on the same figure. For this particular parabola, averages were made over the time period indicated by the two vertical dot lines on the graph. Data retained for later analysis were those where the maximum gravity level was within $\pm 0.04\,g_o$ (g_o is the Earth's gravity), and flow rates of both phases were stable. Two sets of total pressure drop data were obtained from the readings of three transducers over 69 cm and 30.5 cm, respectively. A comparison between the two readings is plotted in figure 3 including all of the experimental data that satisfied the above criteria. The data are closely scattered around the average line. The root mean square deviation between the two sets of data is 10%. This suggests that the pressure drop data obtained through these independent measurements are in good agreement. It is also an indication that the flow can be deemed as fully developed flow. In the following analysis, the pressure gradient value from the difference between the top and bottom transducers ($L = 0.69$ m) is used.

EXPERIMENTAL RESULTS AND DISCUSSIONS

Experimental results

The total pressure loss in two-phase flow can be expressed as the sum of frictional pressure loss, gravitational pressure loss and accelerational pressure loss. For a fully developed, adiabatic and steady-state flow in a tube with a uniform cross section, the pressure loss due to acceleration can be ignored. The frictional pressure gradient can then be obtained from

$$\left(\frac{dp}{dz}\right)_F = \left(\frac{dp}{dz}\right)_{Total} - \left(\frac{dp}{dz}\right)_g. \qquad [1]$$

The pressure drop due to gravity may be a high percentage of the total pressure drop at normal gravity condition (particularly at low liquid and gas flow rates). Even at microgravity, gravitational pressure loss still exists due to the presence of a residual gravity on board the aircraft. This part needs to be estimated accurately. Unfortunately actual void fraction measurements are not presently available. However, a study of void fraction in upward vertical flow was carried on ground by Jiang (1992) using the same tube inside diameter. It was found that, among other correlations, the correlation of Chisholm (1967) gave the best results in correlating the experimental data for a wide range of flow rates (the overall root mean square deviation was 18.8%). The same correlation was then used in the estimation of void fraction in the present study, and the latter was used for calculating the gravitational pressure loss. The void fraction ϵ is given by

$$\epsilon = \frac{\dfrac{x}{\rho_G}}{\dfrac{x}{\rho_G} + K\dfrac{1-x}{\rho_L}}. \qquad [2]$$

where x is the gas quality and coefficient K is given by

$$K = \left[1 + \left(\frac{\rho_L}{\rho_G} - 1\right)x\right]^{1/2}. \qquad [3]$$

The mixture density and then the gravitational pressure drop can be calculated after the void fraction is estimated.

Experimental total pressure drop and frictional pressure drop calculated using the above method at microgravity and terrestrial conditions are given in tables 1 and 2, respectively. In these experiments, the liquid superficial velocity V_{SL} ranged from 0.1 to 2.5 m/s, and the gas superficial velocity V_{SG} ranged from 0.1 to 18 m/s. According to the flow pattern definitions of Zhao & Rezkallah (1993), bubble, slug, frothy slug–annular and annular flows were observed to exist in the tube at those flow rates under microgravity conditions. Bubble, slug, churn and annular flows, as defined by Dukler & Taitel (1986) were observed at normal gravity.

Some of the experimental frictional pressure drop at microgravity and normal gravity conditions are plotted in figure 4 using the volume fraction β [defined as $\beta = V_{SG}/(V_{SL} + V_{SG})$] as the independent variable for $V_{SL} = 0.5$, 1.5 and 2.5 m/s, respectively. Corresponding flow patterns are also indicated beside each data point. Among these, pressure drop data at $V_{SL} = 1.5$ m/s cover the widest range. The β ranged from less than 0.1 to over 0.8. Generally, at a constant V_{SL}, the pressure

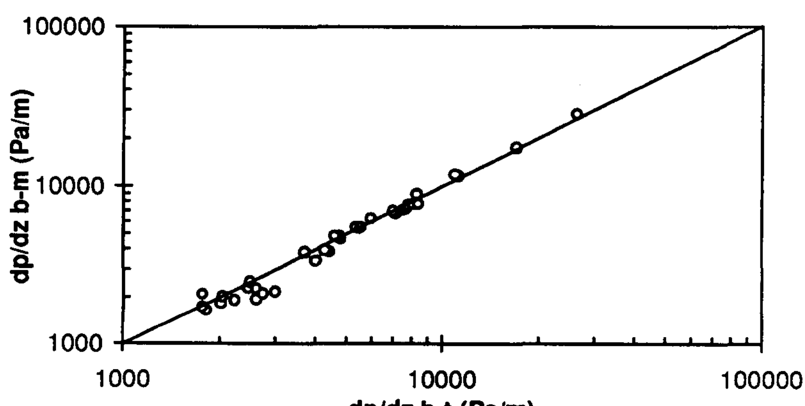

Figure 3. Comparison of total pressure drop values at $\mu - g$ obtained from bottom to top (69.0 cm) and bottom to middle (30.5 cm) transducers.

Table 1. Two-phase pressure drop data at $\mu - g$

V_{SL} (m/s)	V_{SG} (m/s)	Flow-pattern	P_{abs} (psi)	T (°C)	G_z/g_o	dp/dz_{tot} (Pa/m)	dp/dz_f (Pa/m)
0.07	15.89	annular	12.7	24.1	0.002	2018	2017
0.07	17.95	annular	13.6	25.0	0.014	2487	2480
0.11	13.94	annular	13.0	24.8	0.001	2448	2447
0.15	13.99	annular	12.7	26.0	0.017	2038	2023
0.25	11.95	frothy slug–annular	13.3	28.7	0.019	4755	4732
0.26	13.98	annular	14.0	31.8	0.018	5464	5444
0.32	2.46	slug	12.1	30.2	0.02	2228	2174
0.33	9.96	frothy slug–annular	13.5	28.5	0.01	4785	4770
0.41	6.96	frothy slug–annular	13.1	28.1	0.004	4286	4278
0.49	5.96	frothy slug–annular	13.4	32.8	0.013	5534	5505
0.52	3.45	frothy slug–annular	13.3	28.4	0.015	4416	4372
0.71	11.93	frothy slug–annular	16.4	31.1	0.031	11,169	11,108
0.74	3.96	frothy slug–annular	13.7	33.4	0.037	6993	6877
0.84	1.46	frothy slug–annular	12.6	30.2	0.032	4575	4423
0.88	0.96	frothy slug–annular	12.4	29.3	0.008	3686	3642
0.88	1.96	frothy slug–annular	12.9	31.9	0.01	5345	5301
1.25	0.39	slug	12.6	34.1	−0.001	2727	2735
1.38	0.19	slug	12.5	33.4	0.005	2607	2564
1.41	1.47	slug	13.9	34.9	0.029	8292	8127
1.47	0.09	bubble	12.5	32.7	0.029	2587	2320
1.47	0.14	bubble	12.6	32.7	−0.001	2987	2996
1.52	3.95	frothy slug–annular	16.6	33.7	0.006	17,073	17,048
1.53	0.29	slug	12.9	33.2	0.007	4016	3958
1.54	0.77	slug	13.3	34.3	0.007	5954	5905
1.55	8.15	frothy slug–annular	20.2	30.1	0.025	26,463	26,384
1.60	1.96	slug	14.8	32.7	0.004	10,959	10,937
2.47	0.39	slug	14.7	38.9	0.012	8391	8289
2.48	0.09	bubble	14.1	34.3	0.004	7133	7095
2.50	0.24	bubble	14.4	36.2	0.005	7792	7747
2.51	0.29	bubble	14.5	37.7	0.005	8062	8018
2.51	0.19	bubble	14.4	36.4	0.006	7702	7647
2.52	0.15	bubble	14.3	35.3	0.003	7532	7505

drop gradually increases as the volume fraction increases. The frictional pressure drop at $1-g$ and $\mu - g$ are very comparable, with those at $\mu - g$ being slightly higher than (or equal to) dp/dz at $1-g$. The difference is very small, ranging from 1 to 14%. For most of the cases, the differences are within $\pm 10\%$.

The two-phase flow frictional pressure gradient is often correlated by various two-phase multipliers. The liquid two-phase multiplier is defined by

$$\phi_L^2 = \frac{\left(\dfrac{dp}{dz}\right)_F}{\left(\dfrac{dp}{dz}\right)_L}, \qquad [4]$$

where $(dp/dz)_L$ is the single-phase liquid frictional pressure gradient calculated using the actual liquid phase flow rate alone. The multiplier is calculated for these experimental data, and is plotted as a function of quality x in figure 5 for both $\mu - g$ and $1-g$ conditions. Clearly the two-phase multiplier values at $1-g$ and $\mu - g$ conditions are almost identical at the same gas quality.

Discussion of results

For a two-phase liquid–gas flow flowing upwardly and concurrently in a vertical tube, when gravity is reduced (while keeping the liquid and gas flow rates unchanged), the major effect on the flow hydrodynamics results from the reduction of the buoyancy forces on the gas phase. For annular flow, a large change in the flow dynamics is not expected when gravity is changed since the flow in that region is inertia dominated. The behavior of the liquid film as well as its thickness may be altered under reduced gravity conditions.

For bubble and slug flows in an upward vertical co-current system, the flow dynamics may change due to the change of bubble movement when gravity is reduced. The slip ratio between the two phases decreases due to the decrease in the gas phase velocity at microgravity. This leads to a higher gas void fraction in upward flow systems. The liquid phase flowing in the reduced flow area in then accelerated, and the velocity gradient becomes larger near the wall. This would cause the pressure drop to increase. On the other hand, it has been shown (Lance & Bataille 1991) that for bubbly flow at $1-g$, the turbulence in the liquid phase is amplified owing to the hydrodynamic interactions between the bubbles and the wakes of the bubbles (since the bubbles travel at higher speed than their surrounding liquid). The high energy dissipation associated with the turbulence in the flow leads to high frictional pressure drop values. At microgravity, the gas bubbles are moving with virtually the same speed as the surrounding liquid. The turbulence amplification induced by the bubble movement is therefore much more reduced under those conditions. Thus, it could be argued that there are two competing effects at microgravity. One is to increase the liquid velocity due to the increase in void fraction, and consequently the reduction in the liquid flow area. The other is a decrease in the turbulence dissipation under microgravity conditions due to the reduction of the turbulence amplification because of a substantial reduction in the bubble movement at microgravity. The change in pressure drop is determined by the balance of the two effects and their relative magnitude compared with the flow inertia.

When the gas phase density is much smaller than the liquid phase density, the bubble velocity in a gas–liquid flow is expressed by (Wallis 1969):

$$v_b = 1.2U_m + k_1\sqrt{gD} \qquad [5]$$

Table 2. Two-phase pressure drop data at $1-g$

V_{SL} (m/s)	V_{SG} (m/s)	Flow-pattern	P_{abs} (psi)	T (°C)	dp/dz_{tot} (Pa/m)	dp/dz_f (Pa/m)
0.06	15.92	annular	14.20	27.1	2499	1983
0.06	17.95	annular	14.75	25.8	2658	2165
0.06	17.85	annular	14.32	29.8	2818	2320
0.07	15.91	annular	14.32	30.2	2638	2076
0.09	11.92	annular	14.15	27.2	2692	1932
0.09	17.92	annular	14.48	27.5	3717	3102
0.10	13.93	annular	14.31	27.5	3131	2421
0.13	9.93	annular	14.33	33.3	2999	2024
0.13	13.92	annular	14.49	30.5	3759	2924
0.16	9.93	annular	14.34	31.8	3539	2466
0.22	3.45	churn	14.33	32.5	4081	2081
0.25	11.93	annular	14.97	32.2	5558	4328
0.27	13.88	annular	15.28	32.5	6554	5366
0.28	9.92	annular	14.92	32.1	5589	4175
0.40	6.92	churn	15.08	32.6	6335	4405
0.40	7.93	annular	15.19	34.7	6774	4951
0.51	5.93	churn	15.53	34.7	7820	5537
0.53	3.40	churn	15.13	32.8	7098	4182
0.54	11.96	annular	16.57	35	10,729	8990
0.61	8.78	annular	16.41	31.8	10,761	8665
0.70	3.97	churn	15.76	34.3	9505	6446
0.75	6.93	churn	16.66	34	12,410	9894
0.77	5.93	churn	16.46	33	12,359	9652
0.82	1.43	slug	15.26	32.8	7859	3083
0.90	1.97	slug	15.63	34	9105	4702
0.92	0.97	slug	15.31	31.6	8623	2963
1.25	0.39	slug	15.21	34.2	10,800	3106
1.36	0.19	slug	15.15	34	11,506	2866
1.40	1.47	slug	16.47	33.4	12,322	6670
1.50	3.98	slug	18.61	33.6	19,570	15,467
1.50	0.77	slug	16.11	32.8	12,159	5246
1.50	0.29	slug	15.38	34.3	12,016	3700
1.51	0.14	bubble	15.26	33.8	12,201	3178
1.52	8.16	churn	21.92	32.4	28,805	25,671
1.60	1.97	slug	17.32	33.9	15,063	9688
2.48	0.19	bubble	16.62	35.7	16,471	7356
2.49	0.13	bubble	16.50	34.3	16,413	7104
2.49	0.10	bubble	16.41	32.5	16,375	6929
2.49	0.29	slug	16.87	38.6	16,535	7719
2.50	0.23	bubble	16.78	37	16,567	7572
2.50	0.39	slug	17.06	39.6	16,699	8151

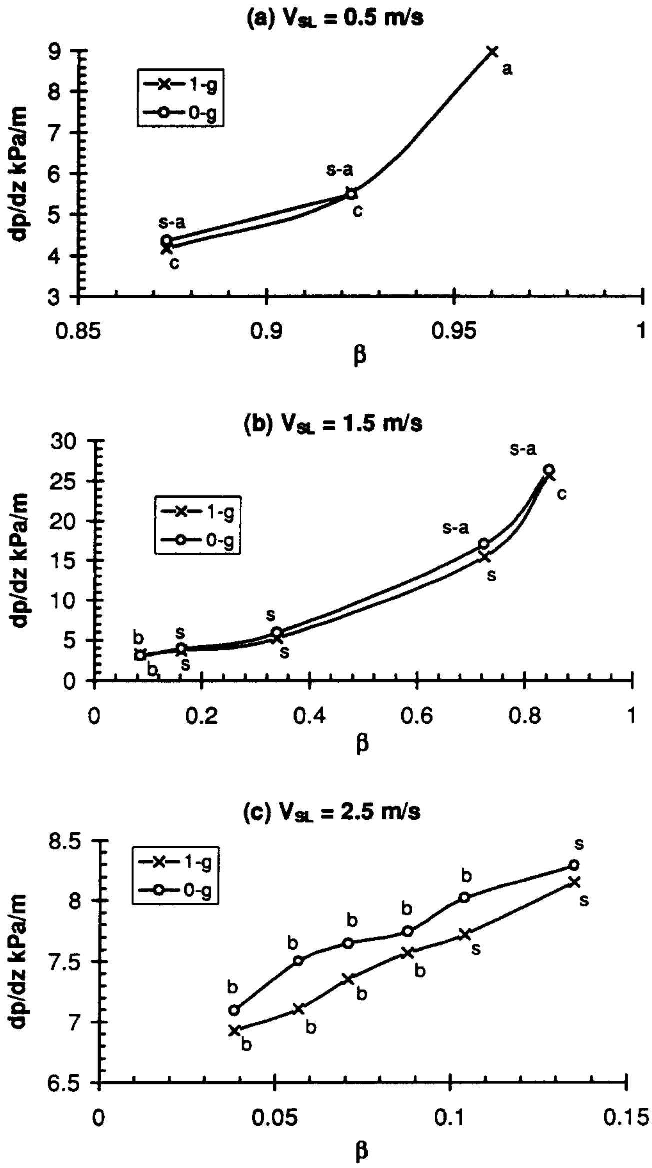

Figure 4. Comparison of two-phase pressure drops at $\mu - g$ and $1 - g$ conditions. (a) Annular flow; (b) bubble flow; (c) churn flow, (s) slug flow, (s-a) frothy slug–annular flow.

For Taylor bubbles, $k_1 = 0.35$; for smaller bubbles, k_1 is a function of the bubble size, with a value less than 1. The second term in [5] has a value between 0.1 and 0.3 for the tube size used in the present experiment (0.009525 m i.d.). The value of the first term ranges from 1.8 to 3.4 under the experimental conditions when slug or bubble flows were observed. It is evident that, on the ground, less than 10% of the bubble velocity is due to buoyancy effect. The Reynolds number of the mixture, Re_m, is in the order of 10^4. This indicates that the flow is well into the turbulent region. A change of less than 10% in the bubble velocity would not make significant changes to the flow dynamics. Perhaps this is the reason that large differences in the pressure drop were not observed when gravity was reduced under the present experimental conditions.

At very low liquid and gas flow rates, the velocity component due to buoyancy would be a significant part of the total bubble velocity. A relatively larger pressure drop change may be observed when gravity is reduced. Unfortunately, accurate pressure drop data at low liquid and gas flow rates were not obtained due to the restriction of the apparatus.

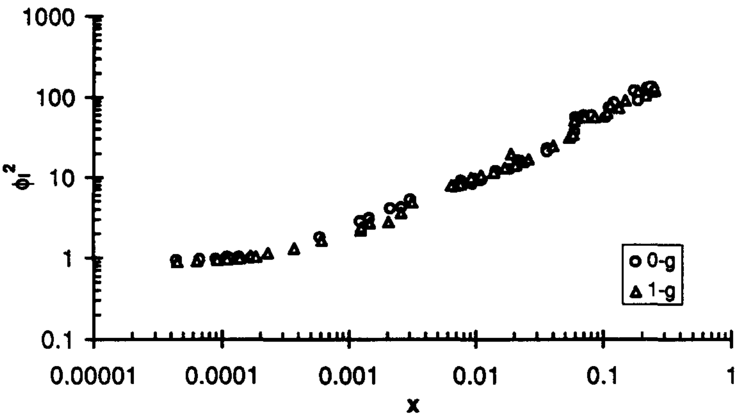

Figure 5. Two-phase multiplier vs quality x at both $\mu - g$ and $1 - g$ conditions.

The present experimental results are somewhat contradictory to the findings by Chen *et al.* (1991), where pressure drop at microgravity was reported to be about 40% higher than that at normal gravity. In that experiment, data were collected at very low liquid velocities (0.02–0.16 m/s), and the data at microgravity were compared with those at normal gravity taken in a horizontal tube section. Since flow stratification takes place in the latter case (which does not occur at $\mu - g$), comparisons of the $\mu - g$ data with horizontal flows is inappropriate and could be also misleading. In addition, the accuracy of the pressure transducers they used was ± 345 Pa (0.05 psi), and the pressure differences were from 62 to 1792 Pa (0.009–0.26 psi) with about half of the data around 345 Pa (0.05 psi). Also, the sampling rate was very low (about one point per two seconds), which makes their conclusions even more questionable.

COMPARISON WITH EXISTING CORRELATIONS

A number of models are available for predicting the two-phase flow pressure drop. The experimental frictional pressure drop data at $\mu - g$ conditions were compared with those models to test their validity under microgravity conditions. Only a few widely used general correlations were used in the comparisons, and no attempt was made to test models for specific flow patterns (e.g. annular flow models).

The homogeneous model

The homogeneous model is a simple model that could be most suitable for microgravity of two-phase flows. The basic assumption of this model is that the two phases are well mixed and the velocities of the two phases are equal. This assumption is closer to what is actually experienced under microgravity. The mixture density is given by

$$\frac{1}{\rho_m} = \frac{x}{\rho_G} + \frac{1-x}{\rho_L} \qquad [6]$$

The calculation of the mixture viscosity could be done using one of several methods. One is to use the liquid viscosity in the calculation of Reynolds number. This is the method recommended by Colin *et al.* (1991) and Sridhar *et al.* (1992). Another is to use a mixture viscosity instead of the liquid viscosity. Several correlations are recommended for μ_m, among which is the one suggested by Dukler *et al.* (1964b); this is given by

$$\mu_m = \mu_G \frac{x\rho_m}{\rho_G} + \mu_m \frac{(1-x)\rho_m}{\rho_L}. \qquad [7]$$

The friction factor C_f can be calculated from the Blasius equation, in which the Reynolds number is given by

$$\mathrm{Re}_m = \frac{\rho_m U_m D}{\mu} \qquad [8]$$

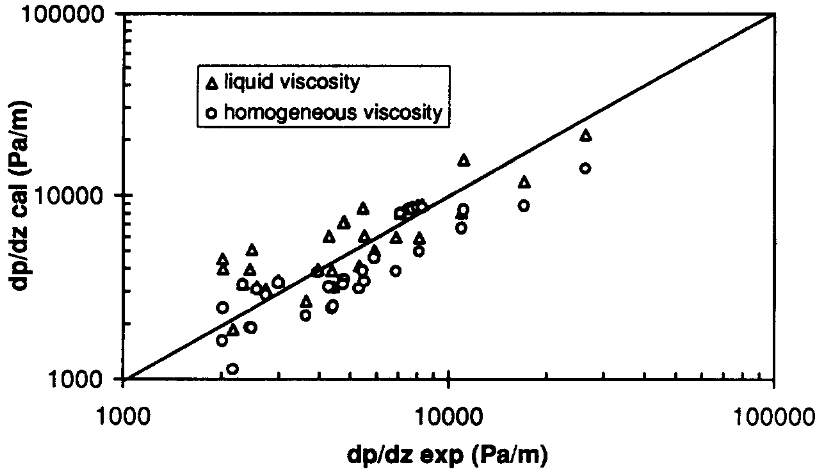

Figure 6. Comparison of two-phase pressure drop at $\mu-g$ with the homogeneous model.

The pressure drop can then be obtained from

$$\left(\frac{dp}{dz}\right)_F = \frac{2}{D} C_f \rho_m U_m^2 \qquad [9]$$

Pressure drops calculated using liquid viscosity and mixture viscosity are compared with the experimental data at $\mu-g$; this is shown in figure 6. The overall root mean square deviations between the experimental and calculated pressure drop values are 28% when a mixture viscosity is used, and 40% when a liquid viscosity is used. The relatively poor performance of the latter is mainly due to the large over-estimation (100%) of pressure drop at annular flow. Generally speaking, when the liquid velocity is much higher than the gas velocity (bubble flow), both models gave equally good predictions. When the liquid velocity is much lower than the gas velocity (annular flow), using the liquid viscosity tends to largely over-estimate the pressure drop, while using the mixture viscosity tends to slightly under-estimate the pressure drop. When the two velocities are comparable (slug and transitional flows), both methods under-predict the pressure drop, with the liquid viscosity yielding better results.

The Lockhart–Martinelli correlation

Another widely used method for the estimation of two-phase flow pressure drop is the Lockhart–Martinelli correlation. The Martinelli parameter X^2 is defined as

$$X^2 = \frac{\left(\frac{dp}{dz}\right)_L}{\left(\frac{dp}{dz}\right)_G}, \qquad [10]$$

where $(dp/dz)_G$ is the single-phase gas frictional pressure gradient calculated using the gas-phase flow rate alone. The original correlation is given in a graphical form (Lockhart & Martinelli 1949). Later, Chisholm (1967) approximated these relationships by the expression:

$$\phi_L^2 = 1 + \frac{C}{X} + \frac{1}{X^2}, \qquad [11]$$

where C is a parameter and its value depends on whether the liquid and gas flows are laminar or turbulent. The calculated two-phase multiplier $\phi_{L\,cal}^2$ using [11] is compared with the experimental multiplier $\phi_{L\,exp}^2$ in figure 7. Generally, the prediction was good with a root mean square deviation of 28%. It is found that when $1/X$ is about 0.01 or larger than 1.0, the predictions are very good; when $1/X$ is about 1.0, the correlation tends to under-predict the pressure drop.

Friedel's model

A more sophisticated empirical equation for two-phase pressure drop was proposed by Friedel (1979). The equation was given in terms of a multiplier ϕ_{Lo}^2, which is defined by:

$$\phi_{\mathrm{Lo}}^2 = \frac{\left(\frac{\mathrm{d}p}{\mathrm{d}z}\right)_{\mathrm{F}}}{\left(\frac{\mathrm{d}p}{\mathrm{d}z}\right)_{\mathrm{Lo}}}, \qquad [12]$$

where $(\mathrm{d}p/\mathrm{d}z)_{\mathrm{Lo}}$ is the single-phase frictional pressure gradient assuming the liquid flowing with the same mass flow rate as the total two-phase flow rate. Friedel's equation is

$$\phi_{\mathrm{Lo}}^2 = E + 3.24FH/(\mathrm{Fr}^{0.045}\mathrm{We}^{0.035}) \qquad [13]$$

where

$$E = (1-x)^2 + x^2 \frac{\rho_{\mathrm{L}} C_{\mathrm{f_{Go}}}}{\rho_{\mathrm{G}} C_{\mathrm{f_{Lo}}}},$$

$$F = x^{0.78}(1-x)^{0.224},$$

$$H = \left(\frac{\rho_{\mathrm{L}}}{\rho_{\mathrm{G}}}\right)^{0.91}\left(\frac{\mu_{\mathrm{G}}}{\mu_{\mathrm{L}}}\right)^{0.19}\left(1-\frac{\mu_{\mathrm{G}}}{\mu_{\mathrm{L}}}\right)^{0.7},$$

$$\mathrm{Fr} = \frac{G^2}{gD\rho_{\mathrm{m}}^2},$$

$$\mathrm{We} = \frac{G^2 D}{\sigma \rho_{\mathrm{m}}},$$

in which $C_{\mathrm{f_{Go}}}$ and $C_{\mathrm{f_{Lo}}}$ are the friction factors assuming the total mass flux flowing with the gas and liquid properties, respectively. It has been considered an accurate general correlation for the frictional two-phase flow pressure gradient when $\mu_{\mathrm{L}}/\mu_{\mathrm{G}} < 1000$ (Whalley 1987). The correlation is the only one that attempts to include the effects of surface tension and gravity. The results of the frictional pressure gradient using [13] are compared with the experimental data; this is shown in figure 8. The root mean square deviation is 29%. Generally speaking, the correlation overestimates the pressure drop. Under the present flow conditions, the term E has a value of about 1 for bubble, slug and transitional flows, and it contributes up to 85% for bubble flow, and 20–50% for slug and transitional flows, depending on the liquid and gas flow rates. For annular flow, the term E

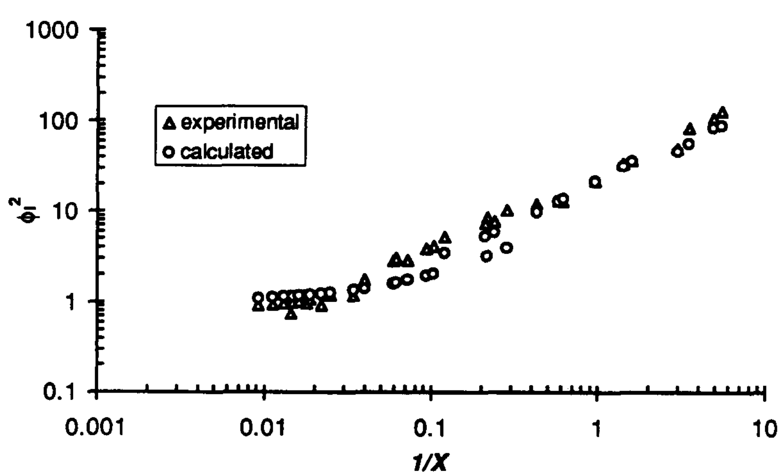

Figure 7. Comparison of two-phase pressure drop at $\mu - g$ with Chisholm's correlation.

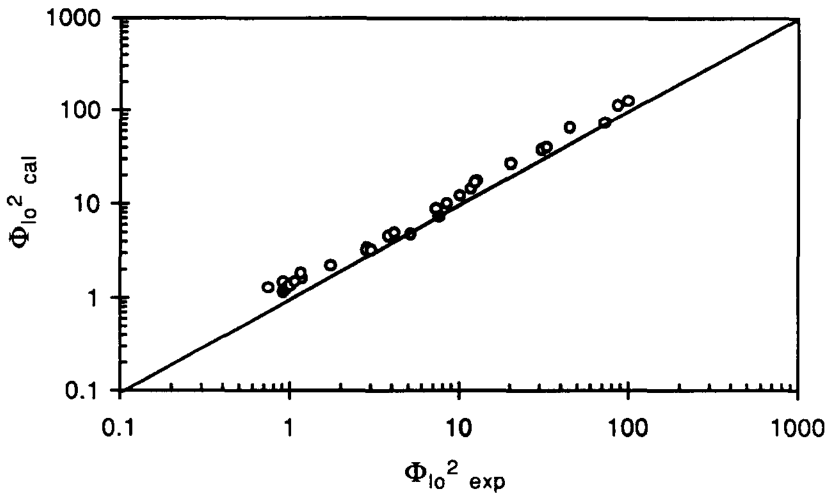

Figure 8. Comparison of two-phase pressure drop at $\mu - g$ with Friedel's model.

may be as high as 20, but it contributes only 10–20% of the ϕ^2_{Lo} value. When gravity is reduced to 0.01 g_0 (which is the average gravity level for the flight data), the second term in [13] is increased by 20%. This means that the effect of changing gravity on the pressure drop is larger for annular flow, and smaller for bubbly flow. This is in contradiction with the analysis given in the last section, and could perhaps explain the reason that the correlation consistently over-predicts the pressure gradient. In general, the overall prediction is good.

CONCLUSION

Two-phase air–water flow experiments were conducted on the ground and aboard the NASA KC-135 aircraft. A new set of experimental pressure drop data at reduced gravity conditions is reported. Associated flow patterns include bubble, slug, frothy slug–annular and annular flows. The pressure drop data were compared with those taken on ground with a vertical orientation. It was found that, within the flow rates examined, the frictional pressure drop at microgravity is very comparable with that at normal gravity at otherwise the same flow conditions.

For a two-phase flow system, when gravity is reduced, it seems that the reduction of buoyancy has two effects: one is to decrease the liquid fraction due to a decrease in the slip ratio (leading to higher liquid velocity, and consequently a higher pressure loss); the other is to reduce the turbulence amplification induced by bubble movement. The balance between the two effects will determine the change in the frictional pressure gradient. Under the present experimental conditions, however, the flow is highly turbulent, and the bubble velocity component due to buoyancy is very small (less than 10% of the total velocity). The flow is therefore dominated by inertia. Perhaps this is the main reason that no significant changes in the pressure gradient were observed when gravity was reduced.

The experimental data were also used to test some widely used empirical methods for the estimation of frictional pressure gradient at a $1 - g$ condition. In general, the homogeneous model, Chisholm's correlation and Friedel's model all gave reasonable predictions. It is found that the homogeneous model using a mixture viscosity or a liquid viscosity gave equally good prediction for bubble, slug and transitional flows, while the first gave much better results for annular flow. When $1/X$ is about 0.1, the Chisholm's correlation tends to under-predict the pressure drop. Friedel's model overestimates the pressure drop in all flow regimes.

Further studies at conditions of low liquid flow rates where the flow is "more laminar" needs to be carried out. Under such conditions, a relatively larger changes in the pressure gradient may be noticeable when gravity is reduced.

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