Interfacial Phenomena and Heat Transfer, 2 (1): 15–40 (2014)

REVIEW AND MODELING OF TWO-PHASE FRICTIONAL PRESSURE GRADIENT AT MICROGRAVITY CONDITIONS

M. M. Awad [1,*] ***& Y. S. Muzychka*** [2]

[1] *Mechanical Power Engineering Department, Faculty of Engineering, Mansoura University, Mansoura, Egypt 35516*

[2] *Faculty of Engineering and Applied Science, Memorial University of Newfoundland, St. John's, Newfoundland, Canada, A1B 3X5*

[*] Address all correspondence to M. M. Awad , E-mail: m_m_awad@mans.edu.eg

First, a detailed review of the two-phase frictional pressure gradient at microgravity conditions is presented. Then, a simple method for calculating the two-phase frictional pressure gradient at microgravity conditions using asymptotic analysis is presented. The two-phase frictional pressure gradient is expressed in terms of the asymptotic single-phase frictional pressure gradients for liquid and gas flowing alone. In the present model, the two-phase frictional pressure gradient for $x \cong 0$ is nearly identical to the single-phase liquid frictional pressure gradient. Also, the two-phase frictional pressure gradient for $x \cong 1$ is nearly identical to the single-phase gas frictional pressure gradient. The proposed model can be transformed into either a two-phase frictional multiplier for liquid flowing alone (ϕ_l^2) or two-phase frictional multiplier for gas flowing alone (ϕ_g^2) as a function of the Lockhart–Martinelli parameter, X. A comparison of the asymptotic model with the experimental data at microgravity conditions is presented, and a robust value of the fitting parameter is chosen as $p = 2/7$.

KEY WORDS: *review, asymptotic, modeling, two-phase, frictional pressure gradient, microgravity conditions*

1. INTRODUCTION

The application of two-phase fluid flow and heat transfer methods in microgravity (μ-g) environments includes control of two-phase power cycles, design and operation of the space station thermal management system, safety and performance issues concerning space nuclear power systems, and storage and transfer of cryogenic fluids. These two-phase systems include single-component flows such as R114 and two-component flows such as air–water. The mass, power, and volume energy savings of two-phase systems for future spacecraft creates many advantages over current single-phase systems. For example, two-phase active thermal control systems (ATCSs) for space platforms with higher power levels and longer transport distances are an attractive option. Two-phase ATCSs typically require less pump power than do single-phase systems, and often weigh less. Two-phase flows in the microgravity environment are known to behave differently than those in Earth gravity due to a lack of buoyancy in the microgravity environment. This limits the effectiveness of system-level ground tests and increases the technical risk for spacecraft two-phase ATCSs. Therefore, current models of two-phase phenomena such as pressure drop, void fraction, and flow regime prediction are still not well defined for space applications. The physics of two-phase flows and their associated pressure drop influenced by the change in gravity must be understood in order to allow development of two-phase active thermal control systems for spacecraft use. Two-phase flow at microgravity conditions has been previously studied in numerous ground-based facilities such as aircraft flying Keplerian parabolic trajectories and drop towers. The use of ground-based facilities

2152–5080/14/$35.00

NOMENCLATURE

ATCS	active thermal control system
a	parameter
a_1, a_2	constants
b_1	constant
C	Chisholm constant
d	diameter (m)
e	error
Eu	Euler number
f	Fanning friction factor
K	summation index
L	length (m)
m	index in the local velocity distribution
m_1, m_2, m_3, m_4, m_5	indices
N	number of data points
n	index in the local velocity distribution near the wall
n_1,n_2,n_3	indices
dp/dz	pressure gradient (Pa/m)
R	radius (m)
r	radial distance (m)
Re	Reynolds number
U	superficial velocity (m/s)
u_m	local velocity distribution (m/s)
u_o	velocity at the pipe center (m/s)
We	Weber number
X	Lockhart–Martinelli parameter
x	mass quality

Greek Symbols

δ	average film thickness (m)
μ	dynamic viscosity (kg/m · s)
ρ	density (kg/m^3)
ϕ^2	two-phase frictional multiplier

Subscripts

f	frictional
g	gas
l	liquid
m	mixture
RMS	root-mean square
tp	two-phase

Superscript

p	fitting parameter

to predict two-phase flow at microgravity conditions could yield significant cost savings because many flight system unknowns could be eliminated at minimal cost. Also, the reliability of microgravity fluid systems could be increased.

This paper presents the results of modeling of a two-phase frictional pressure gradient at microgravity conditions. The paper contains three major sections. The first section presents a review of the data and correlations, which are recently available in the open literature. Next, a discussion on the development of a simple model for the prediction of the two-phase frictional pressure gradient at microgravity conditions using asymptotic analysis is presented. Finally, a discussion of the proposed models and a comparison with published data are presented.

2. LITERATURE REVIEW

A number of previous studies on two-phase flow at microgravity conditions have been reviewed for this work. The earliest studies of two-phase flow under reduced-gravity conditions appear to have been those studies conducted at the National Aeronautics and Space Administration (NASA) Lewis Research Center in the early 1960s. For example, Papell (1962) studied the instability effect for two-phase heat transfer of subcooled water flowing under conditions of zero gravity. In this study, Papell (1962) focused on instabilities that developed during shutdown and startup of a subcooled boiling system.

Later, Evans (1963) made flow visualization tests of different swirling and nonswirling two-phase two-component flow regimes at normal gravity (1-g) and zero gravity (0-g) in a clear plastic tube of $d = 0.5$ in (12.7 mm). The researcher used air and water at adiabatic/isothermal conditions as the two components and investigated bubbly and slug-flow regimes. Swirling flow was generated by using coiled wires with diameters-per-twist ratios (pitch length between wire coils or ribbon twists expressed in tube diameters) of 3.1, 4.4, and 8.5 and twisted ribbons with corresponding ratios of 2.7, 4.2, and 7.5. The researcher analyzed high-speed motion pictures taken of the different flow regimes. The results of his analysis, presented in the form of flow models, indicated that gravity had an effect on the phase orientation and turbulence level of the flow. Generally, under 0-g conditions bubble turbulence became less and the dispersion of bubbles became more homogeneous across the tube and tube wall boundary layer than under 1-g conditions. The notable difference between swirling and nonswirling flow was the formation of distinct cores of bubbles with swirling flow. Vertical swirling flow at 1-g with coiled wires closely resembled flow at 0-g. The use of a 0-g aircraft facility with the experimental package either restrained or allowed to float freely inside the aircraft to achieve weightlessness gave satisfactory and repeatable results. The relatively short periods of weightlessness and the degree of variation from perfect weightlessness inherent in this type of facility did not affect the results of the investigation.

Albers and Macosko (1965) conducted an experimental investigation to determine the differences between the pressure losses of nonwetting (dropwise) condensing flow of mercury vapor in 1-g and 0-g environments. The researchers obtained local and overall pressure-drop data for a horizontal, constant-diameter, stainless-steel tube at different flow rates, pressures, and condensing lengths. The measured overall static pressure drop indicated little difference between 1-g and 0-g pressure losses at flow rates of approximately 0.028 and 0.046 lb_m/s (12.7×10^{-3} and 20.87×10^{-3} kg/s). The overall static pressure drop varied from 0.20 to 2.24 lb_f/in^2 (1378.95 to 15,444.26 Pa), while the total pressure loss varied from 1.4 to 5.4 lb_f/in^2. (9652.66 to 37,231.69 Pa) for the condensing lengths and the flow rates considered.

Albers and Macosko (1966) conducted an experimental investigation to determine the pressure drop of nonwetting (dropwise) condensing flow of mercury vapor in l-g and 0-g environments. The researchers obtained local static pressure data for a uniformly tapered stainless-steel horizontal tube at different flow rates, pressures, and condensing lengths. The overall static pressure difference from the inlet to the interface varied from a pressure rise of 0.9 lb_f/in^2 (6205.28 Pa) to a pressure drop of 0.1 lb_f/in^2 (689.48 Pa), while the overall total pressure drop varied from 0.0 to 1.4 lb_f/in^2 (0.0 to 9652.66 Pa) for the condensing lengths and flow rates investigated. Their experimental data indicated that the gravity effect was negligible for all flow rates investigated.

Block et al. (1967) took high-speed motion pictures of mercury vapor condensing in glass tubes in a ground facility and in a 0-g facility. The researchers investigated a range of mercury flow rates from 0.03 to 0.05 lb_m/s (13.61×10^{-3} to 22.68×10^{-3} kg/s) in constant-diameter tubes ranging from 0.27 to 0.49 in (6.858 to 12.446 mm), in which the condensing lengths were fixed at 60 and 68 in (1524 and 1727.2 mm). Moving drops on the wall accounted for one-half or more of the liquid flow rate at any one station investigated along the condenser. The ratio of the observed average velocity of the drops in the vapor stream to the local vapor velocity varied from 0.3 at the inlet to 1.0 at approximately three-fourths of the condensing length from the inlet. In the 0-g aircraft facility, the 1- and 0-g conditions had little influence on the liquid flow distribution in the 0.27-in.-diameter (6.858-mm-diameter) tube. However, gravity made a substantial difference in the 0.40- and 0.49-in.-diameter (10.16- and 12.446-mm-diameter) tubes. In the l-g environment, there was a concentration of drops on the tube bottom and a shallow sloping interface. In the 0-g environment there was a uniform distribution of drops and a vertically standing interface. Vapor pockets within the liquid leg formed and collapsed within a time interval of approximately 0.04 s.

Siegel (1967) wrote a review article that covered reduced-gravity experiments prior to 1967. First, the researcher talked about the importance of studies at reduced gravity, and then presented an experimental production of reduced gravity using drop tower, airplane trajectory, rockets and satellites, and magnetic forces. Next, Siegel (1967) covered other heat transfer topics such as free convection, pool boiling, forced convection boiling, and condensation without forced flow.

In the 1970s, additional studies of condensing two-phase flow were reported. For instance, Williams et al. (1973) described the development and feasibility testing of a hybrid spacecraft heat rejection system that incorporated a single radiator capable of functioning as either a conventional space radiator or as a condenser in a refrigeration cycle. Emphasis was placed on development of the radiator/condenser (RC) that was considered to be the most critical component of the hybrid system. The researchers described the selection, design, and fabrication of candidate RC configurations together with preliminary parametric analyses necessary to establish pressure-drop, heat transfer, and flow stability characteristics. They described verification testing in 1-g and 0-g environments. The 0-g condition was obtained by means of a C-135 aircraft. The testing included flow visualization (i.e., high-speed photography) of the condensation processes in a parallel-channel quartz-tube system modeling the RC. The researchers presented representative qualitative photographs, in which the results indicated that stable flow conditions prevailed under both 1-g and 0-g operation. Keshock et al. (1974) presented an experimental study of flow condensation phenomena under 0-g conditions in a space radiator system.

In their report, Stark et al. (1974) presented a summarization and categorization of the pertinent literature associated with low-g fluid behavior technology. Initially, the researchers conducted a literature search to obtain pertinent documents for review. They summarized in detail reports determined to be of primary significance. Every summary, where applicable, consisted of (1) report identification; (2) objective(s) of the work; (3) description of pertinent work performed; (4) major results; and (5) comments of the reviewer. Pertinent figures were presented on a single facing page separate from the text. The specific areas covered were interface configuration; interface stability; natural frequency and damping; liquid reorientation; bubbles and droplets; fluid inflow; fluid outflow; convection; boiling and condensation heat transfer; venting effects; and fluid properties. Also, the researchers listed reports that were reviewed and not summarized, along with reasons for not summarizing. They presented cryogenic thermal control and fluid management systems technology.

Keshock (1975) presented and discussed basic equations of momentum and energy with respect to heat transfer and pressure drop for forced flow condensation in horizontal tubes under 1-g and 0-g conditions. The researcher presented some experimental results for condensing R12 in a system of three parallel-connected quartz tubes ($d = 3$ mm, $G = 1.037 – 3.456 \times 10^5\ lb_m/h \cdot \text{ft}^2$), and from high-speed photographs obtained measurements of film thickness, phase velocities, disturbance wavelengths, and flow regimes and their transitions. Based on these measurements, the researcher calculated different dimensionless force ratios (flow and instability para-meters). Under 0-g conditions a uniformly thick redistribution of liquid condensate about the tube walls was found to result in a lowered heat transfer coefficient compared with 1-g conditions, based on fundamental heat transfer theory. Keshock (1975) proposed a model that took into account the difference in heat transfer due to condensate distribution under 1-g and 0-g conditions.

Heppner et al. (1975) conducted experimental work on reduced-gravity gas–liquid forced-flow pressure-drop and flow patterns, in which air–water was used as a working fluid. Their test section had an inside diameter of a 25.4-mm hole bored in a clear plastic rectangular block. The length-to-diameter (L/d) ratio was very short ($\sim$20). The researchers collected flow pattern and pressure-drop data during experiments on the ground with the test section placed in a horizontal orientation, and also aboard the NASA KC-135 aircraft flying parabolic trajectories. The results suggested that the pressure drop at normal gravity with horizontal orientation was lower than that at microgravity. While the interpretation of the results was somewhat questionable due to the short test section used ($L/d \sim$ 20), and the fact that duplicate tests gave different results, the data gave some qualitative measures of possible reduced-gravity effects.

Hill et al. (1987) designed and fabricated a test loop to observe and measure pressure drops of two-phase flow in reduced gravity. Then, the researchers tested a portable flow test loop aboard the NASA-JSC KC135 reduced-gravity aircraft. Their test loop employed the Sundstrand two-phase thermal management system (TPTMS) concept that was specially fitted with a clear two-phase return line and condenser cover for flow observation. The working fluid was R114. A two-phase (liquid–vapor) mixture was produced by pumping nearly saturated liquid through an evaporator and adding heat using electric heaters. Hill et al. (1987) varied the mass quality of the two-phase flow (x) by changing the evaporator heat load. Before and after the KC135 flight tests, they operated the test loop on the ground in order to create a 1-g data base. Their ground testing included all the test points run during the reduced-gravity testing. Two days of reduced-gravity testing aboard the NASA-JSC KC135 were performed. During their flight tests, reduced-gravity, 1-g, and nearly 2-g accelerations were experienced. The researchers took data during the entire flight, which provided flow regime and pressure-drop data for the three operating conditions. Their test results showed that two-phase flow pressure drops and flow regimes could be accurately predicted in zero gravity.

Abdollahian (1988a) developed a mechanistic model for predicting the two-phase friction multiplier and void quality relationship in zero gravity. This model was applicable to fully developed turbulent bubbly flow conditions and it employed separated flow conservation equations. The predictions for gas–liquid flow in the absence of gravity showed significant increase in the two-phase friction multiplier in comparison to equivalent Earth-gravity conditions. The predicted void quality relationship was similar to predictions by the homogeneous equilibrium model. In order to estimate the effect of wall nucleation on the two-phase flow parameters, the adiabatic model was used by neglecting interfacial mass and momentum transfer and the boundary conditions were modified to account for the presence of voids at the wall.

Hill et al. (1988) performed an experiment to observe flow regimes and measure pressure drops of two-phase (liquid–vapor) flow and condensation in reduced gravity. The researchers conducted testing aboard the NASA-JSC KC-135 reduced-gravity aircraft using a prototype TPTMS for large spacecraft. A clear section of the two-phase line enabled visual and photographic observation of the flow regimes. The two-phase mixture was generated by pumping nearly saturated liquid R114 through an evaporator and adding heat through electric heaters. Hill et al. (1988) varied the resultant two-phase flow by changing the evaporator heat load, creating mass qualities from 0.05 to 0.80. Also, they made visual and photographic observations of vapor condensation through a clear cover on the system condenser. The researchers exposed the experiment hardware to gravitational acceleration ranging from near-zero to 1.8-g during the flight tests. Hill et al. (1988) performed ground test simulations of the flight tests before and after the KC-135 flights to generate a comparable 1-g data base. The flight test results showed that two-phase flow pressure drops could be predicted with reasonable accuracy for systems that would operate in reduced gravity by using either the existing Heat Transfer Research Institute (HTRI) method or the Friedel (1979) correlation. Following the testing of primary interest described previously, three additional tests that characterized the thermal management system's performance were successfully completed in reduced gravity. Throughout the entire test program the thermal management system performed as anticipated.

Chen et al. (1988) obtained experimental data of two-phase pressure-drop and flow pattern observations in normal gravity during ground testing and in nearly zero gravity aboard a NASA-JSC reduced-gravity KC-135 aircraft. Their studies investigated saturated R114 two-phase flow through adiabatic test sections of $d = 0.623$ in (15.8 mm) that included two 6 ft (1.83 m) lengths of transparent straight tubes for flow regime observation, as well as a selection with two 45° miter elbows and an arc of curvature. The researchers compared the pressure-drop data with several open literature prediction methods and to a proprietary flow-regime-dependent model. Chen et al. (1988) developed the flow-regime-dependent pressure-drop algorithm to accurately correlate the ground testing results. They related the pressure drops in reduced gravity to those of normal gravity by using flow pattern models for each. As expected, the measured pressure drops during microgravity operation exceeded those measured during ground testing. The observed flow patterns had been plotted on several published flow regime maps. Only slug flow and annular flow were observed in the microgravity testing.

Dukler et al. (1988) studied flow patterns and their transitions for gas–liquid flow at micro-gravity conditions. The researchers explored the flow patterns that existed under microgravity conditions when these body forces were suppressed. They collected extensive data at the NASA Lewis Research Center during parabolic flight on a Learjet and in a 100-ft-high drop tower. Air and water were used as the working fluid. The drop tower experiments provided 2.2 s of near-zero gravity for flowing air and water in a pipe of $d = 9.5$ mm and $L = 460$ mm, while the Learjet gave microgravity sequences 5–8 times longer in experiments carried out in a pipe of $d = 12.5$ mm and $L = 1060$ mm. The researchers obtained flow visualization using a camera operating at 400 frame/s for $\mathrm{Re}_l = 1000$–12,000 and $\mathrm{Re}_g = 100$–23,000. Their experiments showed that essentially three characteristic flow patterns existed: bubbly flow at low gas flow rates, slug flow for moderate gas and liquid flow rates, and annular flow for high gas flow rate. Also, they evolved preliminary models to explain the observed flow pattern map.

Rezkallah (1988) and Abdollahian (1988b) presented more extensive reviews of both two-phase flow and heat transfer at low gravity. Their literature survey covered the pre-1988 literature. Crowely and Izenson (1989) presented a design manual for microgravity two-phase flow and heat transfer. Their design manual was intended for use by designers of these systems. Design methods were presented for predicting two-phase flow regimes and pressure drops in pipe flows from Earth gravity to microgravity conditions. Also, forced convection boiling heat transfer methods for pipes with uniform heat flux as well as methods for analyzing high-vapor-shear condensation in pipes were included. Their design manual incorporated simplified methods (easy-to-use design charts), detailed descriptions of the analysis methods, comparisons with existing microgravity data, and recommended approaches to quantify the range of uncertainty in design calculations.

Wang et al. (1990) described a series of experiments in which an attempt was made to simulate two-phase flow behavior under 0-g conditions by the flow of two immiscible liquids of nearly equal densities. The researchers obtained pressure-drop and void fraction data for the steady flow of two different liquid pairs for widely varying flow conditions.

The two-phase flow in these experiments was in either the bubbly or annular flow regime. They found that values of the two-phase frictional multiplier and void fraction obtained from the measured data correlated well in terms of the Lockhart–Martinelli parameter (X), but the resulting variations of these parameters with X differed significantly from the Lockhart and Martinelli (1949) correlation for these quantities. Also, they conducted an analytical study of annular flow under 0-g conditions using a one-dimensional (1D) two-phase flow model. Using slightly modified versions of available correlations for the interfacial friction factor and turbulent eddy diffusivity, it was found that the predictions from their model agreed well with the data obtained over a wide range of conditions. While some useful insight could be gained from experiments of this type, the results of their study indicated that the flow of two liquids of equal density failed to model some important aspects of liquid–vapor two-phase flow at zero gravity. The researchers discussed in some detail the limitations of this type of experimental simulation.

Sridhar et al. (1990) simulated the dynamics of steady, fully developed dispersed liquid–vapor flow in a straight duct at zero gravity by flowing water containing n-butyl benzoate droplets. Water and benzoate were immiscible and had identical density at room temperature. The researchers gave the theoretical basis of the simulation. Their experiments showed that, for a fixed combined flow rate of water and benzoate, the large changes in the volume fraction of benzoate drops and their size distribution did not have an effect on the frictional pressure drop. The measured power spectra of the static wall pressure fluctuations induced by the turbulent water–benzoate flow also revealed that their dynamics was essentially unaltered by the presence of the droplets. These experimental findings, together with the theoretical analysis, led to the conclusion that the pressure drop in fully developed, dispersed liquid–vapor flow in straight ducts of constant cross section at zero gravity was identical to that due to liquid flowing alone at the same total volumetric flow rate of the liquid–vapor mixture, and therefore could be readily determined.

Chen et al. (1991) presented experimental data of two-phase pressure drop using saturated R-114 as the working fluid under normal gravity and nearly zero gravity aboard a NASA-JSC KC-135 aircraft. They used the obtained data to test the accuracy of a number of empirically based correlations and flow-regime-dependent models. The test section had a diameter of 15.8 mm, and was also mounted horizontally. The pressure-drop data were collected while the range of mass quality (x) = 5–90% and the range of liquid superficial velocity (U_l) = 0.02–0.16 m/s. Slug flow was observed over the mass quality range = 5–10%, and annular flow was found to exist for a mass quality range = 15–90%. Chen et al. (1991) compared the pressure-drop results at microgravity with those at normal gravity obtained with a horizontal orientation. At the same x, the pressure drop at microgravity was found to be higher than that at normal gravity. Different two-phase pressure-drop models for the 1-g condition were compared with their test data. For the reduced-gravity data, the algorithms tested were the following: Lockhart and Martinelli (1949), Troniewski and Ulbrich (1984), Friedel (1979), Chisholm (1973), Beattie and Whalley (1982), an annular flow model using the Premoli et al. (1970) void fraction correlation, and an annular flow model with an interfacial friction factor (Collier, 1981) that was developed from the KC-135 reduced-gravity data. For the ground test results, the two annular models were replaced by stratified flow models, i.e., the Taitel and Dukler (1976) and Chisholm (1983) models. Based on this study, it was concluded that the pressure drops in reduced gravity and those of normal gravity were related to flow pattern models for each. The pressure-drop predictions of the two annular flow models developed herein agreed well with the reduced-gravity data that were found to be significantly larger (by a factor of 2 or more) than the 1-g test data. The stratified models of Taitel and Dukler (1976) and Chisholm (1967) (C = 1.5) correlated best with the ground test data. For making predictions of two-phase pressure drop under microgravity conditions, the flow-regime-prediction and flow-regime-dependent models appeared essential. The homogeneous model using Beattie and Whalley (1982) appeared to correlate the pressure drop well at microgravity in the slug flow regime. An annular flow model, using an empirical interracial friction factor based on their microgravity data, was found to adequately correlate the pressure-drop data in that flow regime.

Colin et al. (1991) reported void fraction, pressure gradient, and flow pattern data for gas–liquid flow at near-zero gravity through a tube of d = 40 mm and L = 3170 mm. The researchers collected these data during a series of parabolic trajectories flown in a jet airplane that provided 15–20 s of reduced gravity at levels $<$0.03-g. The existing flow patterns for all runs were bubbly or slug flow. In order to obtain the bubble size distribution at two axial locations along the tube, they analyzed high-speed videotapes of the flow. The models used to explain the data were examined. A simple form of the drift-flux relationship could be used to predict the cross-sectional average void fraction for bubbly and slug flow near transition. The wall friction could be reasonably estimated using a homogeneous model having the viscosity of the liquid and the mixture density computed from the average void fraction for bubbly or slug flow near transition.

Sridhar et al. (1992) described the prediction of frictional pressure drop in fully developed, turbulent, annular liquid–vapor flows in zero gravity using simulation experiments conducted on Earth. The scheme extended their earlier work on dispersed flows (Sridhar et al., 1990). The simulation experiments used two immiscible liquids of identical density, namely, water and n-butyl benzoate. The proposed scheme resorted to existing semi-empirical correlations because of the lack of rigorous analytical models for turbulent, annular flows. The researchers presented and compared results based on two different correlations. Others might be used. They found that, for both dispersed and annular flow regimes, the predicted frictional pressure gradients in zero gravity were lower than those in normal gravity under otherwise identical conditions. They gave the physical basis for this finding.

Delil (1992) investigated experimentally and theoretically the impact of gravity on condensation pressure drops and heat transfer for an identical flow pattern, namely, annular-wavy mist, observed along almost the entire condensation length (for vapor qualities ranging from 1 down to values below 0.1), both in a low-gravity environment and in vertical downflow in a gravity field. The researcher presented in detail the results of the calculations performed: the impact of gravitation on condenser pressure drop and full condensation length for two different working fluids (ammonia and R114), and different duct diameters and thermal loading conditions (the power transported and the operating and sink temperatures).

Zhao and Rezkallah (1993) obtained experimental data for two-phase flow pressure drop at microgravity conditions aboard the NASA KC-135 aircraft. Air and water were used as the working fluids. The researchers reported the data for frothy slug/annular (a transition from slug-to-annular) and annular flow patterns. They found that the homogeneous model generally under-predicted the pressure drop at microgravity conditions. Also, they compared the data against the Lockhart and Martinelli (1949) correlation. The researchers found a constant $C = 20$ in the Lockhart and Martinelli (1949) correlation to correlate the experimental data very well. For frothy slug/annular flow ($1 < \mathrm{We}_g < 20$), a simple correlation between the two-phase multiplier and the mass quality could predict the pressure drop quite accurately. Their correlation was

$$\phi_l^2 = 260x^{1/4} \tag{1}$$

Kamp et al. (1993) studied the effect of gravity upon void and velocity distributions for bubbly air–water two-phase flow in a pipe of $d = 40$ mm. The researchers assumed that the local velocity distribution could be represented as follows:

$$u_m = u_o \left[1 - \left(\frac{r}{R}\right)^m\right] \tag{2}$$

Using a least-squares fit, they found the index in the local velocity distribution $(m) = 9$ for the test corresponding to the liquid superficial velocity of 0.77 m/s and the gas superficial velocity of 0.044 m/s for air–water two-phase flow in a pipe of $d = 40$ mm ($\mathrm{Re}_{tp} \approx 3{,}000$).

Fujii and Nakazawa (1993) presented a preliminary work toward establishing an accurate correlation for the prediction of gas–liquid two-phase pressure drop under microgravity conditions. This study was concerned with the results of comparison of a few pressure-drop data sets that was made public, i.e., the data obtained by Sundstrand Corporation and by Texas A&M University. The researchers evaluated these comparisons using the two-phase frictional multiplier for the gas phase (ϕ_g^2). Consequently, they found that the experiment under microgravity increased consistently by increasing the Lockhart-Martinelli parameter (X). However, the tendency seemed to be given by a straight line that was different from the shape of the curves of the conventional correlations.

Miller et al. (1993) presented pressure-drop data for microgravity two-phase flow of R-12 in smooth tubes of $d = 0.18$ and 0.41 in (4.6 and 10.5 mm). The researchers obtained the data in an experiment that was flown aboard the NASA KC-135 reduced-gravity aircraft. They obtained pressure-drop measurements for mass flow rates between 47.6 and 476 lb_m/h (0.006 and 0.060 kg/s), and mass qualities over nearly the full two-phase range. They compared their pressure-drop measurements with gravity-insensitive predictions and other reduced-gravity data available in the literature. Also, correlations of the data using the methods of the two-phase frictional multiplier and the interfacial friction factor ratio were explored. A recommendation was made for the pressure-drop predictions that should be used for microgravity two-phase flow in smooth tubes.

Bousman and Dukler (1993) developed a two-phase gas–liquid flow experiment of $d = 12.7$ mm with the NASA Lewis Research Center to study two-phase flows in microgravity. In their experiment, they measured the void fraction, pressure drop, film thickness, and bubble and wave velocities, including high-speed photography. The researchers used three liquids to study the effects of liquid viscosity and surface tension, and presented flow pattern maps for every liquid. These liquids were water, 50–50 wt% water–glycerine, and water with 0.5 wt% Dupont Zonyl FSP fluorosurfactant. These liquids were made conductive for the film thickness and void fraction measurements by the addition of a small amount of NaCl. They used the experimental results to develop mechanistically based models in order to predict the void fraction, bubble velocity, pressure drop, and flow pattern in microgravity.

Ungar et al. (1994) presented the first two-phase pressure-drop data for lunar (0.17 Earth-normal gravity) and Martian (0.38 Earth-normal gravity) gravity conditions for flow of R-12 in horizontal smooth tubes of $d = 0.18$ and 0.41 in (4.6 and 10.5 mm). The researchers obtained the data in an experiment flown aboard the NASA KC-135 reduced-gravity aircraft. They obtained pressure-drop measurements for mass flow rates between 0.005 and 0.05 kg/s (40 and 400 lb_m/h), and mass qualities over nearly the full two-phase range. Flow regime observations were made for the data points as well. Their pressure-drop measurements were compared with commonly used prediction models available in the literature. An interfacial friction factor ratio was calculated for the stratified flow regime data, and the most accurate value for predicting the pressure drop was recommended. A second annular flow interfacial friction factor ratio was investigated as a key parameter for predicting the pressure drop for the eccentric annular and annular flow data. A relationship to predict the friction factor ratio for eccentric annular flow was developed. A recommendation was made for the best prediction methods to be used to predict annular flow pressure drops.

Reinarts et al. (1995) presented the results of a two-phase flow pressure-drop experiment flown on the Space Shuttle. The researchers used saturated ammonia as a working fluid with the nominal saturation temperature of 301 K. The tube had a diameter of 3.34 mm. They obtained pressure-drop data for mass flow rates between 0.0011 and 0.0025 kg/s over nearly the full mass quality range. The data presented here were the first available long-term (greater than 1 min) microgravity two-phase flow pressure-drop measurements. They compared their microgravity pressure-drop data to Earth-normal gravity data obtained with the same apparatus, which were found to be in good agreement. The data were also compared to existing pressure-drop predictions, including those that had been shown to agree well with the ground-based 0-g pressure-drop data available in the literature. Reinarts et al. (1995) evaluated their data along with small-tube pressure-drop data from other research, and the limits of large-tube versus small-tube behavior were found. Standard pressure-drop predictions were identified that agreed well with the data for the small- and large-tube cases.

Fujii et al. (1995) investigated the characteristics of a gas–liquid two-phase flow under microgravity utilizing parabolic trajectory flights. The researchers carried out the experiment in a horizontal transparent acrylic resin tube of $d = 10.5$ mm and $L = 500$ mm, using GN_2 and water as the working fluid, in a range of $U_g = 0.025$–4.6 m/s and $U_l = 0.062$–0.35 m/s. They obtained the flow pattern, pressure drop, and void fraction in the microgravity experiment. They compared their results with the results in the ground test, and also with other experimental results obtained under normal gravity. As a result, the two-phase frictional multiplier (ϕ_l^2) could be expressed by the Lockhart and Martinelli (1949) correlation with $C = 16$.

Bousman and McQuillen (1995) developed a series of two-phase gas–liquid flow experiments to study annular flows in microgravity using the NASA Lewis Learjet. The researchers built a test section to measure the liquid film thickness around the perimeter of the tube permitting the three-dimensional nature of the gas–liquid interface to be observed. They used a second test section to measure the film thickness, pressure drop, and wall shear stress in annular microgravity two-phase flows. They used water, 50–50 wt% water–glycerin, and water–Zonyl FSP as three liquids to determine the effects of liquid viscosity and surface tension. The result of their study provided insight into the wave characteristics, pressure drop, and droplet entrainment in microgravity annular flows.

Colin and Fabre (1995) performed gas–liquid flow experiments in small tubes of $d = 19$, 10, and 6 mm during parabolic flights for a range of superficial liquid velocities (U_l) = 0.1–2 m/s and superficial gas velocities (U_g) = 0.05–10 m/s. The results were compared to those previously obtained by Colin et al. (1991) in a tube of $d = 40$ mm and $L = 3170$ mm. The flow patterns identified were: bubbly flow, slug flow, and a pattern halfway between slug and annular flows. The main difference between the experiments in small tubes and the previous ones concerned the transition between bubbly and slug flow, the role of coalescence, and the wall friction factor. Coalescence was shown to play a major role in the transition from bubbly to slug flow. In particular, at small Reynolds numbers coalescence seemed to be partly inhibited. Single-phase flow correlations for wall shear stress underestimated the wall friction factor in the intermediate range of Reynolds numbers between laminar and turbulent flow.

Zhao and Rezkallah (1995) reported a new set of experimental pressure-drop air–water flow data at microgravity conditions obtained aboard the NASA KC-135 aircraft. Comparisons between pressure-drop values at μ-g and 1-g vertical upward flow suggested 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 tube geometry and flow conditions that are otherwise the same. The main reason seemed 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 such as the homogeneous model, the Lockhart and Martinelli (1949) method, and the Friedel (1979) model. All models gave reasonable predictions.

Based on the experiments carried out over the past decade at microgravity conditions, Colin et al. (1996) presented an overview of their current knowledge of bubbly and slug flows. The researchers discussed the transition from bubble to slug flow, the void fraction, and the pressure drop from the data collected in the literature. The transition from bubble to slug flow might be predicted by introducing a critical void fraction that depended on the fluid properties and the pipe diameter; however, the role of coalescence that controlled this transition was not clearly understood. The void fraction might be accurately calculated using a drift-flux model: it was shown from local measurements that the drift of the gas with respect to the mixture was due to the non-uniform radial distribution of the void fraction. For bubbly flow, the pressure drop happened to be controlled by the liquid flow because the gas phase was thought to be mainly concentrated at the tube axis, and then there might be a gas-free zone near the wall. As a result, the momentum transfer at the wall might be mainly controlled by the liquid motion. The characteristic values that were used in the definition of the two-phase friction factor and that of the two-phase Reynolds number, ought to be those of the liquid phase. Based on these assumptions, Colin et al. (1996) defined the friction factor and the Reynolds number for bubbly flow using the liquid velocity and liquid properties as follows:

$$f_l = \frac{(dp/dz)_f \, d}{2\rho_l U_l^2} \tag{3}$$

$$\mathrm{Re}_l = \frac{\rho_l U_l d}{\mu_l} \tag{4}$$

They suggested that the friction factor could be given as a function of Reynolds number and the gas void fraction but they did not give a correlation between the friction factor and gas void fraction. For slug flow, their experimental results showed that the pressure drops were larger than expected. From their study, the guidelines for future research in microgravity were obtained.

Bousman et al. (1996) developed two-phase gas–liquid flow experiments for use on NASA microgravity aircraft in order to allow for high-speed measurement of the void fraction, liquid film thickness, and pressure drop as well as high-speed photography of the flow features. The researchers conducted numerous experiments to determine the influence of the liquid and gas superficial velocities, tube diameter, liquid viscosity, and surface tension on the occurrence of flow patterns in microgravity. They found that the transition from bubble to slug flow was affected by the tube diameter for air–water and by changes in the liquid viscosity and surface tension. The transition from slug to annular flow was not significantly affected by changes in tube diameter, liquid viscosity, or surface tension. Void fraction–based transition models were developed in order to predict microgravity flow patterns. Also, they evaluated Weber number–based transition models.

Ungar et al. (1998) derived a methodology for developing ground tests that mimic 0-g two-phase flow. The objective of their work was studying the 0-g behavior of two-phase flow in components (e.g., bends, valves, and fittings) so that many flight system unknowns could be eliminated at minimal cost because one of the largest unknowns hindering the development and use of two-phase ATCSs is the 0-g behavior of two-phase flow in these components. Also, the researchers addressed a sample case.

Fujii et al. (1998) studied the characteristics of gas–liquid two-phase annular flow under microgravity conditions utilizing a drop tower. The researchers carried out the experiments in a vertical transparent acrylic tube of $d = 10.5$ mm and $L = 200$ mm, using a mixture of gaseous nitrogen (GN_2) and water as the working fluid, in an annular flow region. They obtained the mean void fraction, pressure drop, and liquid film thickness under microgravity and compared the results with the results of a ground test. They found that the roughness of the liquid film surface was less and that the mean liquid film thickness became greater under microgravity than under normal gravity.

Ohta et al. (2000) conducted experiments onboard aircraft in order to clarify the fundamentals of the gravity effect on behavior in gas–liquid two-phase flow. Annular flow of air–water mixture was realized independent of the gravity level varying along a parabolic trajectory. The researchers systematically clarified the gravity effect on the pressure drop for vertical upward flow in a tube for different combinations of liquid and gas flow rates. They found that the pressure drop became low when the gravity was reduced, and the gravity effect decreased with the increase of the gas or liquid flow rate. The gravity effect corresponded to the change of interfacial shear stress on the surface of annular liquid film. Ohta et al. (2000) introduced a method to correlate the gravity effect on interfacial friction factor with direct influence on the pressure drop.

deJong and Rezkallah (2000) presented a dimensional analysis to study the pressure-drop and film characteristics for two-phase annular flow at microgravity conditions. The researchers correlated the two-phase pressure drop in terms of the superficial liquid Euler number (Eu_l). They based their correlation on a dimensional analysis approach. Their correlation was

$$\mathrm{Eu}_l = \left[\frac{(dp/dz)_f\, d}{\rho U_l^2}\right] = C_l \mathrm{Re}_l^{-0.33} \left(\frac{x}{1-x}\right)^{0.8} \left(\frac{\rho_g}{\rho_l}\right)^{0.5} \left(\frac{\mu_g}{\mu_l}\right)^{-0.1} \tag{5}$$

From Eq. (5), it is clear that the mass quality ratio term $x/(1-x)$ has a direct relationship with the superficial liquid Euler number (Eu_l). Modifying (Eu_l) by dividing it with $[x/(1-x)]^{0.8}$ enabled the researchers to plot the relationship between the modified (Eu_l) and (Re_l). As (Re_l) increases, the effect reduces the Euler number. This relationship is of the power-law type.

Zhao et al. (2001) studied the pressure drop of two-phase gas–liquid flow at microgravity conditions. The researchers compared the measured pressure drops with some commonly used correlations in the literature such as the homogenous model, the Lockhart and Martinelli (1949) correlation, and the Friedel (1979) model. They found that much large differences existed between the experimental data and the predictions. Among these models, the Friedel (1979) model provided relatively good agreement with the experimental data. Zhao et al. (2001) recommended that a more accurate model should be developed based on a more physical analysis of the flow characteristics and a large empirical database be developed with the aid of numerous meticulous experiments both in normal and reduced gravity.

Zhao et al. (2002) reported a new set of experimental pressure-drop data, collected aboard the Russian IL-76MDK, for bubbly air–water two-phase flow in a square channel with a cross-sectional area of 12×12 mm^2. The researchers compared their data to several frequently used empirical models, such as the homogeneous model, the Lockhart-Martinelli-Chisholm (Chisholm, 1967) correlation, and the Friedel (1979) model. They showed that the predictions of the aforementioned models were generally not satisfied. Zhao et al. (2002) mentioned the liquid averaged velocity, U_l, could not be a good representative of the characteristics of the distribution of the local liquid velocity in bubbly two-phase flows both in terrestrial and space environments as suggested by Colin et al. (1996). It was believed that there was no slip between the local velocities of the two phases in bubbly flows at microgravity. The mixture velocity, U_m, would be a better expression for the actual flow of both the liquid and gas phases. Due to the discrepancy between the local velocity distribution and the local void fraction distribution, the mixture velocity was not equal to the liquid-averaged velocity. As a result, the two-phase friction factor and the two-phase Reynolds number ought to be defined as follows:

$$f_{tp} = \frac{(dp/dz)_f\, d}{2\rho_l U_m^2} \tag{6}$$

$$\mathrm{Re}_{tp} = \frac{\rho_l U_m d}{\mu_l} \tag{7}$$

$$U_m = U_l + U_g \tag{8}$$

Based on this analysis of the characteristics of bubbly two-phase flow at reduced gravity, Zhao et al. (2002) developed a new homogeneous model. Their new model was

$$f_{tp} = a\mathrm{Re}_{tp}^{-1} \tag{9}$$

$$a = \frac{4n\,(m+2)}{m} \tag{10}$$

where m is the index in the local velocity distribution determined by Kamp et al. (1993), while n is the index in the local velocity distribution near the wall. Indices m and n and parameter a are generally all dependent on the Reynolds number and other factors. However, for some ranges of the Reynolds number in which the flow is self-preservative, these indexes might be constants. For instance, in fully developed single-phase laminar pipe flows, there is an exactly analytical solution that gives $m = n = 2$ and $a = 16$. In turbulent and/or two-phase flows, there is generally no analytical solution for the velocity distribution; thus, parameter a might be determined empirically. Zhao et al. (2002) found that Eq. (9) with $a = 35$ represented well the Bousman (1994) data in circular pipes for the case of low Reynolds numbers, while Eq. (9) with $a = 120$ represented well their data of the pressure drop for bubbly two-phase flow in a square channel at low gravity and those collected by Zhao and Rezkallah (1993) and Bousman (1994) in circular pipes for the case of large Reynolds numbers. It was shown that there might be a transition of flow structure in the range of $3000 < \mathrm{Re}_{tp} < 4000$, similar to the laminar/turbulent transition in the single-phase flow. However, the friction factor of bubbly two-phase flow in the case of low Reynolds numbers was more than two times that in laminar single-phase flow, while in the case of large Reynolds numbers it was 7.5 times that in laminar single-phase flow. The most obvious difference between the single- and two-phase flows was the Reynolds number's index in the case of large Reynolds numbers, namely, –0.25 for single-phase flow according to the Blasius (1913) relationship and –1 for two-phase flow in this study; however, the reason for this is unknown.

Choi et al. (2002) conducted an experiment aboard the MU-300 aircraft, as well as at normal gravity using the same horizontal tube of $d = 10$ mm and flow conditions. The researchers com-pared the experimental results, obtained under Earth-gravity, hypergravity (2-g), and microgravity environments, with previous models. They compared flow pattern data with data from models for predicting microgravity flow pattern transitions. Also, they compared the mean void fraction under μ-g and 1-g conditions with the Inoue and Aoki model for vertical upward annular flow at normal gravity (Akagawa, 1974). Choi et al. (2002) found that the frictional pressure drop fitted well with the Lockhart and Martinelli (1949) model, and was slightly influenced by the change in gravity levels (microgravity, normal gravity, and hypergravity). However, the effect of changing gravity on the pressure drop was insignificant for turbulent flow.

Choi et al. (2003) obtained data of the flow patterns, void fraction, and frictional pressure drop associated with its characteristics at normal gravity and under microgravity and hypergravity conditions aboard the MU-300 aircraft, which is capable of parabolic trajectory flying. The researchers performed some experiments for an air–water two-phase flow through a 10-mm-diameter adiabatic test section with a 600-mm-long transparent acrylic resin horizontal tube. Choi et al. (2003) compared the results obtained at the three gravity levels (microgravity, normal gravity, and hypergravity) with some of the existing flow pattern transitions, void fraction and frictional pressure-drop models, and correlations. The gravity dependency of flow patterns was more clearly apparent with the decrease in gas and liquid flow rates. The gravity effect on two-phase flow was insignificant in the turbulent flow regions.

Takamasa and Hibiki (2003) presented in their report outlines of the recent progress in studies of gas–liquid two-phase flows at microgravity conditions, especially regarding interfacial area transport and drift flux. The researchers expected that research on two-phase at micro- or reduced-gravity conditions to be conducted more widely in the future, shedding light on two-phase flow phenomena for in space use. In the future studies, extensive experimental works on accurate measurements of local flow parameters should be addressed in order to evaluate the newly developed drift-flux model.

Braisted et al. (2004) followed a two-phase experiment to expand the two-phase database. The researchers created a model of the experiment in the software to determine how well the software could predict the pressure drop observed in the experiment. Of the simulations conducted, the computer model showed good agreement with the pressure drop in their experiment to within 30%. However, the software did begin to over-predict the pressure drop in certain regions of a flow regime map, indicating that some models used in the software package for reduced-gravity modeling needed improvement.

Hurlbert et al. (2004) presented hydrodynamic measurements for two-phase flows in Mars and Moon gravity conditions. High-accuracy pressure-drop and flow rate data were obtained using dichlorodifluoromethane (i.e., R-12) as the working fluid flowing in a nominally 11.1 mm inner diameter tube. The measurements were made at Mars gravity (∼0.38-g) and Moon gravity (∼0.17-g) using NASA's KC-135 aircraft. A simplified scaling approach was developed using dimensional analysis, which can be used to design an Earth-based test bed to simulate a Mars or Moon gravity prototype. For a specific geometry, selected working fluid at a fixed temperature and pressure, and particular flow regime condition, the pressure-drop functional scaling equation is a simple, power-law relationship for the Euler number as a function of only the Froude number. The completed research supports the use of Earth-g tests to predict the behavior of two-phase systems for Moon-g and Mars-g applications.

MacGillivray (2004) examined the influence of the gas density and gravitational acceleration on the annular flow average film thickness and frictional pressure drop. The researcher measured the film thickness using two-wire conductance probes. Experimental data were collected in normal gravity at the University of Saskatchewan, while microgravity and hypergravity data were collected aboard the Novespace Zero-G Airbus microgravity simulator. MacGillivray (2004) collected data for a range of annular flow set points by changing the liquid and gas mass flow rates. The liquid-to-gas density ratio (ρ_l/ρ_g) was examined by collecting annular flow data using helium–water and air–water as the working fluids. The gravitational effect on the film thickness characteristics was examined by collecting the data during the microgravity and pull-up (hypergravity) portions of every parabolic flight.

Because of the matching of the liquid and gas mass flow rates and the flow regime, a direct comparison was possible between the normal gravity data and the microgravity data. The reduction in gravity caused the average film thickness to increase between two and four times from the normal gravity values. The microgravity average frictional pressure drop was within approximately 20% of the normal gravity pressure drop for the same flow conditions. For all gravity levels (normal gravity, microgravity, and hypergravity), the helium–water and the air–water flows gave similar results for both the average film thickness and frictional pressure drop when based on the specific energy of the gas.

The hypergravity average film thickness results were larger than at normal gravity for the same flow conditions. However, no flow regime map existed for the hypergravity condition, thus the similarity of the flow regime could not be confirmed. The hypergravity flow appeared more chaotic, and might be in transition from a churn-type flow. The average frictional pressure drop was increased by ∼20% due to the increase in the gravitational acceleration.

New non-dimensional equations that include the influence of the gas density (helium and air) are presented for all three gravity levels (normal gravity, microgravity, and hypergravity) to predict the average film thickness and the average frictional pressure drop. The equation of the average film thickness is

$$\frac{\rho_l U_l \delta}{\mu_l} = a_1 \mathrm{Re}_l^{m_1} \left(\frac{1-x}{x}\right)^{m_2} \left(\frac{\rho_g}{\rho_l}\right)^{m_3} \tag{11}$$

where the values of a_1, m_1, m_2, and m_3 are given in Table 1 for the different gravity levels.

It should be noted that Eq. (11) does not directly convey the dependence on the gas and liquid flow rates although it accurately represents the experimental data. The film thickness is mainly dependent on the superficial liquid Reynolds number (Re_l) and the gas specific energy, which can be represented in non-dimensional form as the gas Weber number (We_g). As a result, the equation of the average film thickness can also be represented as follows:

$$\frac{\rho_l U_l \delta}{\mu_l} = a_2 \mathrm{Re}_l^{m_4} \mathrm{We}_g^{m_5} \tag{12}$$

where the values of a_2, m_4, and m_5 are given in Table 2 for the different gravity levels.

TABLE 1: Summary of average film thickness based on Eq. (11)

Gravity level	a_1	m_1	m_2	m_3	**Data scatter (%)**
Normal	39	0.2	1.0	0.5	±10
Microgravity	0.23	0.9	0.4	0.2	±10
Hypergravity	0.41	0.8	0.5	0.2	±15

TABLE 2: Summary of average film thickness based on Eq. (12)

Gravity level	a_2	m_4	m_5	**Data scatter (%)**
Normal	0.047	1.2	–0.5	±10
Microgravity	0.016	1.3	–0.2	±10
Hypergravity	0.025	1.3	–0.3	±15

The equation of the average frictional pressure gradient is

$$\frac{(dp/dz)_f\, d}{\rho_l U_l^2} = b_1 \mathrm{Re}_l^{n_1} \left(\frac{x}{1-x}\right)^{n_2} \left(\frac{\rho_l}{\rho_g}\right)^{n_3} \tag{13}$$

where the values of b_1, n_1, n_2, and n_3 are given in Table 3 for the different gravity levels.

Marsden et al. (2005) used a two-phase flow test loop with R-12 as the working fluid to produce and collect pressure-drop data from corrugated tubes and quick-disconnect components and develop correlations and prediction methods for two-phase pressure drops in normal and reduced gravity. They found that it was possible to predict the 0-g pressure drops through the corrugated tubes using the homogeneous equilibrium model and single-phase ground-based pressure-drop measurements. Also, it was found that prediction of the pressure drop through the quick-disconnect attachment could be obtained using the homogeneous equilibrium model (with single-phase ground-based measurements) coupled with an orifice pressure-drop model. The use of single-phase ground-based experiments to predict two-phase reduced-gravity component performance could yield significant cost savings and increased reliability of reduced-gravity fluid systems.

Ishii et al. (2005) presented the results from an experimental investigation of interfacial structures in two-phase flow under simulated microgravity conditions. The researchers performed experiments in a ground-based facility wherein microgravity was simulated using two immiscible liquids of similar density. They discussed the justification for such an approach along with the selection of appropriate working fluids and some important features of the test facility. At the same time, experiments were carried out in bubbly flow and bubbly-to-slug flow transition regions. Based on visual observations, Ishii et al. (2005) presented a flow regime map, and compared the results with those available in the literature. Also, they presented local two-phase flow parameters for two flow conditions.

Hibiki et al. (2006) studied in detail a 1D drift-flux model at reduced-gravity conditions. A constitutive equation of the distribution parameter for bubbly flow, which took into account the gravity effect, was proposed and constitutive equations for slug, churn, and annular flows that could be applicable to reduced-gravity conditions were recommended based on existing experimental and analytical studies. The previously derived constitutive equations of the drift velocity in different two-phase flow regimes, which took into account the frictional pressure loss, were adopted in this study. A comparison of the model with different experimental data over different flow regimes and a wide range of flow parameters taken at microgravity conditions showed satisfactory agreement. The researchers applied the drift-flux model to reduced-gravity conditions such as 1.62 and 3.71 m/s^2, which corresponded to lunar and Martian surface gravities, respectively, and the effect of the gravity on the void fraction in two-phase flow systems was discussed.

Zhao (2010) conducted research on two-phase flow and pool boiling heat transfer in microgravity that included ground-based tests, flight experiments, and theoretical analyses at the National Microgravity Laboratory, Chinese Academy of Sciences (Beijing). The researcher proposed a Weber number model to predict the slug-to-annular flow transition of two-phase gas–liquid flows in microgravity, while the initial bubble size effect on the bubble-to-slug flow transition was investigated numerically using the Monte Carlo method. Zhao (2010) obtained two-phase flow pattern

TABLE 3: Summary of average frictional pressure gradient based on Eq. (13)

Gravity level	b_1	n_1	n_2	n_3	**Data scatter (%)**
Normal	1.2	–0.2	1.0	0.6	±10
Microgravity	0.96	–0.1	1.3	0.6	±10
Hypergravity	1.75	–0.2	1.2	0.6	±15

maps in microgravity in the experiments both aboard the Russian Space Station Mir and aboard the IL-76 reduced-gravity airplane. Also, he used mini-scale modeling to simulate the behavior of microgravity two-phase flow on the ground and experimentally measured two-phase pressure drops in microgravity, which correlated successfully based on its characteristics. Two space experiments on pool boiling phenomena in microgravity were performed aboard the Chinese recoverable satellites. Steady pool boiling of R113 on a thin wire with a temperature-controlled heating method was studied aboard RS-22, while quasi-steady pool boiling of FC-72 on a plate was studied aboard SJ-8. In addition, ground-based experiments were performed both in normal gravity and in short-term microgravity in the drop tower in Beijing. Only slight enhancement of heat transfer was observed in the wire case, while enhancement in the low-heat flux and deterioration in the high-heat flux were observed in the plate case. Lateral motions of vapor bubbles were observed before their departure in microgravity. The relationship between bubble behavior and heat transfer on the plate was analyzed. Also, a model was proposed for predicting the bubble departure diameter during pool boiling on wires. Table 4 presents a summary of the aforementioned previous studies.

TABLE 4: Summary of previous studies

Reference	*d* (mm)	Fluid	Orientation/ condition	Range/ applicability	Technique, basis, observation
Papell (1962)		subcooled water			Studying the instability effect for two-phase heat transfer for subcooled water flowing under conditions of zero gravity.
Evans (1963)	12.7	Air–water		Bubbly flow and slug flow	Visual study of swirling and nonswirling two-phase two-component flow at one and zero gravity.
Albers and Macosko (1965)		Mercury	Horizontal		Experimental pressure-drop investigation of nonwetting condensing flow of mercury vapor in a constant diameter tube in 1-g and 0-g environments.
Albers and Macosko (1966)		Mercury	Horizontal		Study of condensation pressure drop of nonwetting mercury in a uniformly tapered tube in 1-g and 0-g environments.
Block et al. (1967)	6.858 –12.446	Mercury			Photographic study of condensing mercury flow in 0-g and 1-g environments.
Keshock (1975)	3	R12	Horizontal		Presenting experimental and analytical investigation of 0-g condensation in a mechanical refrigeration system application.
Heppner et al. (1975)	25.4	Air–water	Horizontal		The pressure drop at normal gravity with was lower than that at microgravity.
Hill et al. (1987)		R114	Horizontal	Reduced-gravity, 1-g, and nearly 2-g accelerations	Study of two-phase flow in a reduced-gravity environment.

TABLE 4: (Continued)

Reference	*d* (mm)	Fluid	Orientation/ condition	Range/ applicability	Technique, basis, observation
Hill et al. (1988)		R114	Horizontal	x = 5–80%, gravitational acceleration ranging from near-zero to 1.8-g	Two-phase flow pressure drops could be predicted with reasonable accuracy for systems that would operate in reduced gravity by using either the existing HTRI method or the Friedel (1979) correlation.
Chen et al. (1988)	15.8	R114	Horizontal		Only slug flow and annular flow were observed in the microgravity testing.
Dukler et al. (1988)	9.5 and 12.5	Air–water		Re_l = 1,000–12,000 and Re_g = 100–23,000	Three flow patterns existed: bubbly flow at low gas flow rates, slug flow for moderate gas and liquid flow rates, and annular flow for high gas flow rate.
Wang et al. (1990)		Two immiscible liquids of nearly equal densities		Bubble flow and annular flow	Presenting experimental simulation and analytical modeling of two-phase flow.
Sridhar et al. (1990)		Two immiscible liquids of identical density, namely, water and n-butyl benzoate		Dispersed flow	Studying the pressure drop in fully developed, duct flow of dispersed liquid–vapor mixture.
Chen et al. (1991)	15.8	R114	Horizontal	x = 5–90% and U_l = 0.02–0.16 m/s	Slug flow was observed for x = 5–10%, and annular flow was observed for x = 15–90%. Different two-phase pressure-drop models for the 1-g condition were compared with their test data.
Colin et al. (1991)	40			Dispersed bubble flow and slug flow	They reported void fraction, pressure gradient and flow pattern data.
Sridhar et al. (1992)		Two immiscible liquids of identical density, namely, water and n-butyl benzoate		Annular flow	The predicted frictional pressure gradients in 0-g were lower than those in l-g.
Delil (1992)		Ammonia and R114	Vertical downflow	Annular-wavy mist	Studying experimentally and theoretically the gravity effect on condensation pressure drops and heat transfer.

TABLE 4: (Continued)

Reference	*d* (mm)	Fluid	Orientation/ condition	Range/ applicability	Technique, basis, observation
Colin and Fabre (1995)	19, 10, and 6			$U_l = 0.1–2$ m/s and $U_g = 0.05–10$ m/s	The flow patterns identified were: bubbly flow, slug flow, and a pattern halfway between slug and annular flows.
Zhao and Rezkallah (1995)		Air–water	Vertical upward		The experimental data were compared with several widely used empirical models such as homogeneous model, Lockhart and Martinelli (1949) method, and Friedel (1979) model.
Bousman et al. (1996)		Air–water			Studying the effects of tube diameter, liquid viscosity, and surface tension on gas–liquid flow patterns in microgravity.
Fujii et al. (1998)	10.5	N_2–water	Vertical upward	Annular flow region	They obtained the mean void fraction, pressure drop, and liquid film thickness under microgravity.
Ohta et al. (2000)	8	Air–water	Vertical upward	Annular flow region	They found that pressure drop became low when gravity was reduced, and the gravity effect decreased with the increase of gas or liquid flow rate.
deJong and Rezkallah (2000)				Annular flow	Presenting a dimensional analysis to study the pressure-drop and film characteristics for two-phase annular flow at microgravity conditions.
Zhao et al. (2002)	12	Air–water		Bubble flow	Studying the pressure drop of bubbly two-phase flow in a square channel at reduced gravity (aboard the Russian IL-76MDK).
Choi et al. (2002)	10		Horizontal		The frictional pressure drop fitted well with the Lockhart and Martinelli (1949) model, slightly influenced by the change in gravity levels (μg, $1g$, and $2g$).

TABLE 4: (Continued)

Reference	***d* (mm)**	**Fluid**	**Orientation/ condition**	**Range/ applicability**	**Technique, basis, observation**
Choi et al. (2003)	10	Air–water	Horizontal		Obtaining the data of flow patterns, void fraction, and frictional pressure drop associated with its characteristics at normal gravity (1-g) and in microgravity (μ-g) and hypergravity (2-g) conditions aboard MU-300 aircraft capable of parabolic trajectory flying.
Hurlbert et al. (2004)	11.1	R12		Mars gravity, approximately 0.38-g, and Moon gravity, approximately 0.17-g	Scaling two-phase flows to Mars and Moon gravity conditions.
MacGillivray (2004)		Helium–water Air–water		Annular flow	Studying the gravity and gas density effects on annular flow average film thickness and frictional pressure drop.
Marsden et al. (2005)		R12			Collecting pressure-drop data from the corrugated tubes and quick-disconnect components and developing correlations and prediction methods for two-phase pressure drops in normal and reduced gravity.
Ishii et al. (2005)		Two immiscible liquids of similar density		Bubbly flow and bubbly to slug flow transition region	Study of two-phase flow in simulated microgravity condition.
Hibiki et al. (2006)				Lunar surface gravity (1.62 m/s^2) and Martian surface gravity (3.71 m/s^2)	Studying 1D drift-flux model at reduced-gravity conditions.
Zhao (2010)		R113 and FC-72			Studying two-phase flow and pool boiling heat transfer in microgravity.

3. PROPOSED METHODOLOGY

Although there have been extensive studies on this problem, there is still a need for a simple solution method that will give very accurate solutions. The objective of this work is to introduce an asymptotic solution method that provides accurate solutions over the entire range of mass quality from 0 to 1. This solution method can be applied as well to other two-phase flow problems.

Asymptotes appear in many engineering problems such as steady and unsteady internal and external conduction, free and forced internal and external convection, fluid flow, and mass transfer. Often, there exists a smooth transition between two asymptotic solutions (Churchill and Usagi, 1972; Churchill, 1988; Kraus and Bar-Cohen, 1983;

Yovanovich, 2003). This smooth transition indicates that there is no sudden change in slope and no discontinuity within the transition region.

The asymptotic analysis method was first introduced by Churchill and Usagi (1972). Over time, this method of combining asymptotic solutions proved quite to be successful in developing models in many applications. Recently, it has been applied to two-phase flow in circular pipes (Awad, 2007; Muzychka and Awad, 2010), minichannels (Awad, 2007; Muzychka and Awad, 2010; Awad and Muzychka, 2010), and microchannels (Awad, 2007; Muzychka and Awad; 2010, Awad and Muzychka; 2010). Moreover, Awad and Butt (2009a,b,c) have shown that the asymptotic method works well in petroleum industry applications for flows through porous media, liquid-liquid flows, and flows through fractured media.

The asymptotic modeling method in two-phase flow has many advantages over the separated flow models such as the Lockhart and Martinelli (1949) method and separate cylinders model (Turner, 1966) for two-phase flow. First, it takes into account the important frictional interactions that occur at the interface between liquid and gas because the liquid and gas phases are assumed to flow in the same pipe while the separate cylinders model for two-phase flow does not take into account the important frictional interactions that occur at the interface between liquid and gas. Therefore, it would simply neglect the nature of two-phase flow because the liquid and gas phases are assumed to flow independently of each other in two separate parallel circular cylinders. Second, the value of the Reynolds number for the liquid and gas phases is not important because the expressions based on the asymptotic modeling method in two-phase flow are valid for any value of the Reynolds number in the liquid and gas phases. On the other hand, these Re_l and Re_g values determine the flow condition, and hence a suitable expression for this flow condition in the Lockhart and Martinelli (1949) method. For example, Chisholm constant $(C) = 20$, 12, 10, and 5 for turbulent liquid/turbulent gas, laminar liquid/turbulent gas, turbulent liquid/laminar gas, and laminar liquid/laminar gas, respectively (Chisholm, 1967). Third, the asymptotic modeling method in two-phase flow can be applied when the gas is turbulent and the liquid is laminar or turbulent, such as in the Fujii et al. (1998) data where Re_l =430–5800. On the other hand, the Fujii et al. (1998) data should be treated separately when using the Lockhart and Martinelli (1949) method because $C = 20$ for turbulent liquid-turbulent gas and $C = 12$ for laminar liquid/turbulent gas. Fourth, the expressions obtained using the asymptotic modeling method in two-phase flow are explicit for any flow condition while the expressions obtained using the separate cylinders model for two-phase flow are implicit for laminar liquid/turbulent gas and turbulent liquid/laminar gas (Awad, 2007).

Using the asymptotic analysis method, two-phase frictional pressure gradient $(dp/dz)_f$ can be expressed alone as follows in terms of single-phase frictional pressure gradient for liquid flowing $(dp/dz)_{f,l}$ and single-phase frictional pressure gradient for gas flowing alone $(dp/dz)_{f,g}$:

$$\left(\frac{dp}{dz}\right)_f = \left[\left(\frac{dp}{dz}\right)_{f,l}^p + \left(\frac{dp}{dz}\right)_{f,g}^p\right]^{1/p} \tag{14}$$

Equation (14) reduces to $(dp/dz)_{f,l}$ and $(dp/dz)_{f,g}$ as $x = 0$ and 1, respectively.

If two-phase frictional pressure gradient $(dp/dz)_f$ is presented in terms of the single-phase frictional pressure gradient for liquid flowing alone, $(dp/dz)_{f,l}$, then the model can be expressed using the Lockhart-Martinelli parameter $(X) = \left[(dp/dz)_{f,l} \big/ (dp/dz)_{f,g}\right]^{0.5}$ as follows:

$$\left(\frac{dp}{dz}\right)_f = \left(\frac{dp}{dz}\right)_{f,l}\left[1 + \left(\frac{1}{X^2}\right)^p\right]^{1/p} \tag{15}$$

Equation (15) can be expressed in terms of a two-phase frictional multiplier liquid flowing alone (ϕ_l^2) as follows:

$$\phi_l^2 = \left[1 + \left(\frac{1}{X^2}\right)^p\right]^{1/p} \tag{16}$$

On the other hand, if two-phase frictional pressure gradient $(dp/dz)_f$ is presented in terms of the single-phase frictional pressure gradient for gas flowing alone, $(dp/dz)_{f,g}$, then the model can be expressed using the Lockhart-

Martinelli parameter (X) as follows:

$$\left(\frac{dp}{dz}\right)_f = \left(\frac{dp}{dz}\right)_{f,g} \left[1 + \left(X^2\right)^p\right]^{1/p} \tag{17}$$

Equation (17) can be expressed in terms of a two-phase frictional multiplier for gas flowing alone (ϕ_g^2) as follows:

$$\phi_g^2 = [1 + (X^2)^p]^{1/p} \tag{18}$$

The fitting parameter (p) may be affected by many parameters such as the pipe diameter; the superficial velocity of the liquid and gas phases; the physical properties of the liquid and gas phases, such as the density and dynamic viscosity; and the magnitude of gravity. In this method, p is chosen as the value that minimizes the root-mean-square (RMS) error, e_{RMS}, between the model predictions and the available data. The fractional error (e) in applying the model to each available data point is defined as

$$e = \left|\frac{\text{Predicted–Available}}{\text{Available}}\right| \tag{19}$$

For groups of data, e_{RMS} is defined as

$$e_{\mathrm{RMS}} = \left[\frac{1}{N}\sum_{K=1}^{N} e_K^2\right]^{1/2} \tag{20}$$

4. RESULTS AND DISCUSSION

Examples of the two-phase frictional pressure gradient at microgravity conditions for published data of different working fluids with different diameters are presented here to show features of the asymptotes, asymptotic analysis, and development of simple compact models.

Figure 1 shows ϕ_l versus the Lockhart-Martinelli parameter (X) for the Zhao and Rezkallah (1993) data for two-phase turbulent/turbulent flow at microgravity conditions using air–water in a 9.525 mm inside diameter tube. Equation (16) represents the present asymptotic model. It can be seen that the present model with fitting parameter, $p = 1/4$ represents the Zhao and Rezkallah (1993) data in a successful manner. The RMS error is equal to 17.91%. The comparison of the Lockhart and Martinelli (1949) model using the classical Chisholm (1967) relationship ($C = 20$)

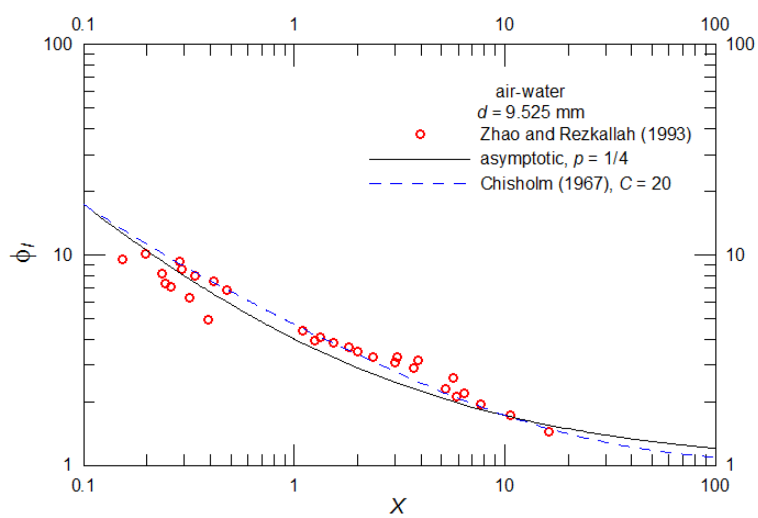

FIG. 1: Parameter ϕ_l versus X for the Zhao and Rezkallah (1993) data.

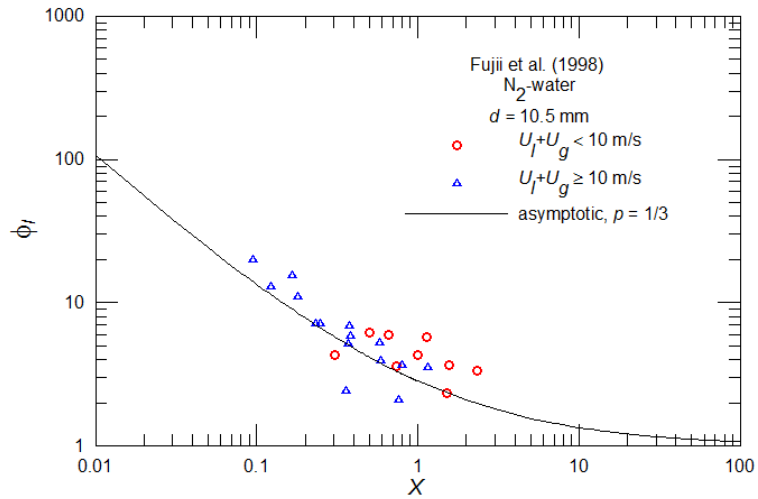

FIG. 2: Parameter ϕ_l versus X for the Fujii et al. (1998) data.

with the experimental data of Zhao and Rezkallah (1993) is also shown in Fig. 1. The RMS error is equal to 19.04% using the Lockhart and Martinelli (1949) model and the classical Chisholm (1967) relationship ($C = 20$).

Figure 2 shows ϕ_l versus the Lockhart-Martinelli parameter (X) for the Fujii et al. (1998) data for two-phase vertical upward flow at microgravity conditions using N_2–water in a 10.5 mm inside diameter tube at different values of $U_l + U_g$. Equation (16) represents the present asymptotic model. It can be seen that the present model with fitting parameter, $p = 1/3$ represents the Fujii et al. (1998) data in a successful manner. The RMS error is equal to 36.49%. If the point at $X = 0.36$ for $U_l + U_g \geq 10$ m/s is excluded, the RMS error will equal 12.60% instead of 36.49%. Here, $p = 1/3$ (not 1/4, as in Fig. 1) because the range of $\text{Re}_l = 430$–5800 (i.e., some data points are in the laminar liquid/turbulent gas region).

Figure 3 shows ϕ_l versus the Lockhart-Martinelli parameter (X) for the Ohta et al. (2000) data for two-phase vertical upward flow at microgravity conditions using air–water in a 8 mm inside diameter tube at different values of U_l. Equation (16) represents the present asymptotic model. It can be seen that the present model with fitting parameter $p = 1/4$ represents the Ohta et al. data (2000) in a successful manner. The RMS error is equal to 19.53%. A

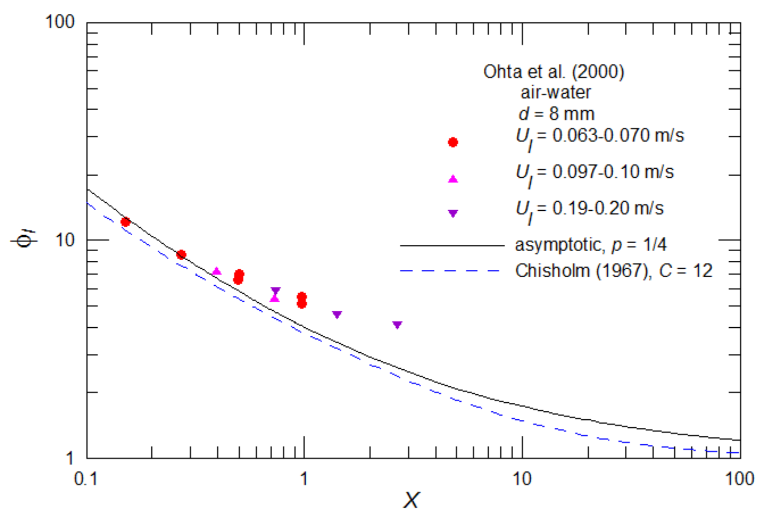

FIG. 3: Parameter ϕ_l versus X for the Ohta et al. (2000) data.

comparison of the Lockhart and Martinelli (1949) model using the classical Chisholm (1967) relationship ($C = 12$) with experimental data of Ohta et al. (2000) is also shown in Fig. 3 because $\mathrm{Re}_l < 2000$ at $U_l = 0.063$–0.070 m/s, $U_l = 0.097$–0.10 m/s, and U_l = 0.19–0.20 m/s (i.e., the laminar liquid region). The RMS error is equal to 24.59% using Lockhart and Martinelli (1949) model and the classical Chisholm (1967) relationship ($C = 12$).

It should be noted that in the case of the Fujii et al. (1998) data, $p = 1/3$ (not 1/4), while in the case of the Ohta et al. (2000) data $p = 1/4$ (not 1/3), although both sets of data were compared with the classical Chisholm (1967) relationship ($C = 12$) for the laminar liquid/turbulent gas region. This may be due to the fitting parameter being dependent on many factors such as the type of working fluid, pipe diameter, flow patterns, etc. For example, the Fujii et al. (1998) data are for two-phase vertical upward flow at microgravity conditions using N_2–water in a 10.5 mm inside diameter tube, while the Ohta et al. (2000) data are for two-phase vertical upward flow at microgravity conditions using air–water in an 8 mm inside diameter tube. On the basis of the experimental data shown in Figs. 1–3, it is clear that the experimental points set in the form of $\phi_l \to \infty$ as $X \to 0$ and $\phi_l \to 1$ as $X \to \infty$ are in line with the expected asymptotic behavior of the Lockhart and Martinelli (1949) correlation.

Figure 4 shows ϕ_g versus the Lockhart-Martinelli parameter (X) for the Chen et al. (1989) data for two-phase turbulent/turbulent horizontal flow at microgravity conditions using R114 in a 15.8 mm inside diameter tube in the annular regime. Equation (18) represents the present asymptotic model. It can be seen that the present model with fitting parameter $p = 1/4$ represents the Chen et al. (1989) data in a successful manner. The RMS error is equal to 24.40%. If the lower point of ϕ_g at $X = 1.23$ is excluded, the RMS error will be equal to 17.78% instead of 24.40%. A comparison of the Lockhart and Martinelli (1949) model using the classical Chisholm (1967) relationship ($C = 20$) with experimental data of Chen et al. (1989) is also shown in Fig. 4. The RMS error is equal to 40.49% using the Lockhart and Martinelli (1949) model and the classical Chisholm (1967) relationship ($C = 20$). If the lower point of ϕ_g at $X = 1.23$ is excluded, the RMS error will be equal to 33.04% instead of 40.49%.

Figure 5 shows ϕ_g versus the the Lockhart–Martinelli parameter (X) for the Wheeler (1992) data for two-phase turbulent/turbulent vertical upward flow at microgravity conditions using R12 in a 10.41 mm inside diameter tube in the annular regime. Equation (18) represents the present asymptotic model. It can be seen that the present model with fitting parameter $p = 1/4$ represents the Wheeler (1992) data in a successful manner. The RMS error is equal to 11.92%. If the lower point of ϕ_g at $X = 0.88$ is excluded, the RMS error will be equal to 8.36% instead of 11.92%. A comparison of the Lockhart and Martinelli (1949) model using the classical Chisholm (1967) relationship ($C = 20$) with the experimental data of Wheeler (1992) is also shown in Fig. 5. The RMS error is equal to 21.56% using the Lockhart and Martinelli (1949) model and the classical Chisholm (1967) relationship ($C = 20$). If the lower point of ϕ_g at $X = 0.88$ is excluded, the RMS error will be equal to 15.87% instead of 21.56%. On the basis of the experimental data shown in Figs. 4 and 5, it is clear that the experimental points set in the form of $\phi_g \to 1$ as $X \to 0$

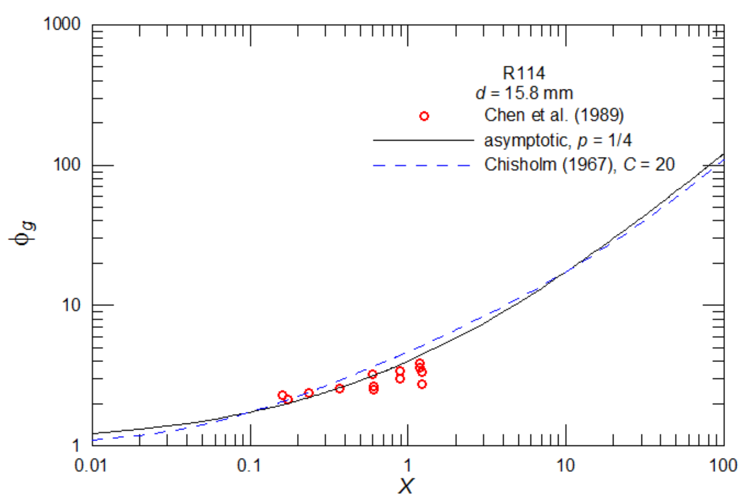

FIG. 4: Parameter ϕ_g versus X for the Chen et al. (1989) data.

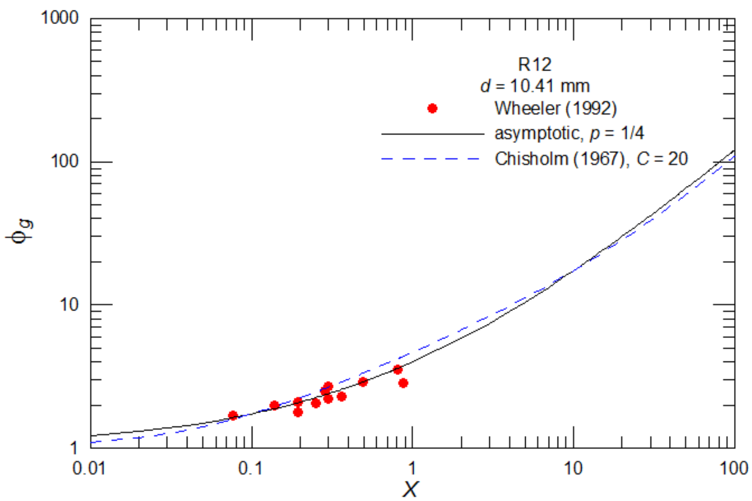

FIG. 5: Parameter ϕ_g versus X for the Wheeler (1992) data.

and $\phi_g \to \infty$ as $X \to \infty$ is in line with the expected asymptotic behavior of the Lockhart and Martinelli (1949) correlation.

Figure 6 shows ϕ_l versus the Lockhart–Martinelli parameter (X) for all data sets shown in Figs. 1–5 (Zhao and Rezkallah, 1993; Fujii et al., 1998; Ohta et al., 2000; Chen et al., 1989; Wheeler, 1992). The data in Figs. 4 and 5 are transformed using the form $\phi_l = \phi_g/X$. To have a robust model (i.e., to have one value of p for different data sets at different conditions such as the pipe diameter; the superficial velocity of the liquid and gas phases; the physical properties of the liquid and gas phases, such as the density and dynamic viscosity; and the magnitude of the gravity instead of different values of p for every data set), one value of the fitting parameter is chosen as $p = 2/7$. When $p = 2/7$, $e_{\mathrm{RMS}} = 28.31$ or 24.03% if the three points mentioned in Figs. 2, 4, and 5, respectively, are excluded.

This value of the fitting parameter, $p = 2/7$, for the microgravity data is different from $p = 4/13$ in the large diameter (macro-scale) and $p = 1/2$ in the small diameter (micro-scale) for the normal data (Awad, 2007). The reason the value of the fitting parameter, $p = 2/7$, for the microgravity data is very close to $p = 4/13$ in the large diameter

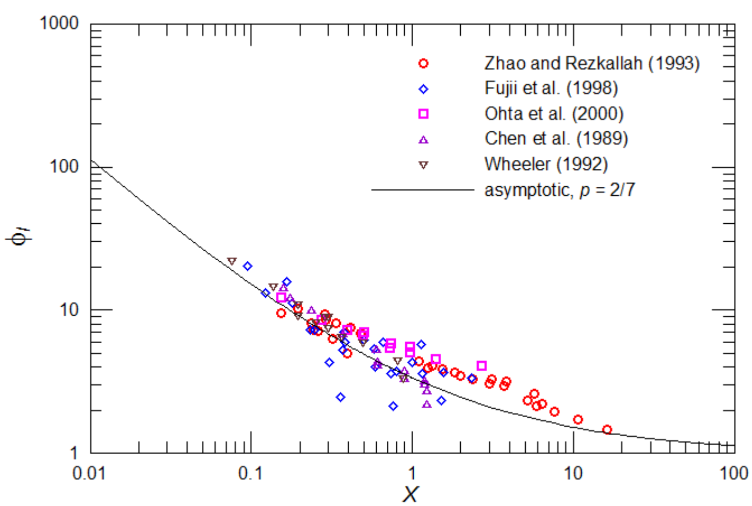

FIG. 6: Parameter ϕ_l versus X for different sets of data.

(macro-scale) for the normal data is that the magnitude of the gravity mainly affects the gravitational component of the total pressure drop. Also, there are some other reasons, such as the previously mentioned flow regions in two-phase flow in large pipes at microgravity being similar to those in large pipes (macro-scale) for the normal data but being much different from those in small pipes (micro-scale) for the normal data.

5. SUMMARY AND CONCLUSIONS

In the present study, a comprehensive review of the two-phase frictional pressure gradient at microgravity conditions and a simple method for calculating the two-phase frictional pressure gradient at microgravity conditions using asymptotic analysis are presented. The method of combining asymptotes is based on the work of Churchill and Usagi (1972). The approximate solution of combining asymptotes is concave downward. The asymptotic modeling method in two-phase flow has many advantages over the separated flow models such as the Lockhart and Martinelli (1949) method and the separate cylinders model (Turner, 1966) for two-phase flow. The only unknown parameter in the asymptotic modeling method in two-phase flow is the fitting parameter (p). The value of the fitting parameter is chosen to correspond to the minimum RMS error (e_{RMS}) for any data set. The approximate solution for this problem was shown to be very accurate for a wide range of different parameters. To have a robust model, one value of the fitting parameter is chosen as $p = 2/7$.

ACKNOWLEDGMENT

The authors acknowledge the financial support of the Natural Sciences and Engineering Research Council of Canada (NSERC) through the Discovery Grants Program.

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