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AN APPLICATION OF MINISCALE EXPERIMENTS ON EARTH TO REFINE MICROGRAVITY ANALYSIS OF ADIABATIC MULTIPHASE FLOW IN SPACE

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ABSTRACT

Adiabatic two-phase flow is of interest to the design of multiphase fluid and thermal management systems for spacecraft. This paper presents original data and unifies existing data for capillary tubes as a step toward assessing existing multiphase flow analysis and engineering software. Comparisons of theory with these data once again confirm the broad accuracy of the theory. Due to the simplicity and low cost of the capillary tube experiments, which were performed on earth, we were able to closely examine for the first time a flow situation that had not previously been examined appreciably by aircraft tests. This is the situation of a slug flow at high quality, near transition to annular flow. Our comparison of software calculations with these data revealed overprediction of pipeline pressure drop by up to a factor of three. In turn, this finding motivated a reexamination of the existing theory, and then development of a new analytical model which is at once more plausible physically and is in far better agreement with the data. This sequence of discovery illustrates the role of inexpensive miniscale modeling on earth to anticipate microgravity behavior in space and to complement and help define needs for aircraft tests.

INTRODUCTION

Rothe (1988) stated the view that steady multiphase flow in microgravity is a well-developed engineering technology. Multiphase flow in space is in fact much simpler than that on earth, thanks to the absence of the gravity body force. The means of engineering analysis already existed in art prior to 1988. That is, engineers could already predict with confidence the two-phase flow regime, the pressure drop, and the inventory of liquid in pipelines and vessels. At this NASA review meeting several design engineers asserted that indeed the minor uncertainties associated with predicting these adiabatic multiphase design factors posed no practical difficulty in their system analysis, nor their specification of hardware, nor their confidence in ultimate system performance. Moreover, thermal components such as evaporators and condensers, and other hardware such as inertial separators could already be designed. This is not to say that it was useless to refine either science or engineering design technology. Rather, no Herculean effort to do so was warranted.

The problem of modeling multiphase flow in spacecraft is not its inherent physical complexity. The scientific community has already successfully addressed a more difficult problem here on earth, namely the omni-directional modeling of multiphase pipeline flows for oil/gas transportation and in process and power plants. Rather the difficulty perceived in 1988 was a dearth of data for spacecraft multiphase flow, particularly at low (e.g., lunar), minigravity (e.g., 0.01 g) and microgravity (e.g., 10^{-4} to 10^{-6} g).

Six years have passed and the literature on adiabatic multiphase flow has expanded markedly. Some fine scientific and engineering technology work has been performed at many organizations, among them the University of Houston, Texas A&M, and Creare, with NASA and Air Force collaboration and sponsorship. Dukler (1988) reports aircraft tests of multiphase flow in a pipeline, typical of many by the University of Houston and other organizations. Reinarts and Best (1993) also report aircraft tests of pipeline flow and present their data and others comparatively. Crowley et al (1992) offer a "design manual" organizing the then available theory, releasing associated engineering software, and assessing the theory by comparison with then available aircraft data. Crowley, Sam and Schuller (1991) report aircraft tests of a generic system including an evaporator, a condenser, a pipeline and a pump and use these data to challenge the main elements of their model. Nothing in any of this new information has produced a single surprise. The technology available before 1988 has transferred straightforwardly to the prediction of spacecraft flows.

Spacecraft tests of various multiphase flows have been proposed. Some such proposals have tended to be prohibitively expensive and broad rather than focused, amounting to general purpose facilities. We suggest that spacecraft tests are best performed for closely defined confirmatory purpose, as a result of comprehensive prior study using earth-based facilities. Aircraft (and drop towers) offer a practical research tool for minigravity tests, but with some limitations. Accelerations less than 0.01 g are difficult to maintain, g-jitter of comparable order is often experienced, test duration at minigravity is of the order of 10 seconds (and begins and ends with a jerk and an inventory transient), and costs are high by comparison with earth tests in a static facility. Moreover, for reasons of safety, only certain fluids can be used.

The idea in scale modeling is to vary governing forces widely while preserving key force ratios, thereby subjecting theory to severe challenges at modest experimental cost. The ratio of acceleration body force to surface force is the Bond number, expressed as

$Bo=aD^2\Delta\rho/\sigma$. This ratio suggests that rather than vary acceleration, there is merit in varying pipeline diameter, which appears to the second power in the Bond number. In particular if diameter is reduced by a factor of 10 then Bond number is reduced by a factor of 100, a change equivalent to reducing gravity by a factor of 100 as in an aircraft test. This suggests the use of tubes of the order of 2.5 mm on earth to model prototypical systems in the range 25 to 100 mm pipeline diameter in space. Such data on earth could be compared with similar data from aircraft tests. Moreover, the two modeling approaches are complementary. Small earthbound facilities can use a wide range of fluids safely and are subject to steady gravity force indefinitely. They are very inexpensive to build and test.

This paper illustrates the usefulness of miniscale tests on earth to anticipate minigravity aircraft tests and microgravity applications. The work is a collaborative effort of researchers at Creare, Dartmouth College and NASA.

Available Data

Table 2 of the report by Martin and Rothe (1994) presents a survey of available experimental data for adiabatic multiphase flow in aircraft pipelines and from capillary tubes on earth. The fluids include water/air, various freons, ammonia (the expected prototype fluid), and some hydrocarbons and pure gases. References are herein.

The data span the main flow regimes of applied interest and include visual data for regime determination, pressure drop measurement, and void fraction (also known as holdup or fluid inventory). The measurements of void fraction are so far very limited in aircraft, relying on the data of one investigator with one fluid and over only a limited range of test experience that did not extend to annular flow. With the exception of the early work by Suo and Griffith (1963) in capillary tubes of diameter 0.5 and 0.8 mm., all of these data, both aircraft and capillary tube, were obtained since 1988.

Crowley et al. (1992) and Reinarts (1993) unify these aircraft data by comparison with a single body of analytical methods, that established by Crowley et al. (1992). Embodied in that system of theoretical tools for the prediction of flow regime, pressure gradient and holdup is a self-consistent body of similitude principles. By this means, the high degree of unification of data achieved to date and the close agreement with theory together indicate effective scale modeling principles.

In this paper we examine this art by additional comparisons of the theory (design methods) with data for capillary tubes. This poses an entirely new challenge to the prior art because the capillary-tube data are quite different from the original data base, and because these data do not suffer from the problems of test duration, g-jitter, and the like experienced by aircraft. In this way we complement and increase confidence in the prior findings. We also extend them.

Comparisons of Theory with Data

Figures 1, 2 and 3 compare the flow regime predictions of Crowley et al. (1992) with the miniscale data of four investigators who coincidentally used capillary tubes of approximately 2.5 mm diameter. The maps illustrate the conditions tested; neither Ungar and Cornwell (1992) nor Duschatko et al. (1992) observed the flow regimes. Direct visual observations by Fukano and Kariyasaki (1993), Martin and Rothe (1994) and Downing (1994) agree consistently and comprehensively with these flow regime predictions, for example, see Figure 2. So these comparisons unify flow regime modeling among capillary tubes on earth, prototype-scale tubes in aircraft, and theory derived from first principles and incorporating fluid dynamic similitude. Once again there is no surprise whatsoever. That is, models available before 1988 continue to predict all available data without difficulty.

Figures 4 to 7 compare the pressure drop measurements of these same four investigators with calculations employing the software developed and described by Crowley et al. (1992). Once again, excellent agreement is achieved for the purpose of engineering design. And again these comparisons unify the available capillary tube data, complement and support the available aircraft data, and confirm the similitude theory inherent in the original theory as compiled and combined in the comprehensive methodology proposed by Crowley et al. (1992). However, this time there was one surprise.

Our initial comparisons with these pressure data were in part unsatisfactory. To achieve the agreement shown in Figures 4 through 7 required an original analytical model. This model was developed by Wallis and employed by Downing (1994). The model was reviewed by Crowley and is a feature of the current version of his software, MICROP (1994). This refinement appreciably affects only certain predictions, only those for slug flow and then only for those slug flows at very high quality, near the transition to annular flow. Nonetheless for those flows the Wallis-Downing (1994) model is superior by a factor of up to three, no small correction. Moreover, the model is more plausible physically and mitigates an unreasonable jump in the predictions between slug and annular flow.

This discrepancy in prior art, the only significant discrepancy found to date since all of the testing initiated in 1988, was not found by an aircraft test. It was found on earth using a small tube.

The Wallis-Downing (1994) Model of Slug Flow

The Wallis-Downing (1994) model considers three elements:

1. friction in a pipe,
2. acceleration in a pipe,
3. acceleration at inlet and outlet.

Of these, the first is the significant technology refinement. The second element is analyzed for completeness and found to be negligible, as was the finding of the original modeling by Crowley and others. The third element is necessary only to the reduction of data, as in the present instance, where the pressure drop is measured in two plena surrounding a pipe. This inlet/outlet acceleration term is found to be small compared with the measured pressure drop in the pipe, and any deviation between this element and the experimental reality represents an experimental uncertainty.

For comparison, the friction terms of the pressure drop model developed by (1) Crowley et al. (1992) used in MICROP (1992) and (2) Wallis-Downing (1994) are:

$$\left[\frac{\partial P}{\partial z}\right]_{frict} = -\frac{2C_f \rho_f j^2}{D}(1-\alpha) \qquad (1)$$

$$\left[\frac{\partial P}{\partial z}\right]_{frict} = \frac{2C_f \rho_f j \; j_f}{D} \qquad (2)$$

Due to space limitations the reader is referred to Downing (1994) for this derivation. Its effect is shown in Figure 8.

Figure 9 presents selected data of Downing (1994), those in the slug flow regime but at relatively high quality near the slug-annular transition. These data are compared in Figure 9 with the model of MICROP (1992), but with the annular regime selected. These data are not annular; they are in the slug regime yet close to annular. Not unexpectedly, the measurements show somewhat higher pressure drop than would be the case if the flow were truly annular. Figure 10 presents the same data in comparison with two slug-flow models, that of MICROP (1992) and the Wallis-Downing model (1994). Both models yield values higher than the measured data. The Wallis-Downing model is a substantial improvement; it is as much as a factor of three lower than the original MICROP (1992) model.

Figure 11 compares the data of Downing (1994) with each of the MICROP models, the original as described by Crowley and Izenson (1992) and the updated software MICROP (1994) incorporating the Wallis-Downing theory above. Plainly the Wallis-Downing model has the expected effect when compared with the Downing data for slug flow at high quality.

Of the four data sets for capillary tubes, only two have data for slug flow in the moderate to high quality range of interest. A similar plot for the data of Fukano and Kariyasaki (1993) confirms this finding. Because the slug flow tests performed by Fukano and Kariyasaki (1993) were generally at low flow rates (of both gas and liquid) well below the quality levels of Downing (1994), the impact of the model change is less severe.

We have examined the available aircraft data and do not present comparisons with them at this time. Several investigators did not produce or report pressure drop data. Others discouraged the use of their data for this purpose, either because the flow conditions were not available in the range of present interest, or because the investigator questioned the accuracy of their data. Comparisons with the data of two investigators were performed and the initial results were equivocal. There is a need for additional aircraft data to examine this range of behavior. Such tests can now be performed with the benefit of prior calculations and in an effort to challenge a modeling hypothesis.

CONCLUSIONS

Original data have been developed for adiabatic two-phase flow in a capillary tube. Such "miniscale" testing complements aircraft tests at minigravity and is a step toward modeling microgravity effects on two-phase flow in spacecraft. These data extend the flow range of prior miniscale tests.

Available capillary tube data have been unified. These include data derived independently by four investigators at one size, approximately 2.5 mm or about one-tenth of prototype scale. The additional work described by Downing (1994) and Rothe and Martin (1994) further unify data at other sizes, diameters from 0.5 to 5.0 mm, which data however are less complete or less satisfactory in various ways.

The art predating 1988 was employed by Crowley et al. during the 1980s and thoroughly documented by Crowley et al. (1992) via their report and also their release of software called MICROP (1992). Their prior assessment of these analytical models and design tools unified and demonstrated agreement with all contemporary aircraft data, circa 1992. The present work extends this assessment to the available miniscale data from capillary tubes on earth. Once again the methodology of Crowley et al. (1992) has been qualified successfully against available data, save a minor refinement.

This qualification revealed a discrepancy limited to the slug flow regime, and further limited to high quality flows near the slug-annular regime transition. An improved model was written from first principles and assessed by Wallis-Downing (1994), improving the prior art both in terms of physical plausibility and in terms of agreement with the miniscale data. In selected cases the calculation of pressure drop has been improved by a factor of up to three.

The particular work reported here can be generalized to show the role of miniscale tests (and possible microscale tests) on earth to complement aircraft tests (and possible spacecraft tests) for the modeling of microgravity effects on two-phase adiabatic flows. The miniscale data provide an inexpensive way to rapidly explore parametric trends as a function of fluid properties, flow rates, physical size and the like. Together a body of data combining miniscale tests on earth with aircraft tests model directly the effects of gravity and overcome concerns about sensitivity to g-jitter, jerk, and short duration of minigravity aircraft tests. The diversity of data derived thereby, encompassing a range of gravity and diameter, provides a strong challenge to analytical modeling.

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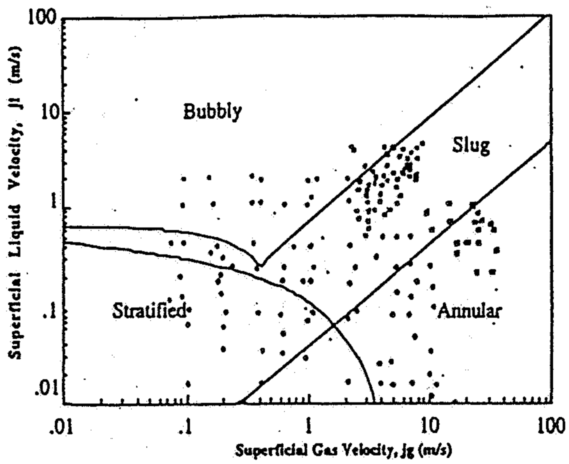


Figure 1. The data of Downing (1994) and Fukano and Kariyasaki (1993) each span the flow regimes and agree closely with the transitions identified by the methodology of Crowley et al (1992).

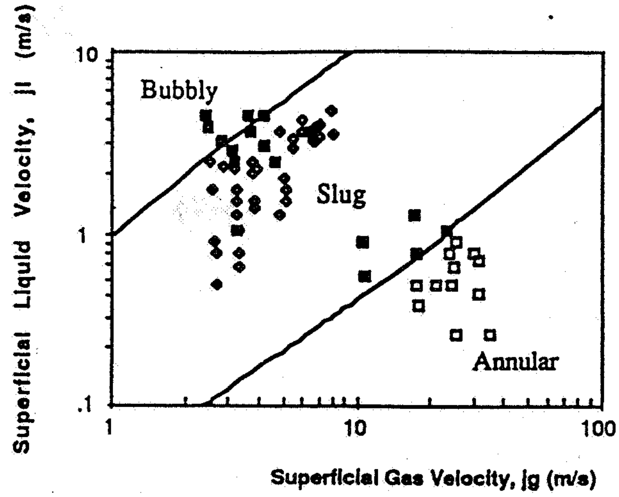


Figure 2. The data of Downing (1994) for a 2.4 mm diameter tube on earth are in close agreement with the flow regimes predicted by the methodology of Crowley et al (1992).

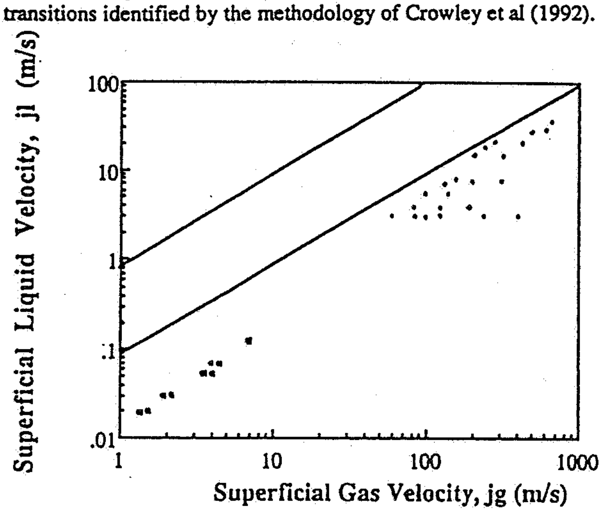


Figure 3. The data of Duschatko et al (1992) and Unger and Cornwell (1992) correspond with the annular flow regime according to the method of Crowley et al (1992). The data are for ammonia flowing in a 2.4 mm tube on earth.

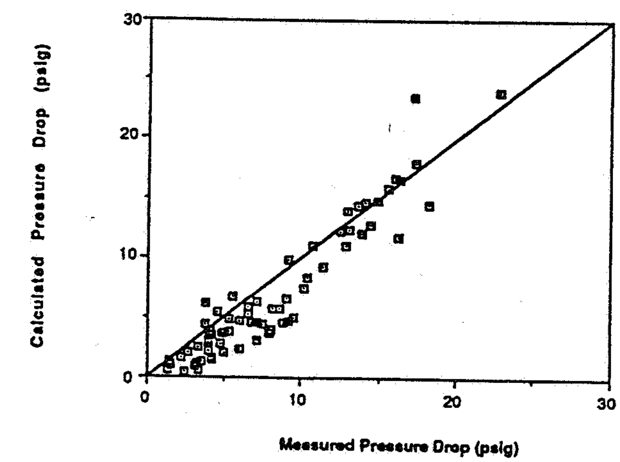


Figure 4. The data of Downing (1994) for bubbly, slug and annular flow regimes in a 2.4 mm diameter tube are in close agreement with the method of Crowley et al (1992), incorporating the Wallis-Downing (1994) model for slug flow.

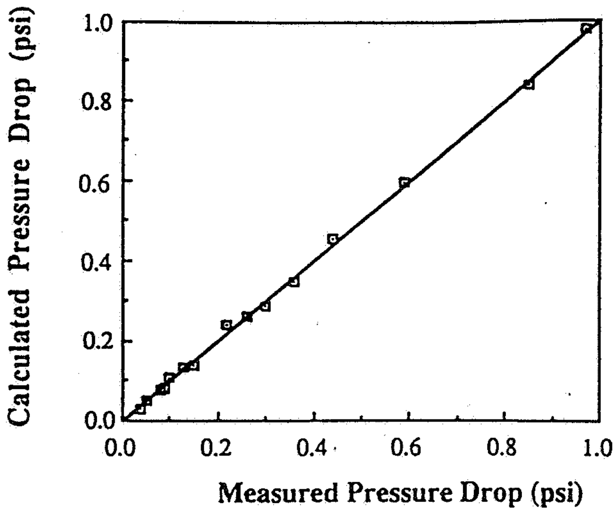


Figure 5. The method of Crowley et al (1992) shows close agreement with the ammonia data of Unger and Cornwell (1992) in the annular flow regime. Tube diameter is 2.6 mm on earth.

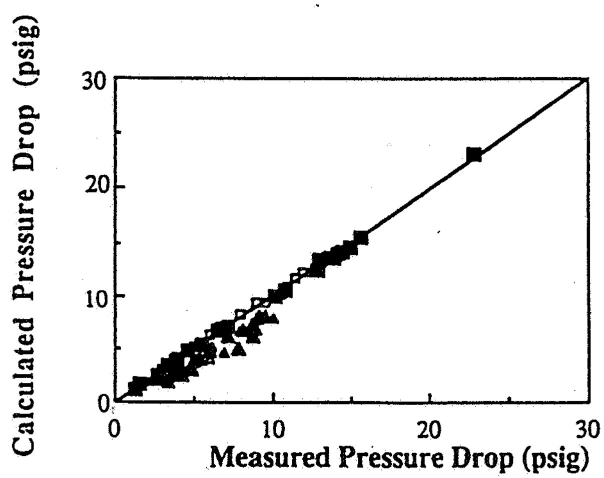
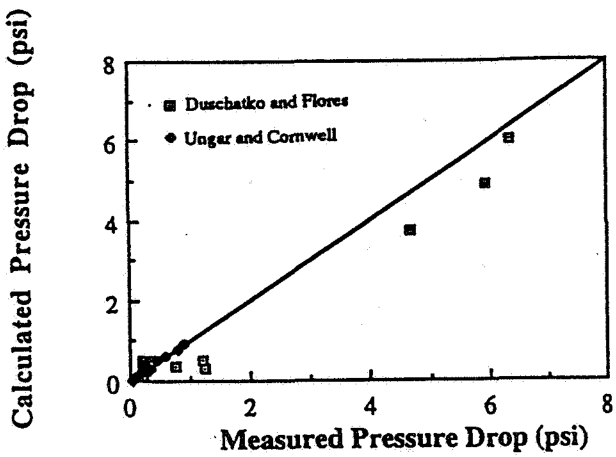


Figure 6. The method of Crowley et al (1992) shows close agreement with the data of Fukano and Kariyasaki (1993) in both the slug and annular regimes. These are Air Water Data for a tube of 2.4 mm diameter. The data of Downing (1994) are also shown.



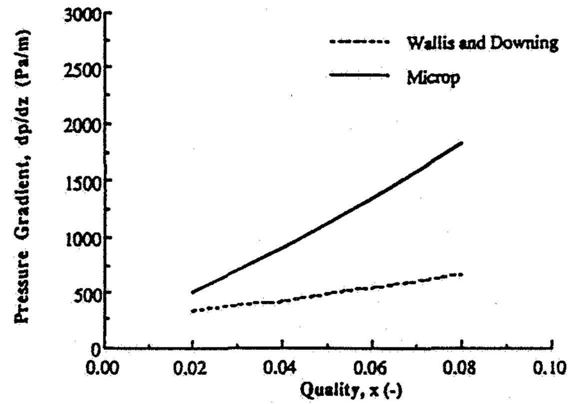
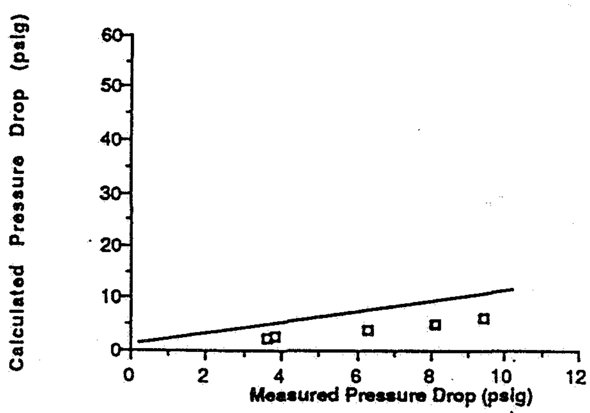


Figure 7. The data of Duschatko et al (1992) and Unger and Cornwell (1992) for ammonia flowing in a 2.4 mm tube on earth agree with the method of Crowley et al (1992). The data of these two investigators is limited to the annular flow regime.

Figure 8. The Wallis-Downing model reduces pressure gradient in the slug flow regime, particularly at high quality near the slug-annular transition.



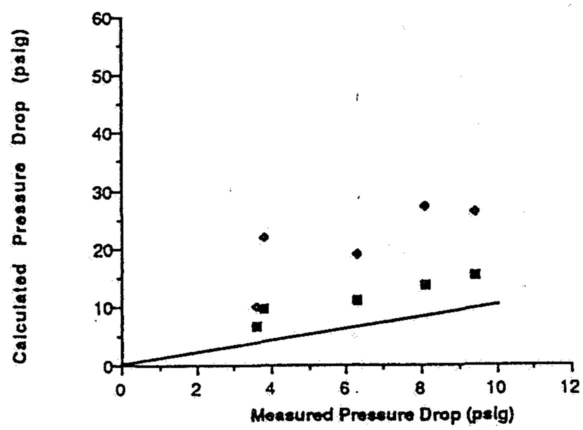


Figure 9. Measured pressure drop by Downing (1994) for slug flows at high quality exceed the annular flow calculation of MICROP (1992).

Figure 10. The model of Wallis-Downing (1994) gives much lower calculated pressure drop (for slug flow at high quality near the slug-annular transition) than does the slug flow of MICROP (1992). This is illustrated by comparison with selected data from Downing (1994) from a 2.4 mm tube on earth.

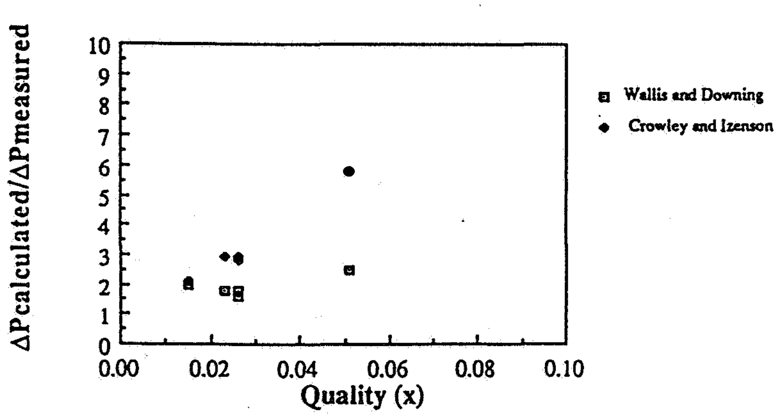


Figure 11. The ratio of calculated to measured pressure drop shows the expected deviation at high quality in the slug flow regime. The data are those of Downing (1994) with slug flow in a 2.4 mm tube on earth. The models are those of Crowley et al (1992) and Wallis-Downing (1994).