MEASUREMENT OF TWO-PHASE FLOW CHARACTERISTICS UNDER MICROGRAVITY CONDITIONS

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SUMMARY

This paper describes the technical approach and initial results of a test program for studying two-phase annular flow under the simulated microgravity conditions of KC-135 aircraft flights. A helical coil flow channel orientation was utilized in order to circumvent the restrictions normally associated with drop tower or aircraft flight tests with respect to two-phase flow, namely spatial restrictions preventing channel lengths of sufficient size to accurately measure pressure drops. Additionally, the helical coil geometry is of interest in itself, considering that operating in a microgravity environment vastly simplifies the two-phase flows occurring in coiled flow channels under 1-g conditions for virtually any orientation. Pressure drop measurements were made across four stainless steel coil test sections, having a range of inside tube diameters (0.95 to 1.9 cm), coil diameters (25 - 50 cm), and length-to-diameter ratios (380 - 720). High-speed video photographic flow observations were made in the transparent straight sections immediately preceding and following the coil test sections. A transparent coil of tygon tubing of 1.9 cm inside diameter was also used to obtain flow visualization information within the coil itself. Initial test data has been obtained from one set of KC-135 flight tests, along with benchmark ground tests. Preliminary results appear to indicate that accurate pressure drop data is obtainable using a helical coil geometry that may be related to straight channel flow behavior. Also, video photographic results appear to indicate that the observed slug-annular flow regime transitions agree quite reasonably with the Dukler microgravity map.

INTRODUCTION

General

The presence of an earth gravitational environment can enormously complicate a two-phase liquid/vapor flow, resulting in a variety of perturbations, instabilities, and generally undesirable unsteady features. As a result, even though two-phase flows have been studied extensively under earth gravity conditions, the accuracy of multiphase predictive tools is quite poor in comparison to those available for single-phase systems. Studying two-phase flow systems in a microgravity environment, can remove such undesirable flow complications, perhaps enabling the development of (1) more accurate predictive methods applicable in our earth gravity environment, and (2) accurate correlations that may be applied to the design of two-phase systems intended to operate under the microgravity conditions of space.

Parabolic aircraft trajectories have been used to obtain data for a very broad range of phenomena for reduced gravity periods of up to about 20 seconds duration. However, in the case of obtaining accurate measurements of two-phase flow behavior and characteristics under such low-gravity conditions, a virtually insurmountable impediment, or restriction, exists because of space limitations alone. This major impediment arises because of the long lengths of flow channel required to avoid entrance or exit effects, particularly insofar as they affect accurate measurements of pressure drop.

Typically, long, extended lengths of straight channel are required to insure a developed flow. Such requirements, using conventional experimental approaches, cannot be accommodated in KC-135 (or smaller) aircraft testing because of spatial constraints. These constraints are even more extreme in facilities available for space experiments.

Early Studies

In early studies of two-phase flow in aircraft parabolic trajectories, observation of flow patterns and their details have been reasonably successful, but associated pressure drop measurements have proven much more difficult to obtain, primarily due to flow channel length limitations. For example, in one of the early studies by Hepner et al [1] flow pattern observations and pressure drop measurements were made of air-water two-phase flow in a 2.54 cm diameter tube. However, since the length-to-diameter ratio (L/D) was only 20, the pressure drop measurements obtained were of little use.

More than a decade later, Chen et al. [2, 3] obtained the most extensive pressure drop data obtained to that time, for adiabatic two-phase flow of R-114 in the low-gravity conditions of KC-135 aircraft flight. Flow occurred in a 1.58 cm diameter and 1.83 m long straight tube, with pressure differential measurements made over a channel length of almost 120 diameters. The results were used to develop a new correlation for the prediction of two-phase pressure drop in a reduced gravity environment, based upon an annular flow model and using an interfacial friction factor developed from their test data. Nevertheless, the magnitudes of the pressure drops upon which the correlation was based were small, so that measurement errors were a significant fraction of the pressure drops measured.

Accordingly, to circumvent the restrictions upon channel length imposed by drop tower and aircraft spatial restrictions, the present study utilizes a flow channel configured in a helical coil arrangement. This geometric arrangement permits a considerable length of flow channel to be "packed into" a compact space having very modest overall dimensions. The substantially larger pressure drop occurring over a much larger length of flow channel are thus much more easily measured with accuracy.

Since the studies of Chen et al cited earlier, a variety of additional studies have been conducted [4 - 8] using smaller channel (tube) sizes, and in both horizontal and vertical configurations, but at the expense of modification of the two-phase flow characteristics. Most recently, efforts have been made to identify conditions (involving tube size and fluid characteristics) that would justify obtaining "zero-g" data by conducting tests in a 1-g environment [9].

Coil Curvature Effects

In single phase flows the friction factor for flow in coils differs from that in a straight geometry under earth gravity conditions because of secondary flows induced by the curved channel geometry. It should be expected that for two-phase flows a coiled flow path would also induce secondary flows within each of the phases, that are not present in a straight-channel geometry. The detailed structure of secondary flows in two-phase flow in curved channels is not well defined. Not surprisingly, the relationship between two-phase pressure drops in coiled and straight flow channels is likewise not well defined. Some of the first results of this type have been obtained by Yan [10], for the vertical up-flow of air-water in circular cross-section (0.325 inches I.D.) helical coils of 3.125 inches coil diameter. A number of two-phase flow studies in helical coil geometries under 1-g conditions are listed in references [11-16].

EXPERIMENTAL PHASE

Coil test sections of small curvature (large coil diameter) were designed to minimize complexities induced by curvature (secondary flow effects), so that the flows would not differ substantially from straight-channel flows. Also, small channel diameters were considered undesirable due to the potential of distorted flow pattern observations, e.g. a single small bubble occupying the entire cross-section of a small diameter tube, so as to give the appearance of a slug flow condition instead. Larger tube sizes are also likely to be more advantageous in detecting entrance and developmental effects.

Four stainless coils of different sizes and lengths, as summarized in Table 1, were designed for use in the present study. A typical coil test section is illustrated in Figure 1. Two of the test sections are of the same inside diameter, 1.91 cm., but one was of more than 13 meters length, while the second was only about half that length. The longer length coil was considered to be of greatest benefit in aircraft flight tests. Its substantial length would insure an easily measurable, large pressure drop, even for such a large tube cross-sectional area. The smaller length test section was utilized to greatest advantage in laboratory ground testing, where it was essential to relate curved channel results to straight tube results – in effect, a correlation factor. The 3.76 meter length for this coil is compatible with the length of a straight channel that may be accommodated in the ground laboratory.

However, there is no justification in terms of physical phenomenological considerations that would justify the use of the same "modification factor" in low-g conditions as in 1-g conditions. Therefore, a fourth test section was designed that could be tested under low-g conditions and which would allow a relationship between straight-channel and curved channel flows. Due to spatial restrictions of the KC-135 flight apparatus, however, a much shorter straight length of flow channel can be utilized for comparisons to a coil configuration. Therefore, a smaller tube diameter is necessitated in order to create a large enough pressure drop in the straight length to be readily measurable. Due to the smaller tube diameter dictated, the coil diameter must also be correspondingly smaller in order to preserve the Dean number scaling parameter, and the d/D ratio contained therein. Accordingly, the fourth test section is of 0.95 cm. I.D., with a coil diameter of 25.40 cm., such that d/D = .0374, as with coils 1 and 2, Table 1.

Both the inlet and exit ends of the tubing were connected to instrumented straight lengths of tubing of the same diameter in which pressure transducers were located, as indicated in the diagram of Figure 1.

All tests were conducted with the coil axes being oriented vertically. In almost all cases, the air/water flows were in the downward direction, primarily because of constraints imposed in accommodation of the test sections to the flight apparatus developed by NASA specifically for two-phase aircraft flight experiments. The range of air/water flows studied under flight conditions was set by the design limitations of the flight test apparatus. Accordingly, liquid superficial liquid velocities were between 0.1 and 1.1 m/s, and superficial gas velocities between 0.1 and 25 m/s. Although the primary focus of the study has been upon annular flow, it was important to establish the conditions under which the slug-annular flow regime transition occurred.

For flow visualization within the curved passages of the coil itself it was necessary to design a transparent coil (50.80 cm coil diameter) of tygon tubing (1.90 cm I.D.), as described more fully in [17]. As with the largest stainless steel coil, the pitch angle is only about 1 degree.

MEASUREMENTS AND RESULTS

Flow patterns were observed in the straight inlet and exit sections immediately preceding and following the coiled test sections, respectively, using high speed video photography, both in 1-g and aircraft flight tests. Comparisons of the observed flow patterns were made with the Choe-Weinberg-Weisman [18] and Taitel-Dukler [19] maps for 1-g conditions and with the Dukler et al [20] map developed specifically for microgravity conditions. Results for the ground laboratory tests indicated good agreement with the Choe et al map for the slug-annular transition. With the limited data obtained from a single set of flight tests, it appears that the slug-annular transition is reasonably well predicted by the Dukler et al [20] flow pattern map developed for straight-channel flows under microgravity conditions, which apparently indicates that the small curvature of the coils did not have an appreciable influence upon this flow pattern transition. Some of these limited initial results are shown in Figure 2.

Representative data for measured pressure traces are shown in Figures 3 and 4 for 1-g and microgravity conditions. Pressure drop values were obtained from taking the difference between the measured pressures across the coil at a sampling rate of 1 kHz. In Figure 3 the differing pressure traces at the coil inlet and exit appear to reflect the changes in flow structure that occurs as the two-phase mixture traverses through the coil. Such changes could very reasonably be expected to occur in long sections of straight flow channels also, however. The inlet and exit traces shown in Figure 4 for an annular flow pattern do not show a marked difference since the opportunity for bubble coalescence or other major flow modifications do not exist in this case.

Measured pressure drop values for a limited number of test conditions are presented in Figure 5, and are compared with values predicted by the Lockhart-Martinelli and homogeneous methods. Far more important will be the comparisons between the coiled and straight lengths of flow channel, both in 1-g and microgravity conditions. A large amount of data is now available from the first successful flight tests. Only these initial representative results can be presented at the time of the writing of this paper. These limited initial results appear very promising and of great interest, both from a practical and a scientific view, but a complete validation of the experimental approach must await the collecting and analysis of a considerable amount of additional data, not only from these first flight tests, but from additional tests to be conducted in the next six-month period.

ACKNOWLEDGMENTS

This work, which was supported through NASA Grant NAG3-1922, is gratefully acknowledged and appreciated.

REFERENCES

1. Hepner, B. B., King, C. DE., and Littles, J. W., "Zero-G Experiments in Two-Phase Flow Regimes, ASME Paper TS-ENAs-24, ICES Conf., San Francisco, 1975.
2. Chen, I. Y., Downing, R. S., Parish, R. and Keshock, E. G., "Observed Flow Regimes and Pressure Drops of Vapor and Liquid Flow in Adiabatic Piping," AIChE Symposium Series, Vol. 84, No. 263, 1988, pp. 203-216.
3. Chen, I.Y., Downing, R.S., Keshock, E.G., and Al-sharif, M., "Measurements and Correlation of Two-Phase Pressure Drop Under Microgravity Conditions," AIAA Jnl. Thermophysics, Vol. T, No. 4, October, 1991.
4. Lambert, A., "KC-135 Zero-Gravity Two-Phase Flow Pressure Drop Experiments and Modeling," M. S. Thesis, Texas A& M University, College Station, TX, 1990.
5. Hill, W. S., and Best, F. R., "Microgravity Two-Phase Flow Experiment and Test Results," SAE Tech. Paper Series 911556, 21st Int. Conf. on Environmental Systems, San Francisco, 1991.
6. Bousman, W. S., and Dukler, A. E., "Studies of Gas-Liquid flow in Microgravity: Void Fraction, Pressure Drop and Flow Patterns," Proc. of ASME Winter Ann. Mtg., New Orleans, AMD-Vol. 174 / FED-Vol. 175, Dec., 1993.
7. Best, F. R., and Huang, D. S., "Microgravity Two Phase Flow Pressure Drop Experiments in the NASA KC-135," Proc. 7th Symp. on Space Nuclear Power Systems, Albuquerque, NM, Jan., 1990.
8. Miller, K. M., Ungar, E. K., Dzenitis, J. M., and Wheeler, M., "Microgravity Two-Phase Pressure Drop Data in Smooth Tubing," Proc. ASME Winter Ann. Mtg., New Orleans, AMD-Vol. 174 / FED-Vol. 175, Dec., 1993.
9. Ungar, E. K., Chen, I. Y., and Chan, S. H., "Selection of Gravity Insensitive Ground Test Fluid and Test Configuration to Allow Simulation of Two-Phase Flow in Microgravity," Seventh AIAA/ASME Joint Thermophysics and Heat Transfer Conference, Albuquerque, NM, June 15-18, 1998.
10. Yan, A., "Study of Two-Phase Flow Patterns and Frictional Pressure Drop in Helical and Spiral Coils," M.

S. Thesis, Mech. and Aerospace Eng. Dept., Univ. of Tennessee, Knoxville, TN, 1992.

11. Whalley, P. B., "Air-Water Two-Phase Flow in a Helically Coiled Tube," Int. Jnl. Multiphase Flow, Vol. 6, pp. 345-356, 1980.

12. Uddin, A. K. M., "A Model to Predict Two-Phase Flow Patterns in Helically Coiled Tubes," Particulate Phenomena and Multiphase Transport, Hemisphere Publ. Corp., 1988.

13. Saxena, A. K., Schumpe, A., Nigam, K. D. P., and Deckwer, W. D., "Flow Regimes, Hold-Up and Pressure Drop for Two Phase Flow in Helical Coils, Can. Jnl. of Chemical Eng. , Vol. 68, Aug., 1990.

14. Awwad, A., Xin, R. C., Dong, Z. F., Ebadian, M. A., and Soliman, H. M., "Flow Patterns and Pressure Drop in Air/Water Two-Phase Flow in Horizontal Helicoidal Pipes," Trans. ASME, Vol. 117, Dec., 1995, pp. 720-725.

15. Xin, R. C., Awwad, A., Dong, Z. F., and Ebadian, M. A., "Heat Transfer of Air/Water Two-Phase Flow in Helicoidal Pipes," Trans. ASME, Vol. 118, May, 1996, pp. 442-448.

16. Yan, A., Keshock, E. G., Omrani, E. G., and Downing, R. S., paper presented at AIChE Annual Meeting, Nov., 1995.

17. Keshock, E. G., Lin, C. S., and Edwards, L. G., "Design of Helical Coil Apparatus for Study of Two-Phase Flow in DC-9 Microgravity Flight Tests," Proc. Sixth Int'l. Symp. on Gas-Liquid Two-Phase Flows, ASME Fluids Eng. Div. Mtg., June, 22-26, 1997, Vancouver, BC, Canada

18. Choe, W. G., Weinberg, L., and Weisman, J., Two-Phase Transport and Reactor Safety, Hemisphere Publishing, Co., 1978.

19. Taitel, Y., and Dukler, A. E., "A Model for Predicting Flow Regime Transitions in Horizontal and Near-Horizontal Cocurrent Gas-Liquid Flow," AIChE Journal, Vol. 22, pp. 47-55, 1976.

20. Dukler, A.E., Fabre, J.A., McQuillen, J.B., and Vernon, R., "Gas-Liquid Flow at Microgravity Conditions: Flow Patterns and Their Transitions," Int. J. Multiphase Flow, V. 14, N. 4, pp. 389-400, 1988.

Coil	Tube O.D. (cm)	Tube I.D. (cm)	Coil Dia. (cm)	Coil Pitch (cm)	Coil Length (cm)	Coil Length-to-Dia. Ratio
No. 1	2.54	1.91	50.80	3.02	1356	710
No. 2	2.54	1.91	50.80	3.02	718	376
No. 3	1.59	1.27	50.80	3.02	718	565
No. 4	1.59	0.95	25.40	1.59	678	714

Table 1. Specifications for Stainless Steel Coil Test Sections.

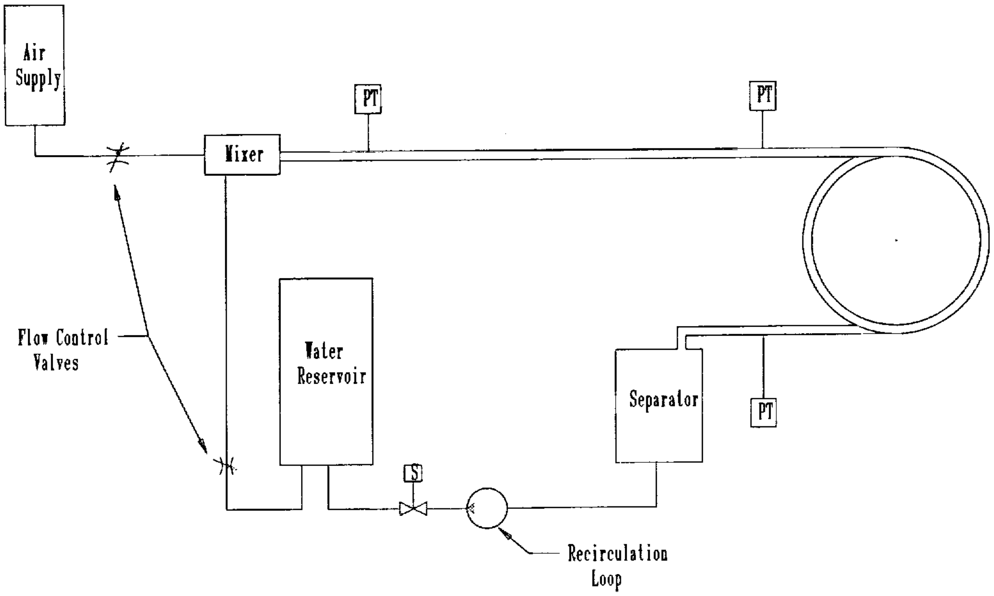

Figure 1. Schematic of aircraft two-phase test apparatus.

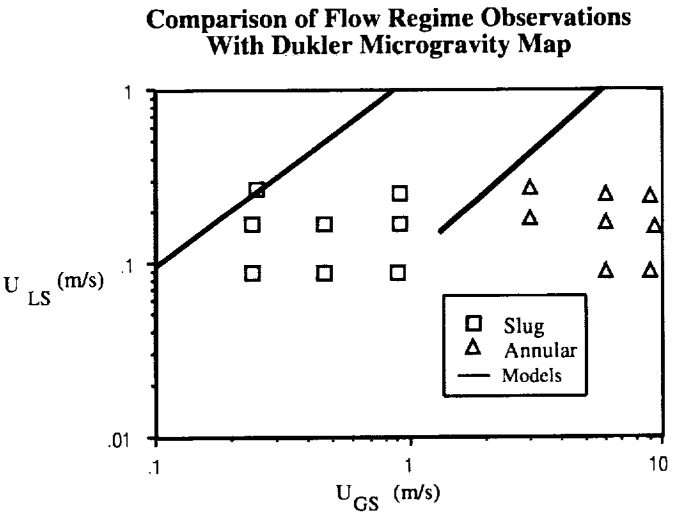

Figure 2.

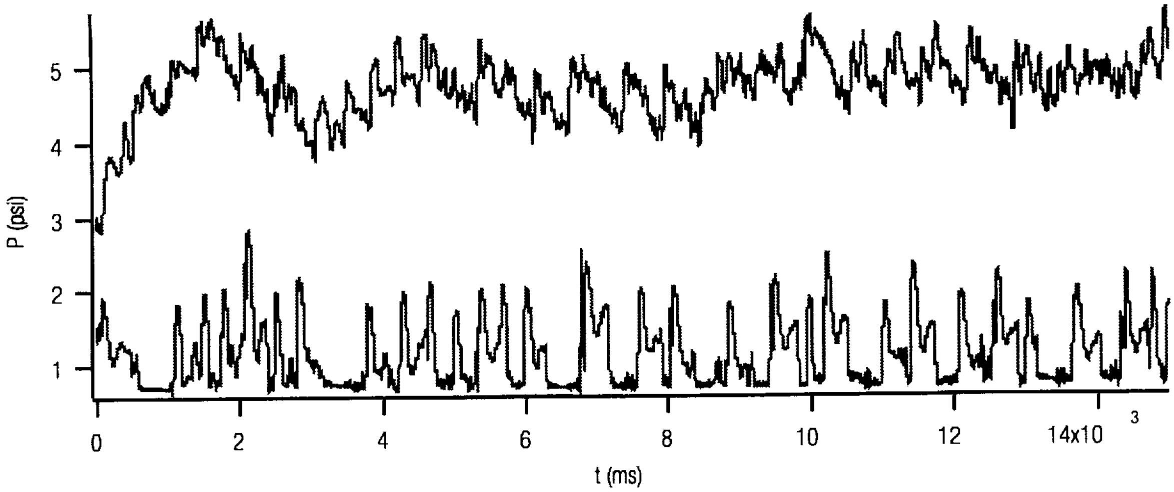

Figure 3. Pressure traces during flight parabola (slug/bubble flow).

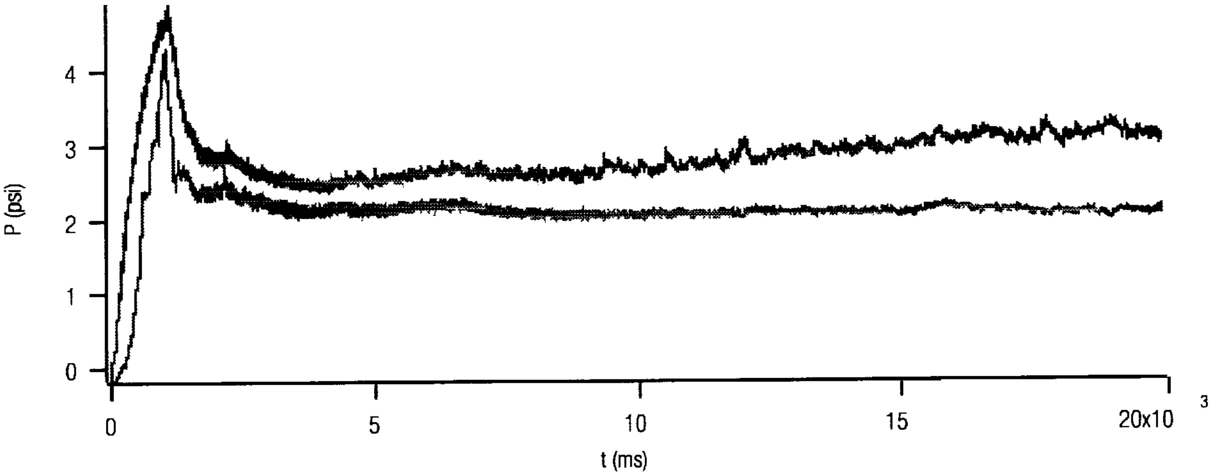

Figure 4. Pressure traces during flight parabola (annular flow).

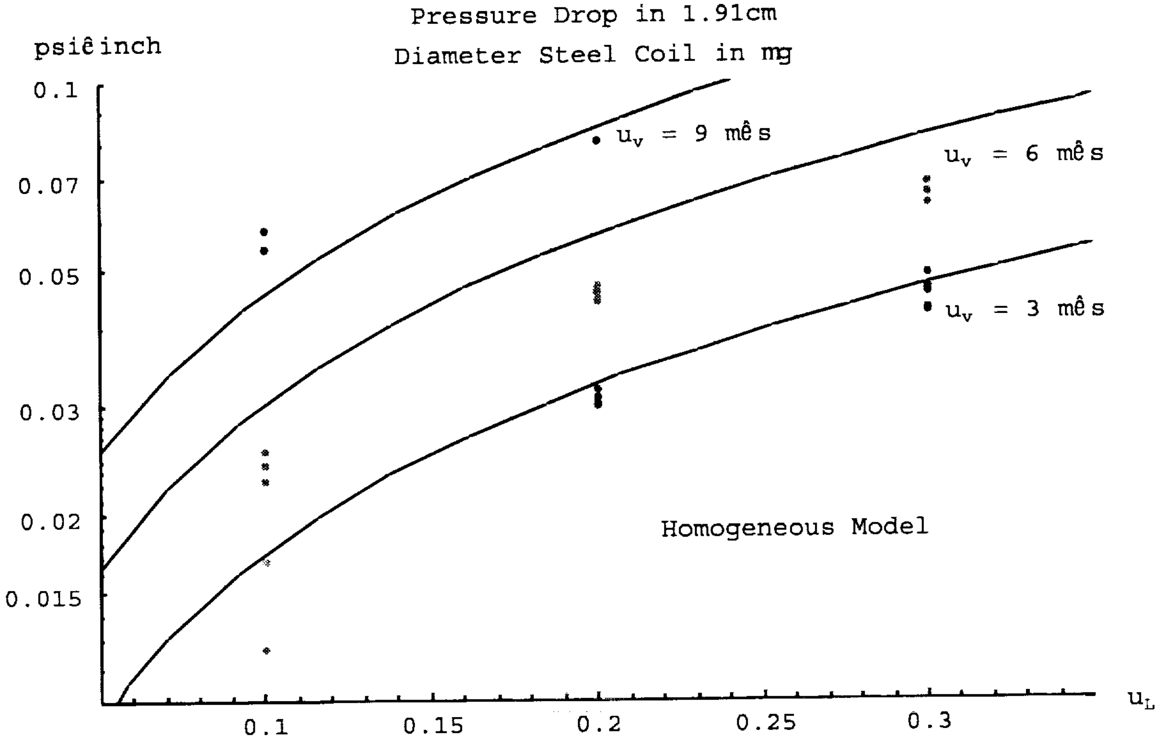

Figure 5. Representative measured Δp values compared with Lockhart-Martinelli predictions.