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INTRODUCTION AND SCOPE OF STUDY

The principal purposes of the present study were to:

(1) Observe and develop a fundamental understanding of the flow regimes and their transitions occurring in helical and spiral coils; and

(2) Obtain pressure drop measurements of such flows, and, if possible, develop a method for predicting pressure drop in these flow geometries.

Elaborating upon the above, the general intent is to develop criteria (preferably generalized) for establishing the nature of the flow dynamics (e.g. flow patterns) and the magnitude of the pressure drop in such configurations over a range of flow rates and fluid properties.

Additionally, the visualization and identification of flow patterns were a fundamental objective of the study. From a practical standpoint, the conditions under which an annular flow pattern exists is of particular practical importance.

In the possible practical applications which would implement these geometries, the working fluids are likely to be refrigerant fluids. In the present

study the working fluids were an air-water mixture, and refrigerant 113 (R-113).

In order to obtain records of flow patterns and their transitions, video photography was employed extensively. Pressure drop measurements were made using pressure differential transducers connected across pressure taps in lines immediately preceding and following the various test sections.

PRINCIPAL OBJECTIVES OF STUDY

Flow regime identification was made using video photography and direct visual observation for each test condition. These observations were presented in terms of plotted data points on various existing flow regime maps, as in [1]. Of particular interest were the conditions at which the transition to an annular flow pattern occurs for each given liquid flow rate. One of the ultimate desirable results of a study such as the present one is to characterize the flow pattern behavior in terms of a parameterized flow map accounting for the range of fluid dynamics and fluid properties. (Several maps of such data obtained in the present study are presented herein. Efforts are in progress in attempting to generate a generalized flow map applicable to flow in coiled systems.)

The pressure drop measurements obtained in the present study will be compared with predictions of several models appearing in the literature, as has been done in [2]. An attempt will be made to utilize the measured results to develop a model for accurately predicting pressure drop in coiled geometries. (This data presentation and comparison is currently in progress.)

EXPERIMENTAL PHASE

An existing two-phase flow loop within the University of Tennessee (Knoxville) Mechanical and Aerospace Engineering Department Laboratories was used to generate a two-phase, liquid/vapor R-113 flow over a range of thermodynamic qualities. This flow served as the inlet flow to individual tests of a variety of transparent coiled test sections. Similarly, using an apparatus (instrumented flow loop) provided by the Sundstrand Corporation, air/water flows were also studied using the same coiled test sections. Schematic diagrams of each of the test loops are presented in Figures 1 and 2.

Description of Test Sections

Four different helical coil test sections were utilized in the study. The first-test section consisted of a 0.325" (8.255mm) I.D. glass tube, wound into a helical coil of pitch 2.4 cm, height 16 cm, and coil diameter of 7.5 cm. The total length of the glass tubing was 1.59 meters.

Three additional helical coil test sections were fabricated from plexiglas. Rectangular cross-section channels were machined into the outer surface of solid plexiglas cylinders, and then covered with a snug-fit outer plexiglas tube. One flow channel cross-section was very nearly square (8.89 mm height, H, by 8.255 mm width, W). The coil diameter was 7.6 cm, the pitch , P, was 2.54 cm, and the total coil length was 2.01 m. The second had dimensions of H = 6.88 mm, W = 10.3 mm, P = 2.54 cm, and a total coil length of 2.04 m.

Dimensions of the third coil were H = 10.3 mm, W = 6.88 mm, P = 2.54 cm, and total coil length of 2.28 m. Thus, for the three rectangular cross-section test sections, H/W ratios were approximately 1, 0.667, and 1.5. In all of the rectangular cross-section coils a short circular cross-section tube was inserted into the test piece body, so that a short transition section existed between the circular cross-section insert and the rectangular cross-section helical coil flow channel.

Finally, a spiral coil glass test section was also investigated. The inner diameter of the tube was 8.26 mm. The innermost spiral was of diameter (approximately) 5.5 cm, while the outermost spiral diameter was approximately 16 cm. The total length of the coil was 1.49 m.

In order to make measurements of pressure drop, pressure differential transducers were connected across pressure taps immediately preceding lengths of rubber tubing that were connected (clamped) to the test sections. The distance between the inlet tap and the inlet of the coil test sections was 19 cm. The distance between the outlet tap and the exit of the test sections differed for the different test sections. The complete listing of dimensions associated with each of the test sections tested in the study is not presented here, but will appear in the final project report.

Methodology and Procedures

General:

The test fluids and conditions anticipated to be tested in the original project specifications called for (1) air-water at a nominal temperature and pressure of 70 F and 30 psia, and (2) refrigerant-113 nominally at 130 F and 18 psia. The range of liquid flow rates to be investigated were to vary from 0.02 to 0.20 gpm. By adjusting the vapor phase flow rate while maintaining a constant liquid phase flow rate, a "quality" range from 0 to 50% was anticipated to be studied at five separate liquid flow rates, resulting in a total of 50 data points to be obtained for each test section. For the five test sections and two working fluids, the total number of data points to be obtained would be 250. No specification was made as to the orientation of the test pieces or the directions of flow.

The original intent was that each of the preceding tests would be conducted using a single orientation and a single flow direction (upward or downward, for example, with either a horizontally or vertically oriented test section).

After the test program was initiated, however, additional requests were made to expand the scope of the study. Consequently, for the air-water tests, all helical coil test sections were studied in both the vertical and horizontal orientations, with the inlet flow being in an upward direction Additionally, in one test of the circular cross-section helical coil oriented vertically, measurements were made for a downward flow. Also, for the R-113 tests, a very large number of test conditions was utilized to obtain a complete "picture" of the trend of pressure drop data over a range of liquid flow rates and vapor qualities. (In this test alone a total of 136 data points were obtained -- more than half of the total number

of data points originally specified for the entire test program.) Consequently, the total number of test conditions far exceeded the 250 values originally planned(actual number, 609).

Air-Water Test Procedures:

The apparatus depicted schematically in Figure 1 was first filled with water and circulated about the loop to flush out any contaminants before draining, refilling the loop and repeating the process again. After taking this means to insure the cleanliness of the system, liquid was circulated at a predetermined, constant mass flow rate. The air flow rate was adjusted so as to create a slug flow within the coiled test section that was slightly below a condition of annular flow. After making videotapes and pressure drop measurements of this flow condition, the vapor flow was increased carefully up to the point at which it was judged that a hydrodynamically defined annular flow just existed. This was designated as the transition condition. The air flow was increased again to a level somewhat above the transition condition. Additional operating conditions spanning the highest and lowest operating points (in terms of vapor quality) were attained, where additional measurements of pressure differential and flow observations were made.

The air flow was then stopped, the liquid flow rate adjusted to the next higher predesignated flow rate, and a range of air flow rates was spanned so as to define the transition condition at that flow rate, and obtain pressure drop data over a range of vapor phase qualities.

These procedures were repeated for each of five test sections. In the case of the helical coils, tests were conducted with the coil axis oriented vertically and horizontally. In the vertical orientation the flow was directed upward through the coil section.

R-113 Test Procedures:

For the refrigerant tests the general procedure was similar to that of the air/water tests. However, the vapor phase flow was generated by means of an electrically heated circular tube preceding the coiled test section(s), as depicted in the schematic diagram of Figure 2. At the beginning of a test run, the flow loop was completely filled with liquid, and circulated through it. Power was applied to the electrically heated tube, generating vapor.

Vapor was vented through a release valve at the uppermost part of the loop to insure that any trapped air would be eventually discharged from the system. After so evacuating air from the system, the liquid flow was adjusted to a fixed rate, and power applied to generate a predetermined vapor quality, resulting in a slug flow condition, just below an annular flow condition.

The same procedure as in the air/water tests was followed to generate measurements and observations over a predetermined span of test conditions. It should be noted that at each test condition equilibrium conditions were attained before taking data, i.e. the liquid saturation temperature was required to be (at) the saturation temperature of the refrigerant corresponding to the measured system pressure.

DATA
PRESSURE DROP

The complete set of pressure drop measurements obtained cannot be presented here in report form due to the proprietary nature of the information, but will only be presented in visual display form. Additionally, a significant amount of the raw data is still being corrected for further analysis and comparison with predicted values. For example, because of the straight lengths of tubing preceding and following the coil test sections, a pressure drop associated with those lengths must be subtracted from the measured values across the entire flow length (inlet, test section, and exit). The average pressure drop along these straight lengths computed by the homogeneous and Lockhart-Martinelli methods are subtracted from the overall measured pressure drop. Also, since there is a difference in elevation between the inlet and exit of the helically coiled test sections, whether oriented horizontally or vertically, the measured pressure differentials must be corrected for the elevation head existing in each situation.

Once having obtained the true, corrected pressure drop measurements across the coils, these values are compared with several conventional methods of predicting two-phase pressure drop, such as Lockhart-Martinelli[3], Chisholm[4], homogeneous [see 2], and others. However, all such methods are intended to be applicable to straight channel flows, and so cannot take into account any effects that channel curvature might have upon pressure drop. Such methods of modifying straight channel pressure drops for applicability to curved geometries have been

proposed by Hart et al [5] and Lopina and Bergles [6]. Comparisons of the corrected measured pressure drop data are also made to these predictive methods. Also, a method has been devised and will be utilized for predicting two-phase pressure drops in helical coil geometries based upon the method developed by Hart et al [5] for single phase flow, for comparison with the measured values.

FLOW REGIME OBSERVATIONS

Flow pattern observations were made at each test condition (i.e. 609 data points). The determinations were generally made from direct visual observations of the flow. However, this became possible only after coordination of these visual observations with the video photographic results which were played back and scrutinized in detail, including freeze-frame analysis of the 1/1000 shutter speed video frames.

Each test sequence recorded on video tape contains a voice description of the test conditions, the test run, and a qualitative description of the flow details observed by the naked eye for that sequence.

Each of the flow patterns observed is identified in terms of the conventionally accepted descriptive nomenclature It should be pointed out that an annular flow was identified as that condition for which a continuous liquid film existed, or was sustained, about the entire interior periphery of the flow channel wall. Just prior to the transition from a slug flow to annular flow, a surge, or wave of liquid might wet the upper portion of the channel wall. However, the liquid film would drain downward from the upper wall, resulting in a dry wall condition until the next surge or wave would rewet the wall completely. Such an intermittent hydrodynamic condition cannot reasonably be interpreted as an annular flow, but the point at which the periphery is continuously covered with a liquid film can very logically be considered the transition condition to an annular flow pattern. The development of flow regime maps, in fact, are based entirely upon such logical hydrodynamic definitions or descriptions of flow patterns.

Whether or not such a transition represents an optimum condition for heat transfer may be another matter, however. Generally, a higher rate of heat transfer occurs when a liquid film is wavy, i.e. has an irregular interface, rather than a smooth one. Of course in an annular flow occurring under earth gravity conditions, the downward liquid drainage that occurs results in a larger thickness of liquid along the channel bottom. Generally, it is this portion that develops a wavy or irregular character first, while at higher and higher vapor flow rates (for the same liquid flow rate), the thinner regions of the annular liquid film then become wavy. Consequently, one might attempt to identify a type of annular flow condition that has special relevance with respect to heat transfer -- that condition for which the film is wavy or irregular about the entire channel wall periphery. However, flow pattern maps, which are intended to identify flow regime transitions are not based upon heat transfer criteria, but upon hydrodynamic criteria. The slug flow/annular flow transitions identified in the present study are based upon the conventional hydrodynamically-based flow pattern descriptions.

The flow regime observations obtained in the present study have been compared with several different flow pattern maps[7-10], but may only be presented in terms of visual projections due to the proprietary nature of the information. One of the flow maps [10] has been developed by Uddin specifically for helical coil geometries. Attempts were made to obtain flow visualization records of the details of secondary flows that have been postulated to occur in curved geometry single- and two-phase systems. Fluorescein dye injection at the inlet to helical coil test sections was used, in combination with high speed photography, video photography, and laser light sheet illumination. None of these techniques proved successful, primarily because of the rapid diffusion of the dye before entering the coiled section itself.

DISCUSSION OF RESULTS

PRESSURE DROP

The actual pressure drop across the coiled test sections are in the process of being extracted from the raw data.

Therefore it is not possible at this time to draw any conclusions regarding trends or generalizations relative to pressure drop. Additionally, however, the proprietary nature prevents any discussion other than that presented in connection with a visual display of the data.

FLOW REGIMES AND FLOW REGIME TRANSITIONS

For every operating condition the flow pattern within the coil test section was identified. Each operating condition thus constituted a data point on one of several flow pattern maps [7-10]. The maps of Baker, Choe and Taite-Dukler are all applicable to horizontally oriented flow channels, and so should not really be expected to predict flow patterns in coiled geometries, which furthermore are slightly inclined with the horizontal in the case of the vertically oriented helical coil systems. The map proposed by Uddin, however, was developed specifically for vertically oriented helical coils, for upward directed two-phase air-water flows. It is worth noting that even for the Uddin map, however, significant differences with the present studies exist. First, only air-water flows were studied by Uddin, with the basis for his map being the experimental observations of air-water flows. Additionally, the coil geometries studied therein had a coil diameter to tube radius ratio (R/r) of 20 to 25, whereas the ratio in the present study was between 9 and 10.

Preliminary examination of the flow regime data indicate that the actual transition (slug-to-annular flow) line for R-113 tests is significantly lower than that predicted by Uddin's transition line. Since the map is semiempirical, and based upon air-water data, it is reasonable to consider modifications to the map which account for variations in properties of fluids, as has been done for the Baker map [9], and the Mandhane map [11], for example.

Preliminary examination of the data seems to indicate little difference in the transition line for circular- or square-cross section channels. The implication is that the hydraulic diameter is the factor of significance in the transition criteria, rather than the channel shape.

Additional observations and conclusions must be deferred until all of the flow pattern maps are available for scrutiny.

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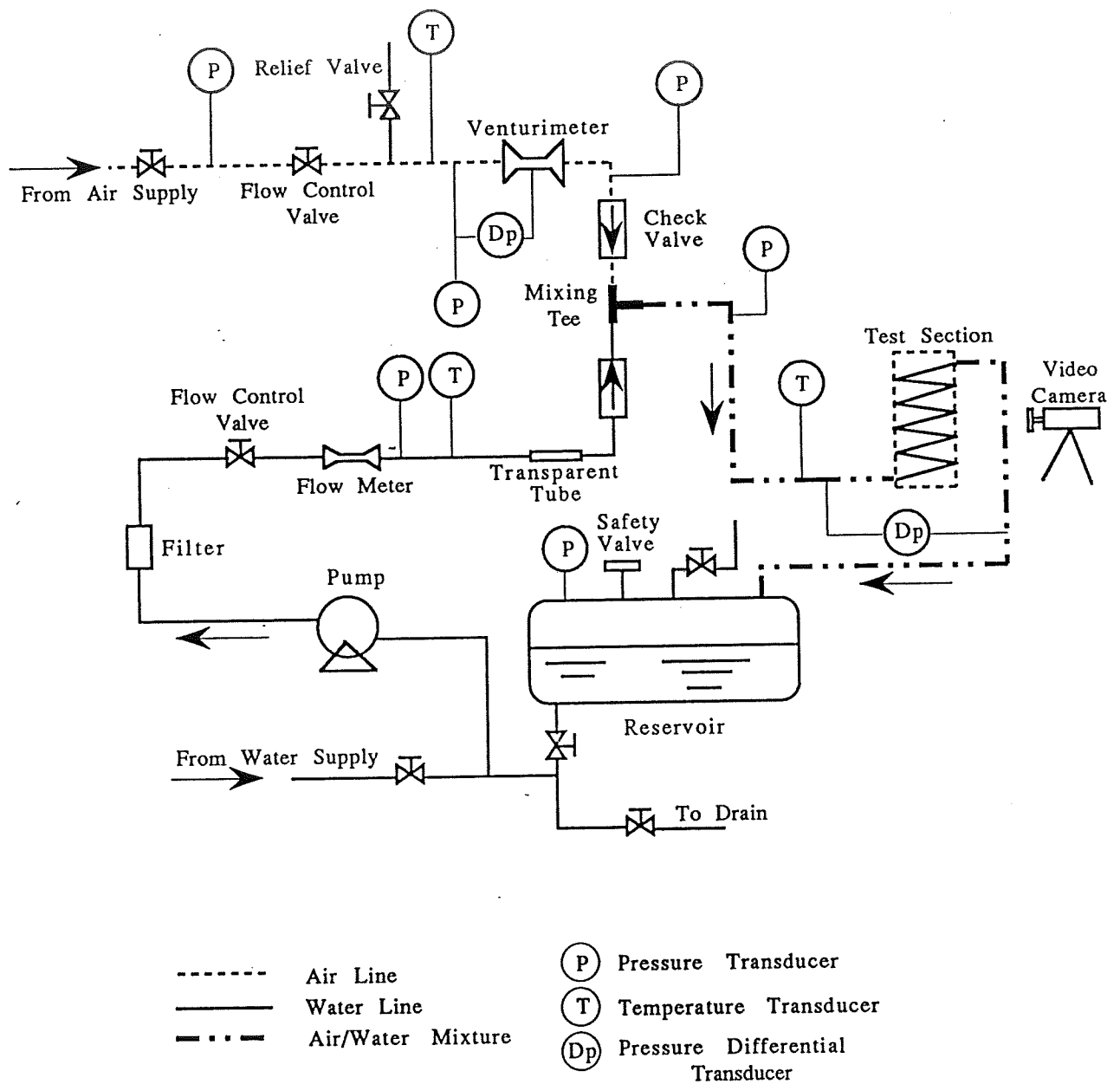
Figure 1   Schematic Diagram of Air-Water
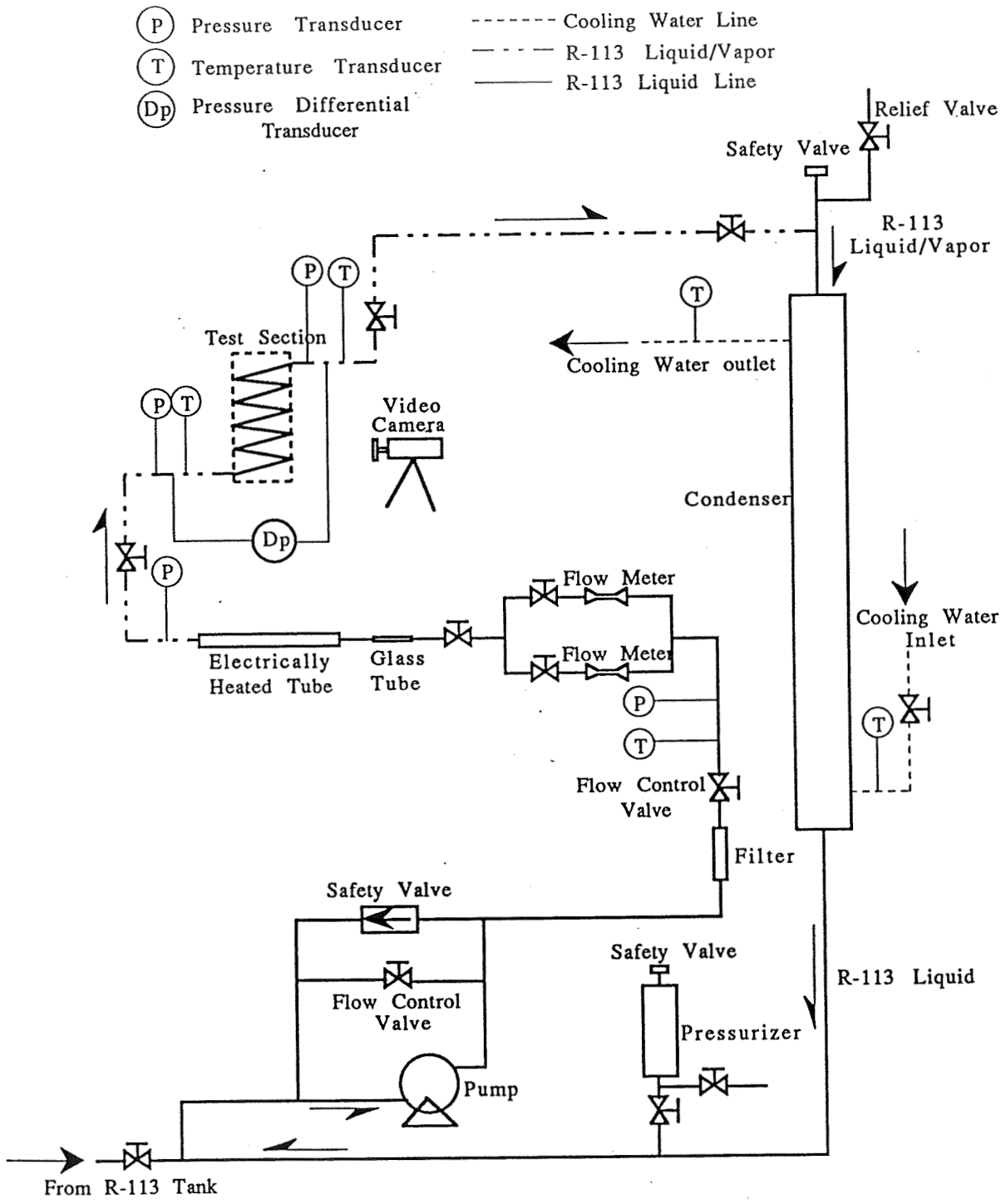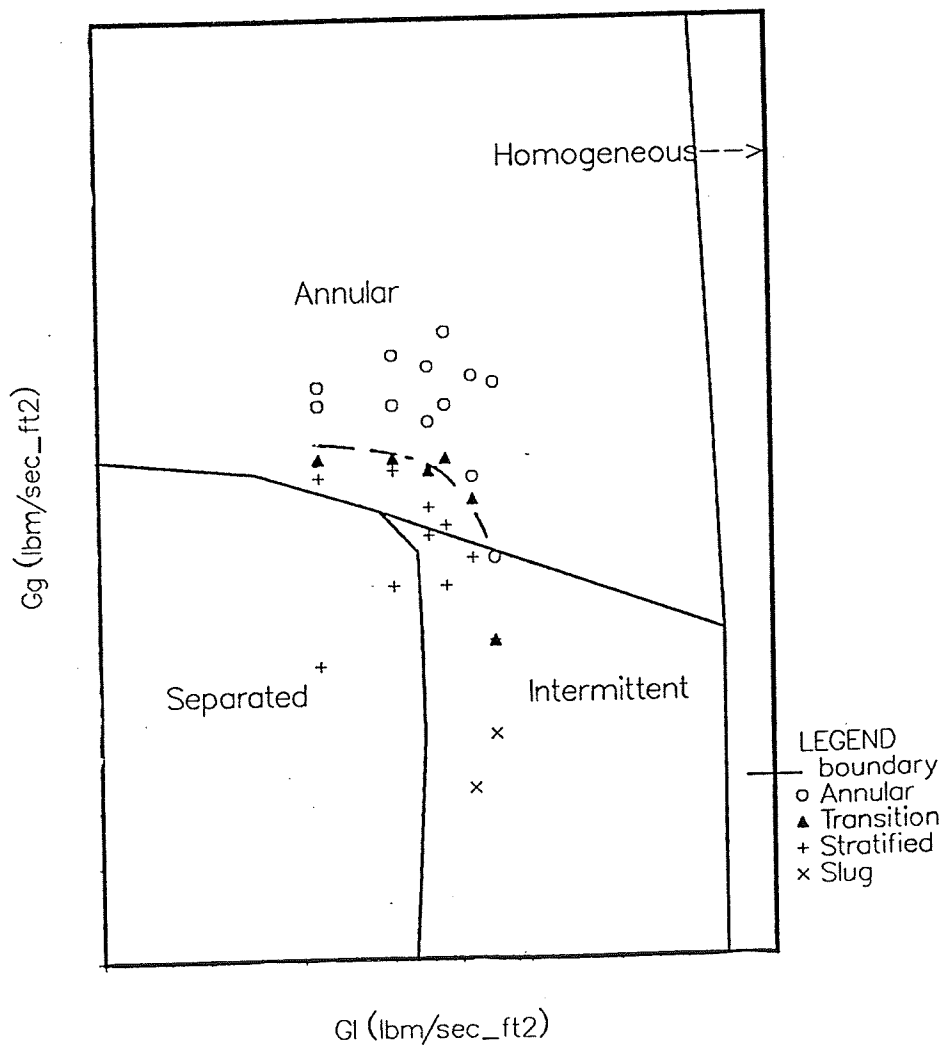Two-Phase Flow Experimental Loop

Legend:

(P) Pressure Transducer

(T) Temperature Transducer

(Dp) Pressure Differential Transducer

------- Cooling Water Line

— · — R-113 Liquid/Vapor

——— R-113 Liquid Line

Relief Valve

Safety Valve

R-113 Liquid/Vapor

Test Section

Cooling Water outlet

Video Camera

Condenser

Flow Meter

Flow Meter

Electrically Heated Tube

Glass Tube

Cooling Water Inlet

Flow Control Valve

Filter

Safety Valve

R-113 Liquid

Safety Valve

Flow Control Valve

Pressurizer

Pump

From R-113 Tank

Figure 2   Schematic Diagram of R-113
Two-Phase Flow Experimental Loop

Figure 3. Comparison of flow regime observations with Choe et al map. (Circular cross-section vertically oriented coil axis, upward flow.)

R113 Liquid/Vapor
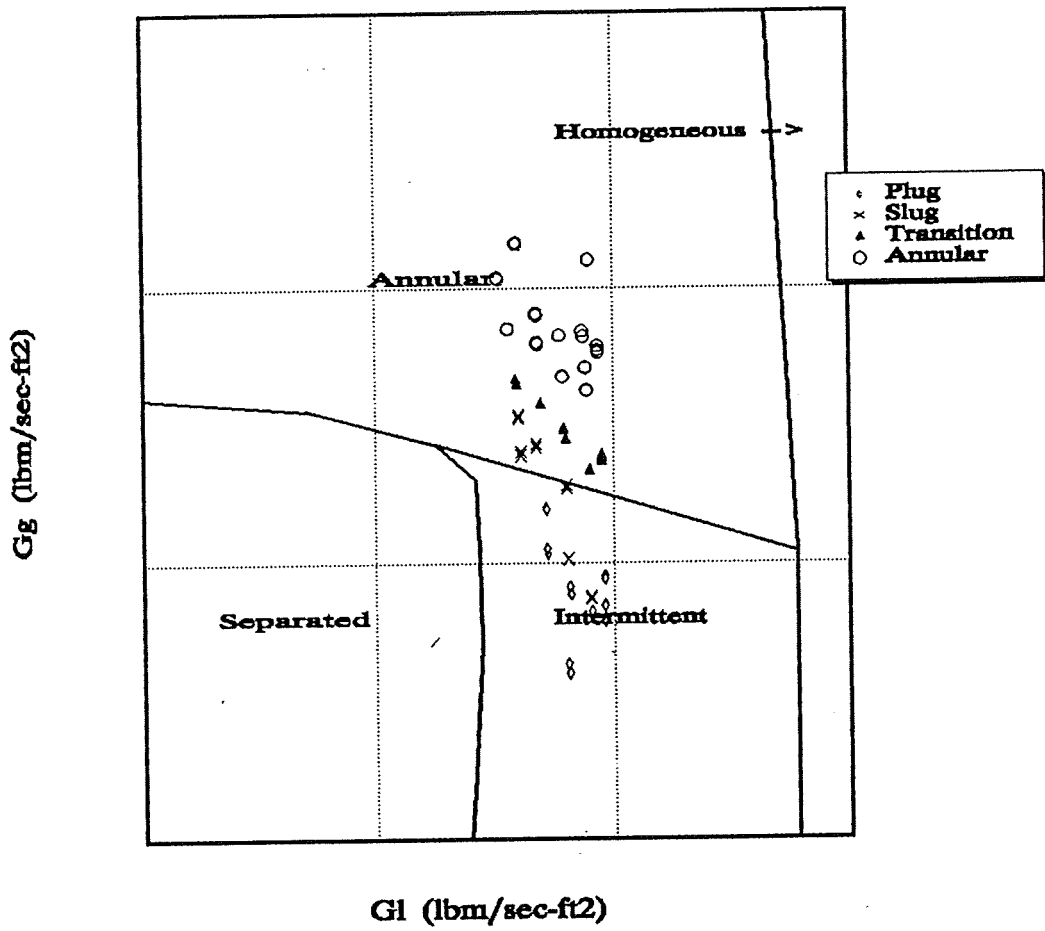Helical Coil, Circular Tube
Vertical-Up Flow
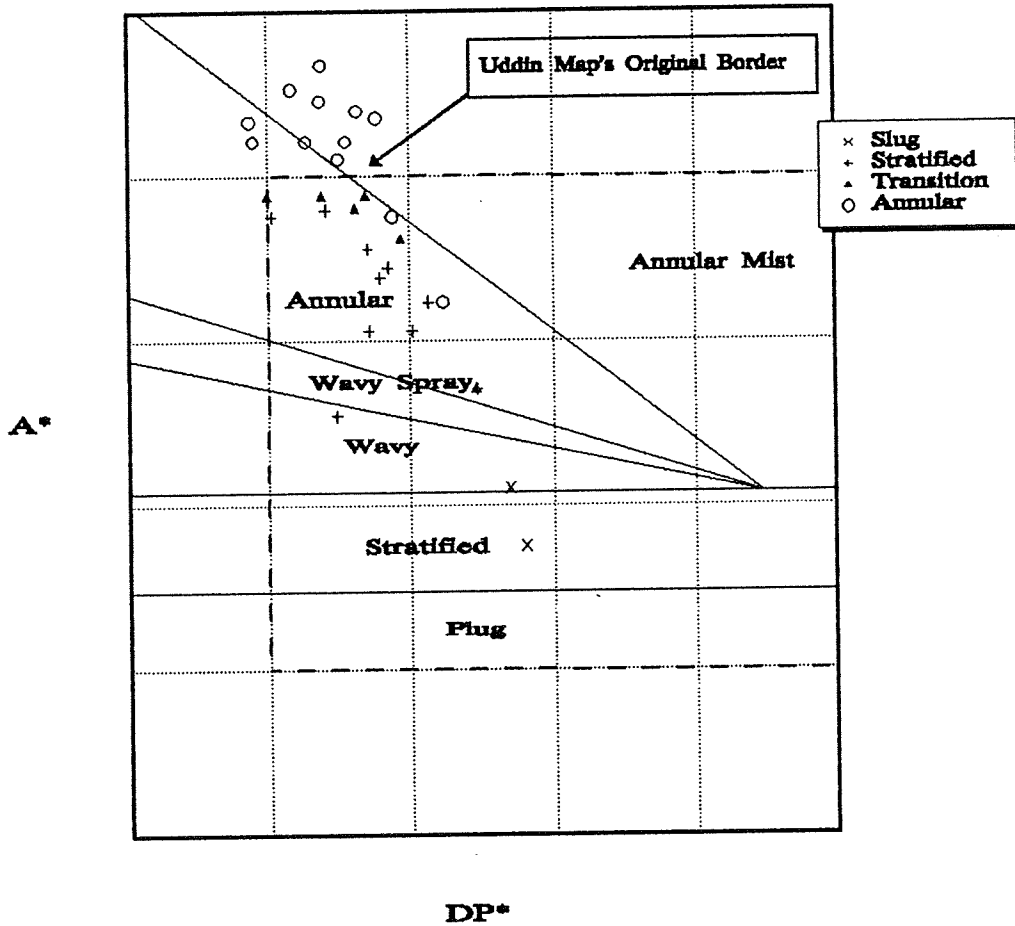
Figure 4. Choe, Weinberg, & Weisman Map

Figure 5. Uddin Flow Map

R113 Liquid/Vapor
Helical Coil, Circular Tube
Vertical-Up Flow

Figure 6.   Uddin Flow Map