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TITLE: TWO-PHASE FLOW STUDIES

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TWO-PHASE FLOW STUDIES

I. BACKGROUND

The two-phase flow program concerns itself with the hydrodynamics and heat transfer characteristics of two-phase flows of interest to the geothermal community. The developing geothermal power industry has specific technical needs related to selecting the size, casing configuration, and production strategies for wells that will optimize the power plant's performance for the specific reservoir being developed. This information can be provided by improved hydrodynamic models of the flow of two-phase geothermal fluids.

The two-phase flow regime is normally characterized by a series of flow patterns that are designated as bubble, slug, churn, and annular flow. The flow pattern is defined by the values of both the liquid and gas (or vapor) superficial velocities as depicted in the flow regime map shown in Fig. 1. The superficial velocities are quantities computed on the basis that the mass of each phase flows alone in the pipe, filling the entire cross-sectional area. Naturally flowing geothermal wells can operate over the entire flow pattern range, making it necessary to be able to predict pressure drops, holdup, and heat transfer rates for each pattern. The physical flow patterns associated with these two-phase flow regimes are shown in Fig. 2 for vertical flow.

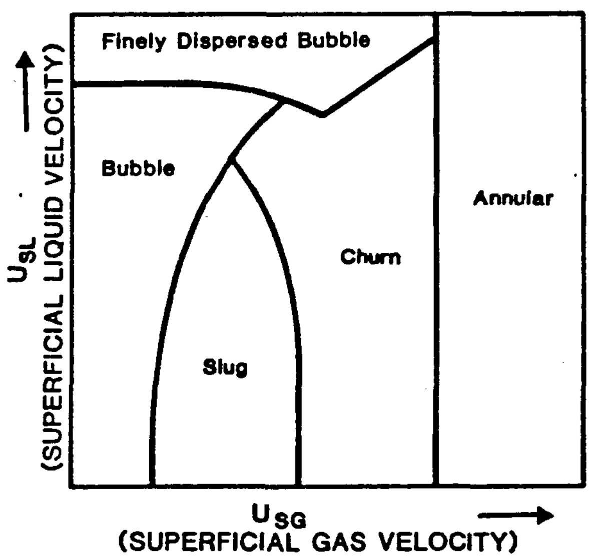

Fig. 1. Flow regime map for two-phase flows.

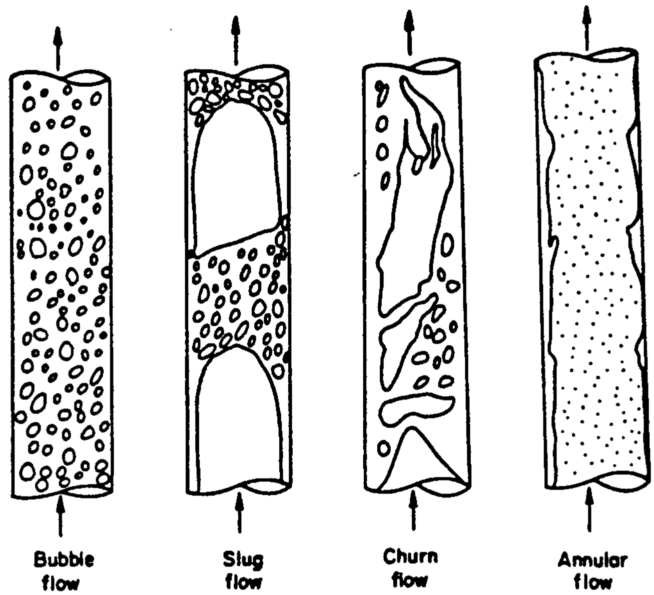

Fig. 2. Flow patterns for vertical two-phase flow.

II. STRATEGY

Hydrodynamic models are available for bubble and slug flow, which allow the calculation of holdup, frictional pressure drop, and heat transfer for these two patterns from physically based models. The annular flow regime is currently being investigated in several laboratories and improved hydrodynamic models for frictional pressure drop and heat transfer for this flow pattern can be expected within the near future. The flow pattern known as churn flow has received very little scientific attention, largely because it is a highly unsteady flow pattern with stochastic or random features. This lack of attention cannot be justified, however, because calculations predict that the churn flow pattern will exist over a substantial portion of the two-phase flow zone in producing geothermal wells. Churn flow can also be expected in surface piping and equipment, thus its understanding and the development of a predictive hydrodynamic model are necessary to complete the analytical modeling of two-phase flows in geothermal systems. Churn flow is being investigated by the University of Houston under contract to Los Alamos.

Most of the relevant experimental data available on two-phase flows have been obtained from laboratory tests with flowing air-water mixtures (i.e., without a phase change). Air-water flows are technically two-component two-phase flows and lack the evaporation and condensation phenomena present in a true single-substance two-phase flow. Brown University has constructed and is operating a unique flow research facility dedicated to two-phase flow of a single substance. The objective is to compare the Brown University one-component results with the available two-component results to evaluate the significance of evaporation, condensation, and compressibility effects. Brown University is conducting this research under contract to Los Alamos.

III. CHURN FLOW STUDIES AT THE UNIVERSITY OF HOUSTON

A. Status of Existing Correlations

The mathematical models of the two-phase flow patterns already developed by the University of Houston have been used by other investigators developing computer models to simulate the entire two-phase flow process. These computer simulations are entirely dependent upon realistic mathematical models of the complex flow phenomena, such as the ones developed at Houston. Under a prior DOE contract and current Los Alamos contract, the Denver Research Institute and Coury and Associates, Inc. have completed an investigation of two-phase flow in geothermal wells. This project included the development of a computer model of the pressure drop in wellbores during two-phase flow and the acquisition of test data from flowing geothermal wells for validation of the model. In a recent report published by the Denver Research Institute entitled, "Theoretical and Experimental Research on Two-Phase Flow in Geothermal Well Bores," the investigators tried various mathematical models for the two-phase pressure drop calculations to be incorporated in their computer model. Quoting from this report: "A new set of two-phase pressure drop correlations, developed at the University of Houston, were coded and tested in the model. Results with this new correlation set showed the best agreement to date between model predictions and field test data."

This represents a strong technical endorsement of the mathematical models developed at Houston as opposed to those offered by other investigators. Computational problems did arise, however, in the churn flow regime, which is the basis for conducting the current research at the University of Houston. The calculations for churn flow had to be based on available models for bubble, slug, and annular flow patterns and this approach led to difficulties and inconsistent results.

The objective of the current University of Houston research is to develop a self-consistent hydrodynamic model for churn flow based on sound physical principles that can be used as a basis for predicting holdup, frictional pressure drop, and heat transfer for this flow pattern in geothermal systems. This work is required to develop a technical understanding of churn flow that can be used in available computer models along with the existing hydrodynamic models for bubble and slug flow and the improving models for annular flow. These activities are summarized in Table I.

B. The Transition to Churn Flow

Churn flow represents the evolution of the slug flow pattern as the superficial gas or vapor velocity is increased beyond the transition boundary. The highly unsteady flow patterns of churn flow with their stochastic or random features are a marked departure from the regular and periodic features of slug flow. The University of Houston has performed a series of experiments on slug flow and its transition boundaries as the starting point in pursuing their understanding of churn flow.

Experiments for fully developed turbulent slug flow were conducted with air-water mixtures flowing in a vertical smooth Plexiglas pipe with an inside diameter of 5 cm and a length of 11 m. Air and water were mixed together in an injection nozzle; water flowed axially, while air was injected radially through a horizontal row of 80 cylindrical holes. The range of conditions covered in these experiments is shown in Fig. 3 where the points represent conditions of the experimental runs and the curves represent the theoretical transition boundaries. The solid triangles in the bubble flow regime and the solid circles in the churn flow regime are from previously reported experiments. Open circles indicate slug flow was observed and the solid squares indicate the

Table I

THEORETICAL AND EXPERIMENTAL STUDY
OF CHURN FLOW IN VERTICAL TUBES

THE TECHNICAL PROBLEMS:

- DEVELOP A PREDICTIVE MODEL FOR THE TRANSITION FROM SLUG TO CHURN FLOW.
- DEVELOP A PREDICTIVE MODEL FOR THE CHARACTERISTICS OF CHURN FLOW INCLUDING HOLDUP AND PRESSURE DROP.

RELEVANCE:

SLUG AND CHURN FLOW ARE KNOWN TO EXIST OVER MUCH OF THE LENGTH OF A FLASHING GEOTHERMAL WELL. IN CHURN FLOW THE FLUID PATTERN IS HIGHLY CHAOTIC AND NO SUITABLE PREDICTIVE MODEL EXISTS.

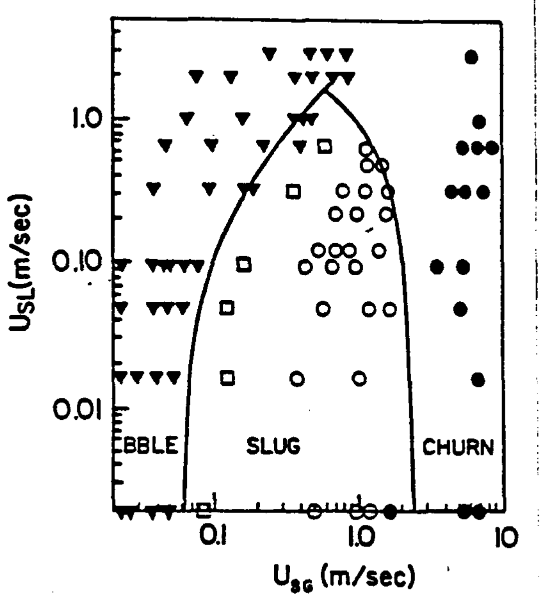

Fig. 3. Experimental data plotted on flow regime map.

transition from bubble to slug flow. The vertical and horizontal scales are the superficial liquid and gas velocities, respectively.

Volume-average void fraction measurements over a wide range of liquid and gas rates were accomplished by a special quick closing valve system, which consisted of two identical valve/actuator sets. The valves utilized were full ported ball valves so that when they were fully open the flow was completely unobstructed. The spring-diaphragm actuators were designed to ensure a fast closing action of the ball valves. The total time interval required to move the ball from a fully open to a fully closed position was determined at 0.053 s. The actuators were connected to a common on-off electrical switch to ensure a simultaneous closure of the valves.

The length of the measuring station was made short (equal to 0.346 m) so that it could entrap the central portion of liquid slugs or of Taylor bubbles, while the distance between the injection nozzle and the measuring station was made long (equal to 130 pipe diameter) to ensure fully developed slug flow within the measuring station. The relative experimental uncertainties in the measured void fractions were less than 1%.

Velocities and lengths of Taylor bubbles and liquid slugs were measured by means of a photographic technique which utilized a 16 mm movie camera at a speed of 16 frames/second. The photographs were taken with the camera fixed with respect to the vertical column. From these measurements, the ratio between the length of the Taylor bubble and the length of the slug unit (β) could be calculated for each gas-liquid flow rate pair. With the measured values of α_{TB} (void fraction of the Taylor bubble), α_{LS} (void fraction of the liquid slug), and β, the volume-average void fraction of a complete slug unit could be determined. Because of the variations that occur in gas-liquid slug flows, repeated measurements of void fractions, velocities, lengths of Taylor bubbles, and lengths of liquid slugs were taken for each given pair of superficial velocities.

Theoretically computed values were obtained from the existing slug flow model for each experimental condition that was run. The experimental and theoretical results for β, α_{LS}, and α_{TB} were compared and in all cases the agreement was very good. The measured values of α_{TB} fell in the narrow range of 83.2 to 87.2%, while the theoretical values ranged from 85.8 to 88.1%. With these corroborating results as a starting point, the University of Houston is initiating a similar experimental program in the churn flow regime and in the transition region between slug and churn flow.

C. Current Research

The slug flow model has been completed and tested against experimental results from the air-water two-phase vertical flow loop. A technical paper has been prepared on these results. The bubble/slug and slug/churn flow transition boundary investigation is progressing well and nearing completion. Emphasis is currently being directed at flow experiments within the churn flow regime and on the development of new instrumentation to permit dynamic measurements of the void fraction during churn flow.

A new radio frequency probe has been developed for measuring the local void fraction. It has been used to measure the void fraction in slugs as the conditions for churn flow were being approached. A possible theory is that the local void fraction in the slugs increases to the point where coalescence takes place and the slugs break up causing churning. Data from this new probe are being analyzed.

The microwave cavity cross-sectional average void fraction measurement system has been designed, constructed, and initially tested. Major fringe effects were noted that make the system sensitive to conditions adjacent to the actual cavity. Theoretical and experimental investigations are being undertaken to correct this problem.

A new method for dynamic measurement of both the direction and magnitude of the wall shear stresses has been developed. This technique is based on the use of a microprobe embedded in the tube wall. Measurements have been made over a range of gas flow rates as the system moves from churn to annular flow. Use of this probe has verified not only the large changes in shear stress magnitude that occur during churn flow, but also the fact that the flow velocity alternates in direction near the wall. These activities, representing significant new accomplishments in two-phase flow research, are summarized in Table II.

IV. TWO-PHASE FLOW EXPERIMENTS AT BROWN UNIVERSITY

A. Two-Phase Flow Facility

Brown University has constructed and is presently operating a unique two-phase flow research facility specifically designed to address flow problems of relevance to the geothermal industry. An important feature of the facility is that it is dedicated to two-phase flow of a single substance. Freon R-114 is currently being used as the working fluid as this allows two-phase experiments to be performed at manageable temperatures and pressures. Through the use of fluid dynamic similarity relations, the R-114 data can be extrapolated to steam-water systems.

Because gravity plays an important roll in all two-phase flows, the experimental set-up is flexible enough to allow fluid flow in horizontal, vertical and inclined directions. The facility allows the visual observation

Table II

ACCOMPLISHMENTS

- SLUG FLOW MODEL COMPLETED AND TESTED.
- NEW RADIO FREQUENCY PROBE DEVELOPED FOR LOCAL VOID MEASUREMENTS.
- MICRO WAVE CAVITY CROSS-SECTIONAL AVERAGE VOID MEASUREMENT SYSTEM CONSTRUCTED.
- WALL SHEAR STRESS PROBE DEVELOPED AND TESTED IN CHURN FLOW.
- BUBBLE/SLUG AND SLUG/CHURN FLOW TRANSITION BOUNDARIES INVESTIGATED.

of the flow patterns and the determination of the frictional pressure losses in a wide range of flows from purely liquid through two-phase flows of varying quality. This facility is uniquely capable of producing experimental results that can be used to check the reliability and applicability of various two-phase flow models that are currently used to model geothermal flow systems. It can also investigate the flow in a typical geothermal well, including the step changes in diameter that occur when the diameter of the well casing changes. Photographs of this facility at Brown University are shown in Figs. 4 and 5.

Brown University is performing comparisons between the data obtained from the two-phase flow testing facility using R-114 as the working fluid and pertinent two-phase two-component experimental data available in the open literature. Particular attention is being directed toward data published by the University of Houston on air/water two-phase systems. Where significant discrepancies are apparent in the experimental data from one-component and two-component systems, attempts will be made to characterize these discrepancies in terms of the Reynolds number, Froude number, and Mach number of the flows.

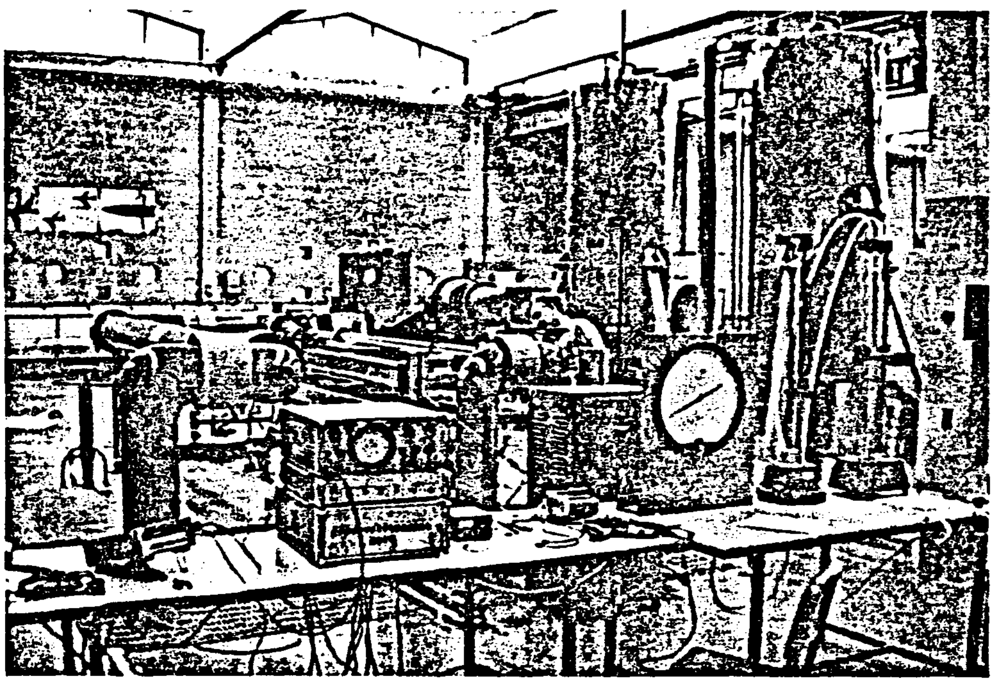

Fig. 4. Brown University two-phase flow facility viewed from first-floor level. Large tanks are freon booster and accumulator storage vessels. Condenser, dump tank, and chiller are located on basement level.

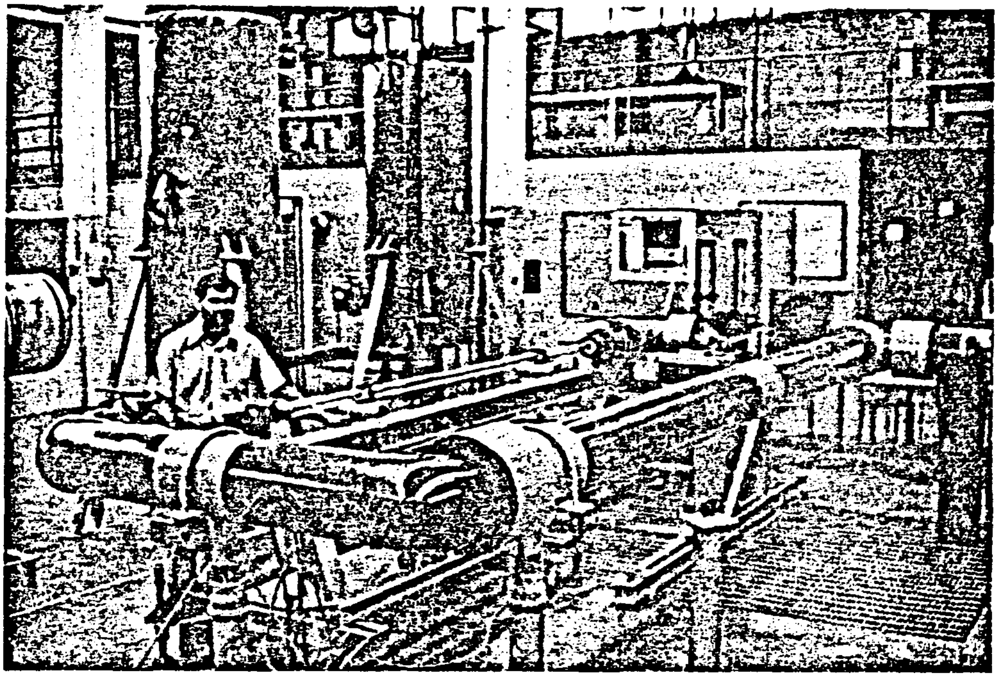

Fig. 5. View of flow loop with glass test section in horizontal position.

The two-phase flow facility has already been employed for the successful measurement of pressure drops in horizontal two-phase flows. The 10-m test section has been reoriented into a vertical configuration, and numerous test runs have been carried out. Remarkable still photographs have been produced, showing a wide range of flow conditions within the test section (see Figs. 6-9).

B. Two-Fluid Model

A two-fluid model is being developed that consists of a set of equations that govern the flow (continuity, momentum, energy, and dissipation), each written for one of the two phases present. Only three of these equations are independent, and there are more unknowns than independent governing equations. The need arises, therefore, for closure equations describing certain phenomenological aspects of the flow, namely the shear forces acting on the fluid at the boundaries and the interface between the phases. Since the model is a two-fluid one, slip between the phases (i.e., two velocity fields) is built into the basic equations.

One of the intriguing features of the Brown work that sets it apart from the work of others is the effect of phase change on fluid compressibility. The compressibility of the fluids we are dealing with under typical geothermal conditions is made up of three contributions: liquid compressibility, vapor compressibility, and phase-change compressibility. The first two of these are actually quite small because the speed of sound in each case is high. Since the low-quality sound speed is only a few tens of m/s, the bulk of the contribution to the fluid compressibility comes from the phase change effect. No such effect is present in laboratory work that involves mixtures of air and water since both components may be taken as incompressible. A strong acceleration term will result from this phase-change compressibility effect that will lead to a more rapid pressure drop, or alternatively an increase in slip between the phases or a decrease in void fraction.

Work on the two-fluid model and a similarity analysis are continuing on the theoretical side. Measurements in the vertical test section are underway, and preparations are now being made to design, fabricate, and install an abrupt area-change test section that would simulate a geothermal well with a change in production casing diameter.

C. Allowable Void Fractions

Brown University has examined the physical mechanisms that impose limits on the existence of two-phase flow in a horizontal pipe. With the aid of this analysis and the use of the Martinelli two-phase flow variable, they have developed a method for determining the range of possible void fractions for a given two-phase flow. This method allows a direct comparison to be made for the void fraction predicted by available two-phase flow correlations, as well as between correlation predictions and actual experimental results. They have used this method to compare four well-known void fraction correlations against each other and with experimental results obtained from the Brown University two-phase flow facility. These comparisons are shown graphically in Fig. 10.

The horizontal scale is the Martinelli variable (X), which dates back to the original two-phase flow correlation proposed by Martinelli. Martinelli expressed his variable as the ratio of the superficial liquid pressure drop to the superficial gas pressure drop, i.e.,

$$X^2 = \left(\frac{\Delta P}{\Delta L}\right)_{\text{liquid (superficial)}} \Big/ \left(\frac{\Delta P}{\Delta L}\right)_{\text{gas (superficial)}}$$

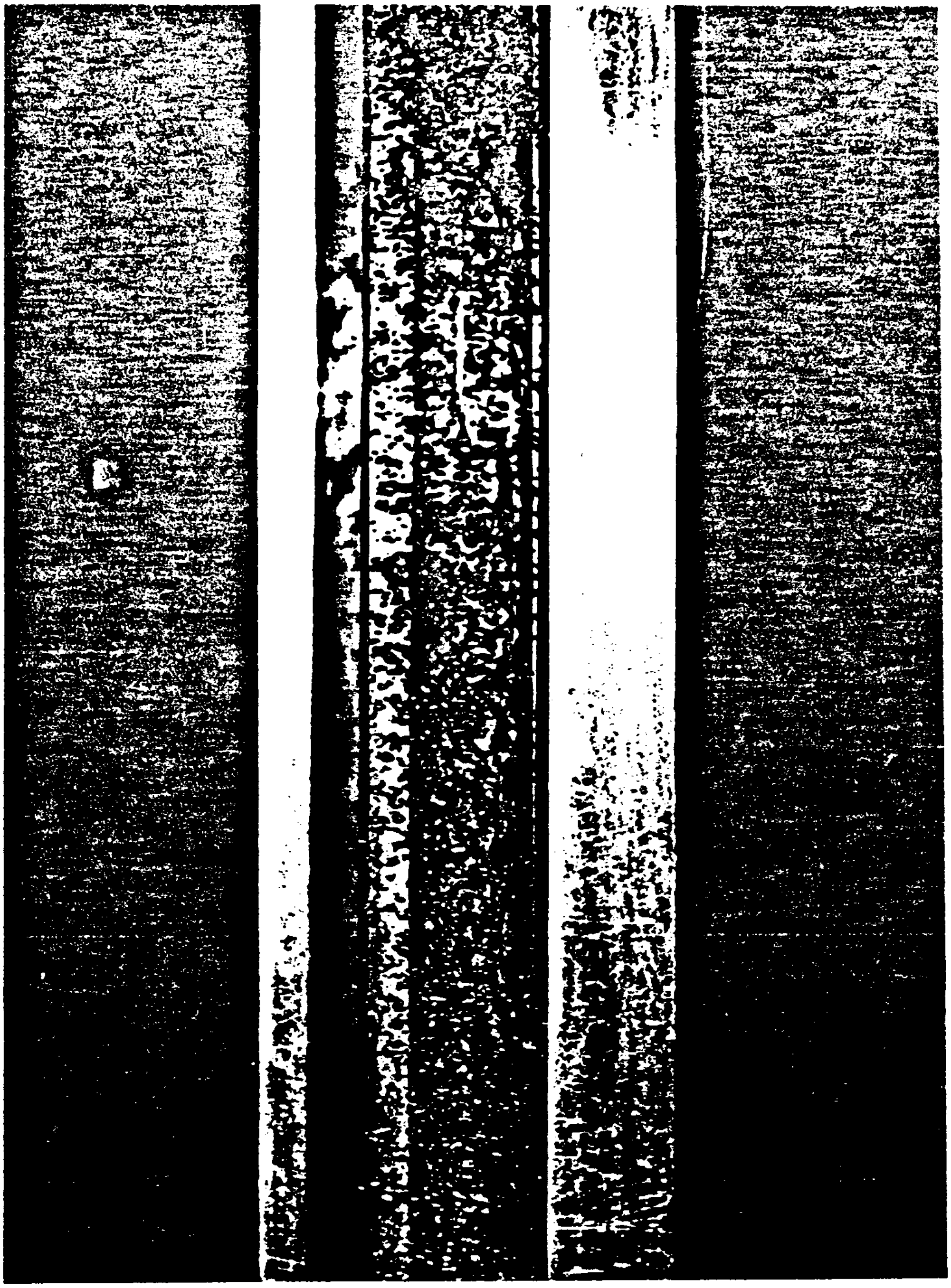

Fig. 6. Rising swarm of small bubbles. This shows the three-dimensional nature of the flow in that a large number of bubbles rise together in a tube without much interaction. Note that very little coalescence is taking place despite the large number of bubbles.

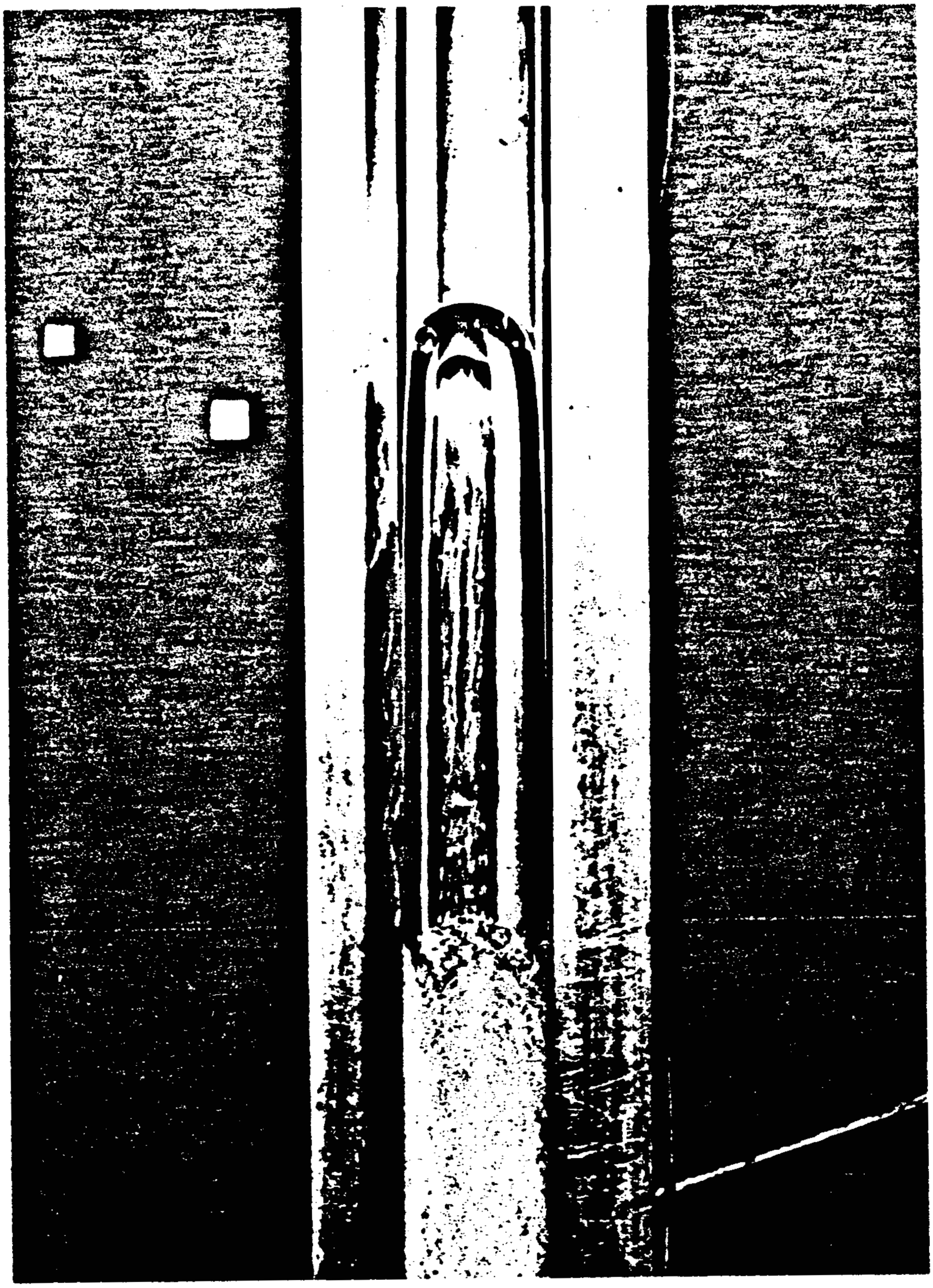

Fig. 7. Mature Taylor bubble. This nearly perfectly symmetrical bubble is about 8.2-in. long and is growing longer as it rises into the liquid column.

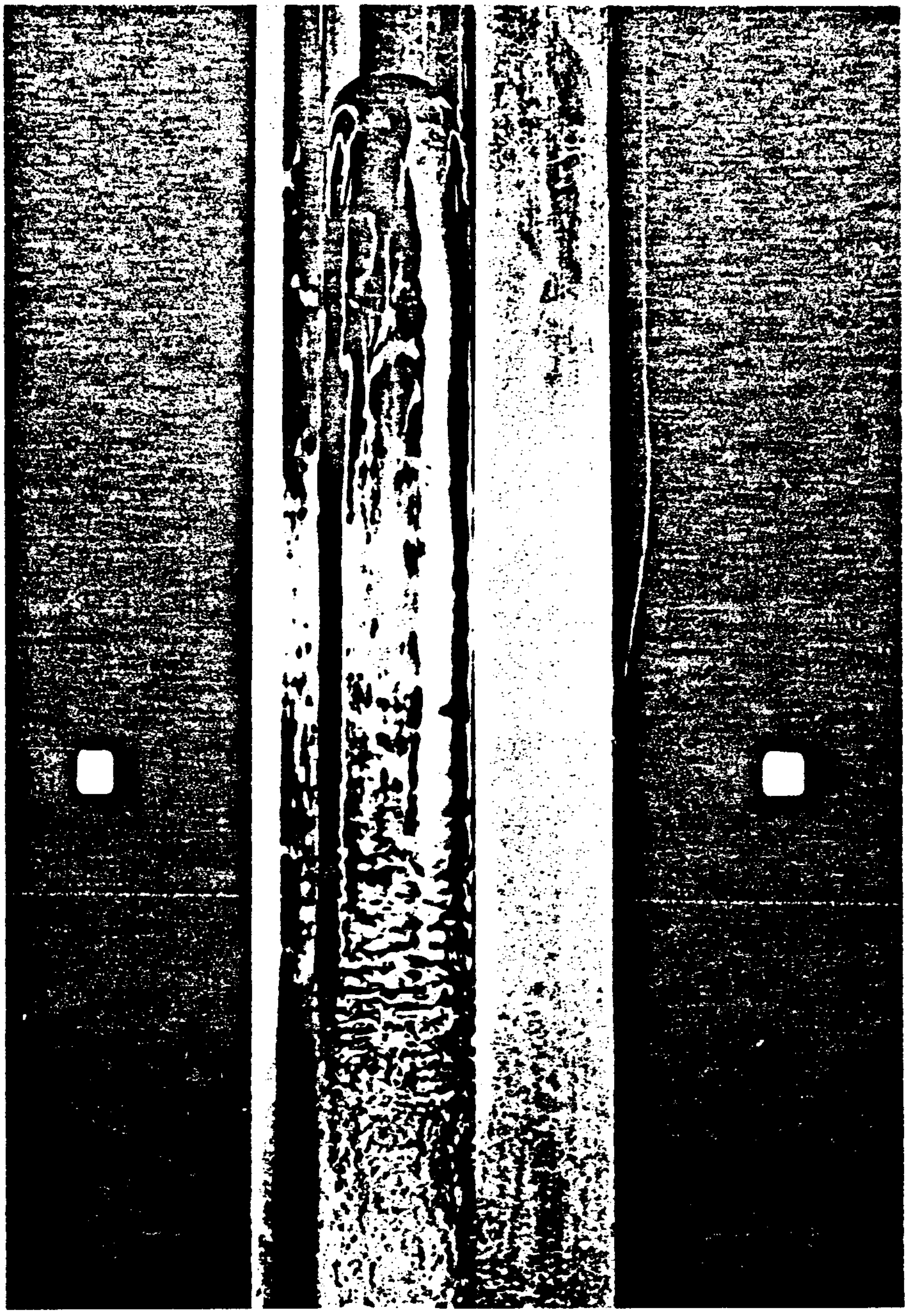

Fig. 8. Mature Taylor bubble. A pattern of ripples or waves can be seen about the lower portion of this 11-in. long bubble. These ripples mark the beginning of the end for the bubble.

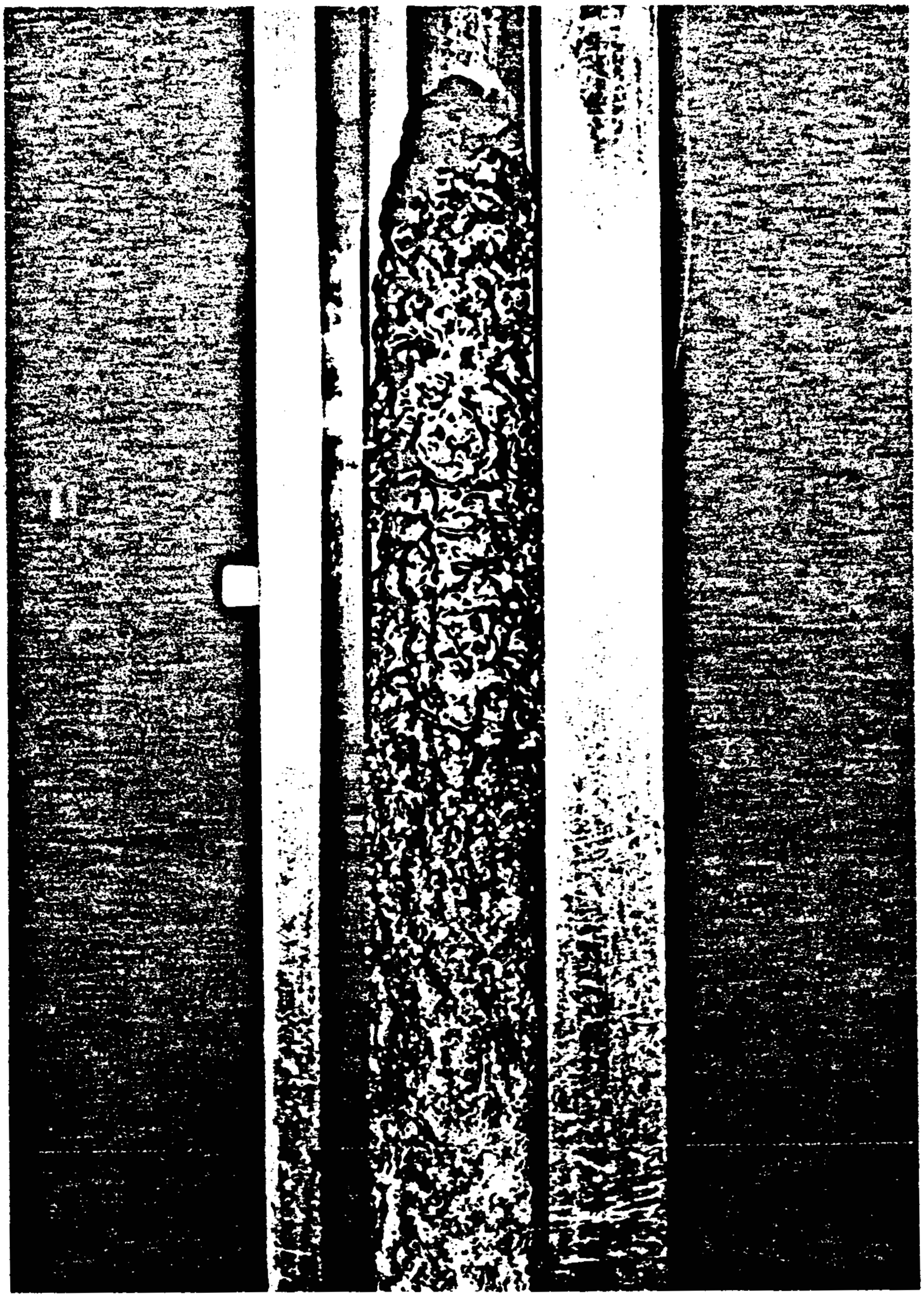

Fig. 9. Collapsing Taylor bubble. In this remarkable photograph we see the pronounced rippled flow in which waves have overspread the entire surface of the Taylor bubble. In a few tenths of a second, the bubble will vanish in a blur of froth.

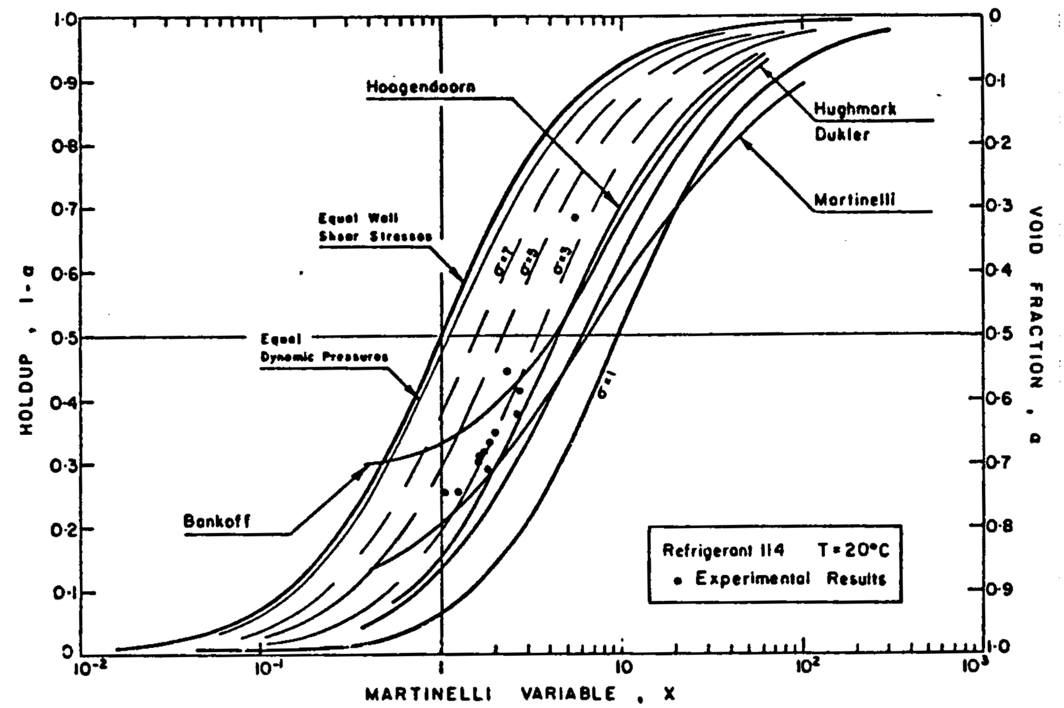

Fig. 10. Holdup as a function of Martinelli variable.

The vertical scales are the holdup (H) and the void fraction (α), which are related by the simple expression:

$$H = 1 - \alpha \quad .$$

When $H = 1$ ($\alpha = 0$), the flow is entirely in the liquid state, and when $H = 0$ ($\alpha = 1$), the flow is entirely in the vapor or gaseous state,. Based on the definition of the Martinelli variable (X), it is clear that the holdup will approach unity at large values of X and will approach zero at small values of X.

Based on the Brown analysis, it may be concluded that two-phase flow can exist only between the limits of equal phase velocities and equal wall shear stresses. Defining σ as the ratio of the average gas velocity to the average liquid velocity ($\sigma = w_g/w_l$), one boundary of the allowable two-phase flow region will be the $\sigma = 1$ line. This represents the no-slip case and results in the highest void fraction for a given value of X. The limit of equal wall shear stresses produces the maximum slip ratio and results in the lowest void fraction for a given value of X. Both of these limiting cases are plotted in Fig. 10 and the region between them represents the envelope of allowable two-phase flows.

Dukler has compared several void fraction correlations in an attempt to find one that gives the best agreement with the experimental results contained in his data bank. The correlations that he tested are the ones proposed by Martinelli, Hoogendoorn, Hughmark, and Bankoff. He came to the conclusion that although none of these correlations was entirely satisfactory over the whole range of his data, the one by Hughmark performed the best overall, followed closely by Hoogendoorn's. Predictions based on these correlations are also plotted in Fig. 10. Hughmark's and Hoogendoorn's correlations appear as constant slip lines that correspond to a slip ratio of between 2 and 3, suggesting that two-phase flow proceeds with constant slip ratio. Martinelli's correlation falls between the previous two near the middle of the void fraction range and diverts at the two ends of the range. Martinelli's correlation suggests, however, that two-phase flow proceeds with an increasing slip ratio. Bankoff's correlation, although it falls between Hoogendoorn's and Hughmark's correlations at the lower half of the void fraction range, eventually diverts and levels off at a void fraction value of about 0.7.

Experiments performed at Brown do not cover the entire void fraction range. Within the range covered, however, the void fractions observed are lower than those predicted by the correlations at a given X, although they fall close to Hoogendoorn's correlation. These results were obtained during the flow of R-114, which evaporates as it flows downstream. This phase change results in an increase of the amount of vapor and consequently a decrease in the mean density of the flow. This gives rise to compressibility effects. The pressure decreases more rapidly and the vapor is accelerated faster than the liquid. Thus, the slip ratio increases and the void fraction decreases. It can be concluded that compressibility effects reduce the void fraction.

None of the correlations tested take compressibility effects into consideration, since they are developed from experimental results obtained during two-component (e.g., air-water) two-phase flow, where the fluids can be considered incompressible. Consequently, these correlations overestimate void fractions taken during the flow of a one-component fluid.

The void fraction graph developed in this study can be a very useful tool in the future assessment of void fractions in two-phase flow. Besides showing the allowable void fraction region, it has the advantage that experimental results from many experiments obtained under many flow conditions can be indicated on it. Furthermore, curves corresponding to various void fraction correlations can easily be superimposed on it. Consequently, this method can serve to compare experimental results against correlations and correlations against each other.