MASTER

TWO PHASE FLOW IN GEOTHERMAL SYSTEMS

FINAL REPORT

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I. CONTRACT MANAGEMENT SUMMARY

During the contract period, the following people have worked on the project:

Dr. Paul F. Maeder, Professor of Engineering

Dr. Joseph Kestin, Research Professor of Engineering

Dr. Ronald DiPippo, Adjunct Professor of Engineering (Research)

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Mr. Dimitris E. Nikitopoulos, Research Assistant

Mr. Raymond N. Laoulache, Research Assistant

Mr. Roger Follansbee, Technical Assistant

II. STATEMENT OF WORK

The following has been excerpted from the official AWARD/CONTRACT Agreement for the present work.

The contractor shall perform experimental studies to better understand the physical mechanisms involved in two-phase, single substance flow and their thermodynamic and fluid-dynamic implications. The work shall be performed utilizing a two-phase flow research facility available at the University.

Specific tasks include the following:

1. Measure flow properties over a wide-range of flow conditions from low-flash Mach number to high-flash Mach numbers and so to simulate actual two-phase flow over the full length of a geothermal well from the flash horizon to the choked wellhead. Measurements and observation shall be aimed at calculation of void fraction and friction factors and entropy production. These studies shall be obtained on vertical flow with constant

cross-sections and with choked flow particularly for the case of abrupt enlargement. Smooth transition of choked flow to a larger cross-sectional area may be initiated.

2. Develop a theoretical model for two-phase flow based on the two-fluid approach.

III. VERTICAL FLOW IN CONSTANT-AREA PIPE

1. Test Facility

The Brown University Two-Phase Flow Research Facility [1] was re-configured to permit observation and measurement of flashing flows in a vertical section of glass tubing. The basic design was unchanged from the previous testing program that involved horizontal two-phase flow, but the vertical test section necessitated certain modifications to the instrumentation. A schematic diagram of the test section is shown in Fig. 3b of the report attached as Appendix A. The complete description of the apparatus and its use in flow testing can be found in Appendix A.

2. Test Plan

Two series of tests were performed at different values of the flashing Mach number, Ma^* , while keeping the flashing Froude number, Fr^* , and the flashing Reynolds number, Re^* , roughly constant. The values of these important dimensionless variables were as follows:

	<u>Series 1</u>	<u>Series 2</u>
Flash Mach no., Ma^*	0.498	0.331
Flash Froude no., Fr^*	1.62	1.60
Flash Reynolds no., Re^*	238,000	269,000

The 13% difference in Re^* should not be significant since the flows are both well into the turbulent regime.

3. Definitions of Terms

The losses that occur in two-phase flow can be characterized in a number of ways. We use five different parameters in this regard: the reduced kinetic energy change, ΔK_R ; the reduced energy change, ΔE_R ; the reduced pressure difference, ΔP_R ; the entropy production, Sp_R ; and the Euler number, Eu . Each of these quantities can be evaluated locally along the flow and represented as a function of the ratio v/v_f where v is the local specific volume of the liquid and vapor mixture. At the flash point, $v=v_f$ and $v/v_f=1$. As one samples farther downstream, one finds that v increases because of phase change. One may convert easily from v/v_f to z/D as the independent variables, as will be shown later.

These loss parameters are defined as follows.

(i) Reduced pressure difference

$$\Delta P_R = \frac{\left[\frac{\Delta P}{\Delta z} \right]_{2-Ph}}{\left[\frac{\Delta P}{\Delta z} \right]_{LIQ}^*}, \quad (1)$$

where

$$\left[\frac{\Delta P}{\Delta z} \right]_{2-Ph} = \text{acceleration and wall friction and hydrostatic pressure drops (measured)}$$

$$\left[\frac{\Delta P}{\Delta z} \right]_{LIQ}^* = \text{wall friction and hydrostatic pressure drops}$$

$$= \frac{f}{D} \rho_f^* \frac{w^*}{2} + \rho_f^* g$$

(ii) Entropy production

$$S_{PR} = \frac{\left[T \frac{\Delta S}{\Delta Z} \right]_{2-Ph}}{\left[T \frac{\Delta S}{\Delta Z} \right]_{LIQ}^*} \quad , \quad (2)$$

where

$$\left[T \frac{\Delta S}{\Delta Z} \right]_{2-Ph} = \text{dissipated energy (entropy production) in 2-phase flow (calculated from measurements)}$$

$$\left[T \frac{\Delta S}{\Delta Z} \right]_{LIQ}^* = \text{entropy production in pure liquid flow at flashing conditions}$$

$$= \frac{f w^{*2}}{D 2} \quad .$$

(iii) Reduced kinetic energy change

$$\Delta K_R = \frac{\left[\frac{\Delta(w^2/2)}{\Delta Z} \right]_{2-Ph}}{\left[T \frac{\Delta S}{\Delta Z} \right]_{LIQ}^*} \quad , \quad (3)$$

where

$$\left[\frac{\Delta(w^2/2)}{\Delta Z} \right]_{2-Ph} = \text{change in kinetic energy of 2-phase flow (calculated from measurements).}$$

(iv) Reduced energy change

$$\Delta E_R = \Delta K_R + S_{PR} \quad . \quad (4)$$

(v) Euler number

$$Eu = \frac{P_{2-Ph} - P_{sat}^*}{P_{dyn}^*} \quad , \quad (5)$$

where

$$P_{\text{dyn}}^* = \frac{1}{2} \rho_f^* (w^*)^2 = \text{dynamic pressure of liquid at flash conditions.}$$

4. Results and Interpretation

The chosen independent variable, v/v_f , is a function of the dimensionless distance measured downstream from the flash horizon, z/D , for any particular value of the flash Mach number, Ma^* . The functional relationship between v/v_f and z/D is depicted in Fig. 1 for $Ma^* = 0.331$ and 0.498 , i.e., Series 2 and 1, respectively. This may be used to relate the results that are about to be presented to positions in the flow downstream of the flash point.

The primary observation that can be made from the pressure drop measurements that are presented in Figures 2 and 3 is that the total pressure drop in two-phase flow for Series 1 and 2 is only a fraction of the pressure drop that would occur in single-phase liquid flow under flashing conditions. The pressure loss variable ΔP_R is equal to unity at flashing ($v/v_f = 1$). The value of ΔP_R drops sharply immediately after flashing because of the substantial reduction in the density of the fluid as phase change occurs. In this region, therefore, the change in hydrostatic pressure exceeds the accelerational and frictional components. As the flow evolves downstream the hydrostatic pressure drop becomes less important and ΔP_R reaches a minimum. Acceleration and friction start to be the dominant factors from this point and ΔP_R rises rapidly due to the increase in accelerational and frictional pressure loss.

The change in kinetic energy ΔK_R and entropy production Sp_R as a function of v/v_f is presented in Figures 4 and 5 for Series 1 and 2,

respectively. One observes that at high values of v/v_f near choking the kinetic energy change in the flow rises sharply, overpowering the entropy production by a factor of 2 for both series.

The entropy production is due to wall friction and the interaction between the phases as it is indicated by the dissipation equation (Eq. 11). The change in kinetic energy and entropy production are of the same order near flashing for both cases. However, for the case of low flashing Mach number (Series 2) there is a region where entropy production is larger than the kinetic energy change. This region can be related to the neighborhood of the minimum pressure loss as can be observed from a comparison of Figures 3 and 5. A similar region is not observed in the case of high flashing Mach number since the flow is more compressible and acceleration becomes prominent much earlier.

A first look at Figures 4 and 5 indicates that ΔK_R grows exponentially with v/v_f and Sp_R is approximately linear with v/v_f .

The combined change of kinetic energy and entropy production represented by the variable ΔE_R is presented for both Series 1 and 2 in Figure 6. Near flashing where the characteristic parameter for the flow is the Froude number, the experimental points for both series coincide. (Note that the flashing Froude number is the same for both series.) For higher values of v/v_f , however, when acceleration of the flow becomes important and the local Froude number is high, the difference between the two series is considerable. The Mach number is then the most important parameter. A high initial (flashing) Mach number implies a shorter choking length as confirmed by the specific volume and Euler number evolution of the flow presented in Figures 1 and 2, respectively.

Rough average void fraction measurements were made for Series 1 and 2 by simultaneously closing the isolation valves at the beginning and at the end of the test-section at the end of a run and then measuring the volume of liquid trapped in the test-section. Although these measurements are not quantitatively accurate, they can provide some insight on the void fraction evolution in the flow and be utilized as a guide for a more sophisticated measuring technique. Quick-closing valves have been designed for this purpose and will be used in future experimentation (See progress report April 1 - May 31, 1984).

The average void fraction and slip are given as a function of v/v_f in Figures 7 and 8. The slip was calculated from the average void fraction measured using an average quality and temperature over the length of the test section. The average void fraction, α , increases sharply near flashing due to the large density difference between vapor and liquid. For high v/v_f near choking, the variation of α is slow. In general, the experiment shows that α is proportional to $(1 - v/v_f)$. The average slip ratio shows an increasing trend as one moves away from flashing and its values range from 2 to 3.5 for both series as can be observed from Figure 8.

V. VERTICAL FLOW THROUGH AN ABRUPT ENLARGEMENT

1. Test Facility

The test section was modified so as to accommodate a 1 1/4"-diameter Plexiglas tube within the lowest portion of the section between the orifice plate and the first measuring station. See Figure 9. In addition to the usual measuring probes at stations 3-5, pressure taps were installed at locations 2 and 1 to record the static pressure just below the lip of the enlargement and in the "back-water" region, respectively. A temperature probe was also inserted at a location corresponding to 2.

2. Test Plan

A single series of measurements was conducted with the following values of the important flow-governing parameters:

Flash Mach no., $Ma^* = 0.7$

Flash Froude no., $Fr^* = 15.0$

Flash Reynolds no., $Re^* = 310,000$.

These values were referred to the 1 1/4"-diameter pipe. (See Fig. 9.) Our calculations show that the flow was nearly, but not quite, choked at the abrupt enlargement.

3. Results

A number of test runs were carried out for the above-stated conditions; data were acquired, reduced, plotted, and interpreted; high-speed flash photographs were taken during the runs to provide added insight into the phenomena. A sample collection of the photographs is included as Appendix B.

The results for five cases of flow through the abrupt enlargement are presented in Figures 10 and 11 where one can see the variation of Euler number (Eu) and temperature ($\Delta T = T - T^*$), respectively. We are providing a short description of flow conditions for each case:

Case 1: Liquid flow in the small cross-sectional area pipe and flashing at the lip of the abrupt enlargement (Station 2).

Cases 2-4: Two-phase flow in the small cross-sectional area pipe and expansion of the two-phase flow at the abrupt enlargement.

Case 5: Flow is essentially choked at the lip of the abrupt enlargement.

The experimental results show that when flashing occurs at the lip of the abrupt enlargement there is no pressure lag between the exit of the small pipe

(Station 2) and the "back-water" area (Station 1). As the flash point is moved upstream into the small pipe and conditions are near sonic, a small pressure lag between these two points is observed (case 2) which becomes more prominent as the flow approaches the choking point at the lip of the enlargement (cases 3,4). The pressure lag is maximized when the flow chokes at the lip (case 5).

In order to make a statement about pressure recovery after the abrupt enlargement, one has to provide a definition of the recovery point. Due to the nature of two-phase flow, this is not an easy task since pressures downstream of the abrupt enlargement may exceed lip pressure in the small cross-sectional area pipe. Therefore, we define the recovery point as the point where the pressure has reached the original level before the abrupt enlargement (Station 2 in our experiment). In view of this definition, one may conclude that recovery occurs within 24 diameters of the large pipe from the abrupt enlargement as the measurements indicate (Figure 10; cases 2-5). This is also confirmed by the temperature profile along the flow presented in Figure 11.

V. THEORETICAL TWO-FLUID FLOW MODEL

The fundamental equations for the description of two-phase, liquid-vapor flow for a single substance have been developed and refined over a period of time. We will briefly summarize the equations for the case of vertical flow.

Conservation of mass

$$\psi = \rho_g w_g \alpha_g + \rho_f w_f \alpha_f \quad (6)$$

$$= \rho_g w_g \alpha_g / x_g \quad (6a)$$

$$= \rho_f w_f \alpha_f / x_f \quad (6b)$$

$$\text{where } \alpha_g = A_g/A, \quad \alpha_f = A_f/A, \quad x_g = \dot{m}_g/\dot{m}, \quad \text{and } x_f = \dot{m}_f/\dot{m} \quad (6c)$$

$$w_v = \psi/\rho = \alpha_g w_g + \alpha_f w_f \quad (7)$$

$$dA/dz = 0; \quad A = \text{constant}$$

$$d\dot{m}/dz = 0; \quad \dot{m} = \text{constant}$$

$$d\psi/dz = 0; \quad \psi = \text{constant}$$

$$d(\rho w_v)/dz = 0; \quad \rho w_v = \text{constant.}$$

Momentum equation

$$\frac{dP}{dz} = \left. \frac{dP}{dz} \right|_{\text{accel}} + \left. \frac{dP}{dz} \right|_{\text{frict}} + \left. \frac{dP}{dz} \right|_{\text{grav}} \quad (8)$$

$$= \psi \frac{dw_{cm}}{dz} + \bar{\tau}_{wf} + \bar{\tau}_{wg} + \rho_m g \quad (8a)$$

where

$$w_{cm} = x_g w_g + x_f w_f \quad \text{and} \quad \rho_m = \alpha_g \rho_g + \alpha_f \rho_f \quad (8b)$$

Energy equation

$$\frac{KE}{\dot{m}} = \frac{1}{2} w_{rms}^2 = \frac{1}{2} [x_g w_g^2 + x_f w_f^2] \quad (9)$$

$$= \frac{1}{2} (\psi/\rho_f)^2 [x_g (\sigma^2 - 1) + 1] [x_g (\frac{\gamma}{\sigma} - 1) + 1]^2 \quad (9a)$$

where $\sigma = w_g/w_f$ and $\gamma = \rho_f/\rho_g$.

$$dh_0/dz = 0 ; \quad h_0 = h + \frac{1}{2} w_{rms}^2 + gz = \text{constant.} \quad (10)$$

Dissipation equation

$$T \frac{ds}{dz} = \bar{\tau}_{wg} w_g + \bar{\tau}_i (w_g - w_f) + \bar{\tau}_{wf} w_f \quad (11)$$

The solution to the two-fluid equations turns on the proper representation of the so-called "closures", i.e., the wall shear stresses $\bar{\tau}_{wg}$ and $\bar{\tau}_{wf}$, and the interfacial shear stress, $\bar{\tau}_i$.

To guide our search for a reasonable closure, we have examined the drift-flux model [2]. In many instances, the assumption of a one-dimensional formulation can be adequate for analyzing the flow, depending on the amount of information which is needed to describe the flow field. However, if the prediction is to be accurate one can describe the flow field in an ascending order of sophistication, especially in the measurement of void fraction. Instead of using uniform properties, one can define local parameters and describe the flow field by averaging those parameters over time and then over space. In the case of the slip between phases, for example, one finds from this formulation that the slip is actually made up of two parts: one is the "pseudo-slip" due to the assumption of nonuniformity; the other is the local slip between the phases.

The basic definitions for the one-dimensional, non-uniform, formulation are given as follows: Consider a point P in space characterized by a phase function $\tilde{\alpha}$ defined as follows:

$$\tilde{\alpha}(\vec{r}, t) = \begin{cases} 0 & \text{if } P \text{ is liquid.} \\ 1 & \text{if } P \text{ is vapor.} \end{cases} \quad (12)$$

where $\vec{r}$ is the position, and t is the time. The time-averaged void fraction at point P is defined as

$$\bar{\alpha}(\vec{r}) = \frac{1}{T} \int_T \tilde{\alpha} dt, \quad (13)$$

where T is time interval. If we consider any parameter Y , other than the void fraction, its time-averaged value at point P is defined as

$$\bar{Y}(\vec{r}) = \frac{\frac{1}{T} \int_T \tilde{\alpha} \tilde{Y} dt}{\frac{1}{T} \int_T \tilde{\alpha} dt} \quad (14)$$

where $\tilde{Y}(\vec{r}, t)$ is the instantaneous value of Y at point P .

The space-averaged void fraction over a cross section is defined as

$$\alpha \equiv \langle \bar{\alpha} \rangle = \frac{1}{A} \int_A \bar{\alpha} dA, \quad (15)$$

and the space-averaged value of Y over a cross section is defined as

$$Y \equiv \frac{\langle \bar{\alpha} \bar{Y} \rangle}{\langle \bar{\alpha} \rangle} = \frac{\frac{1}{A} \int_A \bar{\alpha} \bar{Y} dA}{\frac{1}{A} \int_A \bar{\alpha} dA} \quad (16)$$

From the above definition one can easily see that the space-averaged gas velocity is

$$w_g \equiv \frac{\langle \bar{\alpha} \bar{w}_g \rangle}{\langle \bar{\alpha} \rangle} = \frac{w_{sg}}{\alpha} . \quad (17)$$

Similarly, the space-averaged liquid velocity is

$$w_f \equiv \frac{\langle (1-\bar{\alpha}) \bar{w}_f \rangle}{\langle \bar{\alpha} \rangle} = \frac{w_{sf}}{\alpha} . \quad (18)$$

The w_{sg} and w_{sf} are the space-averaged superficial velocities of the gas and of the liquid defined as $w_{sg} \equiv \langle \bar{\alpha} \bar{w}_g \rangle$ and $w_{sf} \equiv \langle (1-\bar{\alpha}) \bar{w}_f \rangle$, respectively. The local mixture superficial velocity is by definition:

$$w_{vl} = \bar{\alpha} \bar{w}_g + (1 - \bar{\alpha}) \bar{w}_f . \quad (19)$$

The space-averaged mixture superficial velocity is the "volumetric velocity" of the mixture, which can be written as

$$w_v \equiv \langle w_{vl} \rangle = \langle \bar{\alpha} \bar{w}_g \rangle + \langle (1 - \bar{\alpha}) \bar{w}_f \rangle = w_{sg} + w_{sf} . \quad (20)$$

Finally the local "drift velocity" of the gas is defined as:

$$w_{dl} = \bar{w}_g - w_{vl} . \quad (21)$$

From the above definitions one can derive an expression for the space-averaged gas velocity in the form:

$$w_g = C_0 w_v + \frac{\overline{\langle \alpha w_{dl} \rangle}}{\overline{\langle \alpha \rangle}}, \quad (22)$$

where

$$C_0 \equiv \frac{\overline{\langle \alpha w_{vl} \rangle}}{\overline{\langle \alpha \rangle} \overline{\langle w_{vl} \rangle}} \quad (22a)$$

is the pseudo-slip and the second term on the right-hand side is the local slip between phases. In most two-phase applications, the pseudo-slip which is due to non-uniform void fraction and velocities is much greater than the local slip between phases.

The last equation has a simple geometrical interpretation, namely that of a straight line in (w_g, w_v) coordinates, where the w_g -intercept is the value of the local slip and the slope is the pseudo-slip. (See Fig. 12.)

If in a particular regime, the pseudo-slip and local slip are constants, one may predict a linear relationship between the gas velocity and the volumetric velocity. Otherwise, this relationship is non-linear and its shape is governed by the choice of distribution functions for $\bar{\alpha}$, w_{vl} , and w_{dl} .

REFERENCES

- [1] "Design and Operation of a Two-Phase Flow Research Facility", P. F. Maeder, J. Kestin, D. A. Dickinson, R. DiPippo and H. Olia, Brown University Rep. No. GEOFLO/16, DOE No. LA-UR-92-1838, May 1982.

- [2] "Average Volumetric Concentration in Two-Phase Flow Systems," N. Zuber, and J. A. Findlay, Journal of Heat Transfer, Trans. ASME, Series C, vol. 87, 1965, pp. 453-468.

FIGURE CAPTIONS

- Figure 1. v/v_f vs. z/D for Series 1 and 2.
- Figure 2. Eu vs. z/D for Series 1 and 2.
- Figure 3. ΔP_R vs. v/v_f for Series 1 and 2.
- Figure 4. $\Delta K_R, Sp_R$ vs. v/v_f for Series 1.
- Figure 5. $\Delta K_R, Sp_R$ vs. v/v_f for Series 2.
- Figure 6. ΔE_R vs. v/v_f for Series 1 and 2.
- Figure 7. α (void fraction) vs. v/v_f for Series 1 and 2.
- Figure 8. σ (slip ratio) vs. v/v_f for Series 1 and 2.
- Figure 9. Step well configuration.
- Figure 10. Eu vs. z/D for Step well (1-1/4" abrupt transition to 2").
- Figure 11. ΔT vs. z/D for Step well (1-1/4" abrupt transition to 2").
- Figure 12. Effect of slip and pseudoslip (w_g vs. w_v).

Figure 1

Figure 2.

Figure 3.

Series 1.

Figure 4.

Series 2.

v/v_f
Figure 5.

Figure 6.

Figure 7.

v/v_f
Figure 8.

- NOTES
1. NOT TO SCALE.
 2. ALL DIMENSIONS IN mm.

Figure 9

Figure 10

Figure 11

FIGURE 12

APPENDIX A

A FACILITY FOR THE EXPERIMENTAL INVESTIGATION
OF SINGLE SUBSTANCE TWO PHASE FLOW

by

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Abstract

The paper describes a research facility dedicated to single-substance two-phase flow. The working fluid is dichlorotetrafluoroethane (or refrigerant R-114), allowing both operation at manageable pressures, temperatures and flowrates, and application of results to practical situations through similarity. Operation is in the blowdown mode. The control and data acquisition systems are fully automated and computer controlled. A range of flow conditions from predominantly liquid flow to high velocity, high void fraction choked flow can be attained.

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Introduction

A facility has been constructed at Brown University to conduct experimental research on two-phase flow. The results from the testing program will complement ongoing analytical work on the subject. The purpose of this paper is to provide a detailed description of the facility and to form the basis for the unified presentation of results from both thrusts of the investigation.

From the 1940's until recent times, most two-phase flow experimentation was concerned with two-substance mixtures (such as air-water), partly for convenience but mainly because of the prevalence of this type of flow in the chemical and petroleum industries. Since this type of flow is essentially incompressible, it does not allow the study of certain phenomena (e.g. choking) [1] that are very important in geothermal and nuclear power system applications. To investigate these phenomena it becomes necessary to conduct experiments in single-substance two-phase flow, which is highly compressible due to phase change.

The facility is intended specifically for the study of single-substance flow, with all aspects including measuring systems and flow control having been designed accordingly [2]. It is presently arranged for essentially adiabatic flow in a pipe of constant flow area. The design is flexible and can accommodate a number of different configurations of practical interest, such as pipes of various geometries and scaled models of equipment that are used in practice. The working fluid is

refrigerant 114 (dichlorotetrafluoroethane, or R114). Studies of substance similarity [3,4] indicate that this fluid can be used to model adequately the two-phase flow of water at conditions encountered in practical applications.

Physical Arrangement and Operation

A simplified schematic diagram of the system is given in Fig.1, which shows only the main fluid path; auxiliary piping and control systems have been omitted for the sake of clarity. The main fluid circuit consists of the vessels A, B, C and D, and the piping indicated by solid lines. The components are arranged in a closed loop containing only R114 in liquid, vapor or 2-phase states. When the system is not in operation the bulk of the R114 is stored in tank D as a saturated liquid at room temperature, with vapor occupying the rest of the system.

The system operates in a "blowdown" or intermittent mode rather than as a continuous, steady flow loop. This eliminates the need for a large, steady power input. A typical experimental run lasts approximately 30 seconds to 3 minutes, with about one and a half hours required for preparation between runs. At the beginning of a run, liquid is pumped from the storage tank (D) to the accumulator (A) and booster (B) tanks which are simultaneously heated to the desired starting conditions by means of electric immersion heaters (H). Since the tanks contain saturated liquid and vapor, the pressure is adjusted solely by setting the fluid temperature by means of the heaters.

A run is then started by opening the isolation valves (IV). Liquid flows from the accumulator through a specially-designed venturi flow meter (V) and enters the test section. The function of the booster tank is to provide vapor at higher pressure to the accumulator through a pressure regulating valve (PR).

After passing through the venturi the liquid working fluid enters the test section from a 5 inch (127 mm) diameter pipe which serves as a settling chamber. The transition occurs through a contraction which was designed to avoid separation of the flow. Flashing of the liquid into vapor occurs along the test section because of the decrease in pressure due to friction and gravity (for the non-horizontal case). Temperature and differential pressure measurements are taken at successive stations. The main portion of the test section consists of transparent glass pipe (allowing direct observation of the flow) with 2 inch (50 mm) I.D. and 26 ft (8 m) length. It can be oriented vertically for upward flow, inclined at various intermediate angles or horizontally. A length extension up to 12 ft (3.7 m) is possible in the latter mode. Finally the fluid passes through a diffuser and into a 5 inch (127 mm) diameter return pipe which leads to the condenser (C) where it is converted into liquid and collected in the storage or "dump" tank (D). The condenser is cooled by a methanol-water solution (shown in the diagram by dashed lines) circulated from a cold storage tank (CS). The latter is maintained at a temperature of approximately -20°C by a standard refrigeration chiller which uses city water as its heat sink. The facility occupies portions of the first floor and basement of the

laboratory. Plan views and a section showing the scale are given in Figs. 2a and 2b.

The high pressure vapor supply provided by the booster enables the operator of the system to control stagnation conditions in the accumulator using the pressure regulating valve. The vapor becomes superheated when throttled at the valve and condenses very slowly, maintaining the preset pressure in the accumulator as that tank empties during a run.

Control and Monitoring

When the facility is idle, conditions throughout the system are continuously monitored by a desk-top computer which also acts as controller. When the system is being prepared for a run, the procedure is monitored and controlled by the same computer. The link between the computer and the physical system is provided by an interface bus which allows the computer to read instruments and operate equipment by switching relays. The computer is programmed to take all necessary actions to maintain conditions throughout the system within prescribed limits.

Two types of measurements are taken for automatic control and monitoring purposes: temperatures and liquid levels in the vessels. Temperatures are measured using thermistors attached to the exterior wall of the vessels beneath the insulation. Liquid levels are determined from readings of differential pressure transducers connected between the top

and bottom of the vessel to sense hydrostatic pressure. In addition monitoring of temperatures, pressures and liquid levels is possible, when needed, using standard mercury-in-glass thermometers, dial pressure gauges and sight glasses, respectively.

A set of computer programs have been developed to perform certain standard operations such as: preparing the system for a run or distilling the working fluid for cleaning purposes. To prepare the system for an experimental run, the operator executes the appropriate program and enters the desired starting time for the experiment. All required steps will be initiated and controlled automatically (operation of pumps, heaters, valves) and the system will reach the programmed starting conditions at the prescribed time without further manual intervention. Once starting conditions for a run have been reached, the system will automatically maintain such conditions by cycling heaters, and circulating the working fluid to maintain temperature uniformity. maintenance procedure and provide a "control program" that will be used by the computer to conduct the experiment in the desired manner. The control program can be entered for each run from the keyboard or simply read by the computer from disk or tape if previous conditions are being repeated.

The computer controls the experiment by operating the isolation valves, gate valve, pressure regulating valve and condenser. It scans all instruments in the test section and the venturi, at preset time intervals (0 to 1 s). Signal measurements of several probes can also be taken at a maximum frequency of 3.3 kHz. Data collected during a run

are stored in memory in real time. Later the data are transcribed on disk or tape and can be printed in raw form (i.e., voltage measurements from each instrument as read during the scans). Another set of programs do the reduction of the data, using the probe calibration functions, and perform basic statistics. They also provide graphic display of any of the measured quantities as a function of time. Further reduction of the collected data and calculation of secondary quantities from the ones directly measured during the experiment are left up to the judgement of the investigators.

Automation of both the preparation and execution of the experiment allows procedures to be developed and optimized beforehand, and then assures their precise performance. This eliminates inconsistencies and possible errors resulting from manual operation and facilitates reproducibility of experimental conditions. It also allows the operator mechanics of conducting the experiment, especially since the running time is relatively short.

Test Section

A number of characteristics of the test section are common to both horizontal and vertical operation (Figs. 3a and 3b, respectively). For clarity these will be described first. The test section is located between the two isolation valves as shown in Fig. 1. With the exception of mass flow rate all experimental measurements and observations are made between these two valves. They are of the butterfly type and are pneumatically controlled for fast operation either by hand or automatically by the computer. The valves are always either fully open

or closed and are not used to condition flow in the test section in any way. The upstream valve isolates the settling chamber from the pipe leading from the venturi flow meter; the downstream valve isolates the diffuser from the return pipe and the condenser. The settling chamber has a diameter of 5 inches. An insert of machined plastic (Delrin) provides a smooth transition to the 2 inch transparent portion of the test section, which consists of a series of pyrex glass tubes of variable length connected by clamps fitted at flanged ends. (See Fig. 4). The lengths used range from 6 in to 10 ft. A 2 inch gate valve is located at the end of the test section followed by the diffuser that provides an expansion to the 5 inch isolation valve and the return pipe. A flexible rubber tube and a fixed support isolate the glass pipe from the gate valve and diffuser. The settling chamber, glass pipe and the fixed support are mounted on a 6 inch square aluminum I-beam which runs the full length of the test section. The glass sections are supported on this beam by adjustable stands that clamp onto the beam and allow alignment of the glass. Hence the test section is supported separately and isolated from other piping and equipment to eliminate vibration.

Pressure and temperature transducers are accommodated along the test section in special Delrin inserts with 2 inch I.D. fitted between the ends of the glass pipe. A photograph of a typical measuring station is provided in Fig. 4. Pressure transducers are connected by plastic tubing and held in place by a brass fitting threaded into a well in the Delrin insert. A small hole connects the well to the inner surface of the insert so that static pressure is measured at the wall. Temperature probes are held in a similar brass fitting; their design allows them to

be set at different radial positions within the pipe. A temperature probe and an absolute pressure transducer are mounted similarly at the settling chamber with fittings threaded into the steel pipe wall, and are used for measuring stagnation conditions.

Flow control for the test section (apart from the simple on-off provided by the isolation valves) is provided by a throttle plate and a throttle valve. The throttle plate is an aluminum disc with a number of holes drilled to provide a specified flow area (See Fig. 5). The disc is clamped in an aluminum holder which fits between two glass sections in the same manner as the Delrin inserts. Flow control is accomplished by causing the liquid entering the test section to flash and choke at this plate [5]. The flow rate can therefore be held constant during a run, independent of changes that occur in the flow further downstream. With a throttle plate of a given flow area, the flow rate can be adjusted over a limited range by changing the "boost" in the accumulator (the boost being the over-pressure above saturation in that tank). If a larger variation is required a plate with a larger flow area is required. The numerous holes in the throttle plate produce a multiple jet sufficiently dispersed and far enough upstream that the flow at the first measuring station is fully developed. The downstream gate valve serves as the throttle valve which can be adjusted to control the amount of flashing that takes place in the test section by changing the back pressure on the throttle plate. Pressure in the diffuser is maintained sufficiently low by the condenser so that the two-phase flow leaving the test section is choked at the gate valve. As a result the flow in the test section occurs between two choked cross sections under conditions

that are unaffected by fluctuations that may occur in other parts of the system.

For given stagnation conditions, each setting of the downstream throttle valve produces a flow in the test section that corresponds to flow that would occur at some section in a much longer pipe, since the orifice simulates the effect of the initial portion of the pipe. Flow at various "sections" may be simulated by changing the setting of the throttle valve. Measurements have been performed with flow varying from pure liquid to high vapor content at conditions close to choking. Thus, the entire range of flow states possible from given stagnation conditions can be achieved in a relatively short test section through a series of test runs.

For operation in the horizontal mode, temperature measurements are taken by probes placed along the test section. Differential pressure measurements are taken across each of the 4 ft sections by placing transducers between the test section and a reference pressure line filled with hydraulic oil, and then calculating the difference between these measurements. The conventional method of directly connecting the differential transducers between stations cannot be used for two-phase measurements. If this were done, the freon in the connecting tubes would undergo phase change, thereby introducing indeterminable pressure fluctuations into the measurements.

The pressure in the reference line is set by the pressure in the test section at the first measuring station. A freon-mercury-oil interface

is used to prevent contamination of the freon by the oil in the reference line. The interface consists of a small mercury-filled U-tube with oil and freon vapor occupying opposite sides. The U-tube is heated to prevent the freon from condensing as the pressure fluctuates in the test section. Thus, the reference pressure remains essentially constant during a run. Absolute pressure measurements at each station were ruled out because absolute pressure transducers of wide range and therefore poor accuracy would be necessary to cover the pressures encountered in the test section.

For operation in the vertical mode, the inlet control valve and the settling chamber are at the bottom of the test section, and the gate valve (throttle valve) followed by the outlet control valve are at the top. The flow is thus directed upwards into the test section, gravity counteracting the flow (Fig. 3b). The temperature and pressure measurements are taken at four consecutive stations placed at 4 ft intervals. The first measuring station is located 10 ft downstream of the throttling plate, and the last measuring station is located 3 ft upstream of the throttling valve, as shown in Fig. 3b. Differential pressure transducers of a wider range than those of the horizontal setup are used, because of the large hydrostatic pressure drop that characterizes vertical flow. In every other respect the configuration of the test section and reference pressure line remains the same as in the horizontal setup.

Instrumentation

The instrumentation for the experimental measurements consists of three

types of sensors: temperature, absolute pressure, and differential pressure. The sensors are of the same basic types as used for the monitoring measurements, but are calibrated and mounted so as to produce the highest accuracy possible.

Although not located in the test section proper, the venturi meter allows measurement of flow rate by means of a differential pressure transducer connected between its inlet and throat sections. Details on the test section instrumentation and the venturi are given later in this section.

Temperature instrumentation

The sensors selected for measuring temperatures are thermistors. The thermistors were selected for their sensitivity over the required temperature range and an output compatible with the A-to D-conversion equipment, based on the manufacturer's specifications. A method for mounting was designed and implemented, and calibrations were then carried out for each thermistor.

Since the thermistor had to be placed in a fluid flow and along the radius of a circular cross section, the type selected was a glass-coated bead with adjacent leads. This allowed the thermistor to be mounted as shown in (Fig. 7), with the leads passing through a sealed tube. The tube is held in a fitting attached to the Delrin pipe insert and allows the tube to be positioned radially and locked in place.

Thermistors with resistance values at 25°C of either 1 k Ω or 2 k Ω are presently in use. With an applied short-pulsed current of 200 μ A, the

resulting voltage is between 0 and 1 V over the range of calibration 0 to 30°C. The 1 k Ω thermistors allow temperatures lower than 0°C to be measured when needed without exceeding 1 V output of the A-to-D converter. Calibration of the temperature transducers was carried out using standard methods. A sample calibration correlation is given in Fig. 7a, showing the input data, resulting correlation equation, standard deviation, and deviation of data from the smooth curve.

b) Pressure instrumentation

The type of probe selected for measuring absolute and differential pressure is an integrated circuit pressure transducer which provides a voltage output that is linear with the applied pressure or pressure difference. The transducer consists of a single-crystal silicon sensor and circuit elements mounted in a ceramic housing. Attached directly to the housing are ports of brass tubing for connection to the pressure source, and electrical connections for a 15-volt excitation signal and output voltage. For this application, it was decided to mount the transducer in a metal box, as shown in (Fig. 8), which allows the transducer to be isolated from stress created by the external tubing and electrical connections.

Differential pressure transducers of two different ranges were selected. One set of transducers covers a range of -5 to +5 lbf/in² (-30 to +30 kPa) and the other covers a range of -15 to +15 lbf/in² (-103 to +103 kPa). The absolute pressure transducers used have a range of 0-60 lbf/in² (0-414 kPa). Both differential and absolute pressure transducers have a voltage output that ranges from 0 to 12 volts and an

offset of approximately 7 V when both ports are at the same pressure. Calibration is carried out by using standard methods. A sample calibration correlation, for the most sensitive type of the differential pressure transducers, is shown in (Fig. 8a). The units of pressure are mbar.

c) Flow-rate instrumentation

The flow rate is measured by means of a liquid venturi flow meter. Because the fluid is close to saturation and flashing is possible inside the flowmeter, it was decided to design and fabricate the venturi rather than purchase a standard instrument. The meter consists of an outer tube and flanges made of stainless steel which fit between adjacent pipe flanges in a conventional manner. The throat section is machined from Delrin, and slides into the outer tube. It is held in place by means of two end plates. Sealing, both internally around the throat pressure chamber and externally at the flanges, is accomplished using O-rings. A drawing of the outer tube and insert is given in (Fig. 9). There are three interchangeable throat sections, allowing a flow measurement range of about 1 to 21 kg/s, corresponding to a range of test section mass flux from roughly 400 to 10,000 kg/m²s, with throat diameters of 3/4, 1-1/4 and 2 inches.

Measurement of pressure at the meter is accomplished using a differential pressure transducer of the type discussed earlier, except mounted in a zinc housing (as supplied). It is bolted to a vibration

isolator at the venturi and connected by the necessary fittings and valves. The inlet pressure tap is located in the upstream pipe section rather than the venturi unit itself. A temperature probe, of the type discussed earlier, is located at the same position for accurate determination of the fluid density.

The accuracy of the venturi was checked by directly measuring the quantity of fluid which leaves the accumulator tank in a given time period and comparing this to the flow rate measured by the venturi. Calibration data for two different venturi throat sections, which cover the range of mass flow rate used in the experiments, are given in Figs. 9a 9b. Mass flow rate measured by the venturi is plotted against the known calculated flow rate. The straight reference lines are lines of equality between these two quantities. No correction factor on the standard venturi flow equation above has been found necessary, to an accuracy of approximately 2%.

d) Void fraction measurement

A pair of quick-closing guillotine-type valves has been designed for average void fraction measurements within a section of the pipe. The closing time is approximately 100 m and the valves are pneumatically activated. The void fraction is defined as the ratio of the volume occupied by the vapor to the total volume of the two-phase mixture. The void fraction measurement is taken by closing the two valves simultaneously while there is flow in the test section; thus a portion of the two-phase mixture is trapped between them. As soon as the two

phases separate, the level of the meniscus formed by the liquid is measured. The average void fraction can be calculated from this measurement and the known geometry of the test section.

Data Acquisition and Control System

a) Computer and interface

The Hewlett-Packard 85 desk-top computer was selected as the controller and monitor of the facility. This machine is equipped with an internal memory of 32 kB, a number of enhancement read-only memories (ROMs) and the interface to the HP-IB bus. It uses enhanced BASIC as the computer language and together with the selected interface has a basic data acquisition speed of 20 kB/s. A Hewlett Packard 9121 dual disk drive and a Hewlett-Packard 7470A plotter are also available for data storage and graphics respectively. Communication of the computer and the rest of the system is established via the Hewlett-Packard Interface Bus (HP-IB), the HP 59500A Multiprogrammer Interface and the HP 6940B Multiprogrammer.⁽¹⁾ The HP-IB is a 16 bit bus: eight bits are used for data transmission; three bits are used for acquisition control ("handshake"), and five bits are used for control of the bus itself and the instruments connected to it.

(1) The system can also be controlled by the operator, from any within the area occupied by the facility, by using a Hewlett-Packard 41C (HP-41CV) hand-held minicomputer linked to the HP-85 controller via an interface loop (HP-IL) and the Interface Bus (HP-IB).

A schematic diagram of the data acquisition and control system is shown in Fig. 10.

b) The Multiprogrammer and its cards

At the present time there are connected to the Interface bus a precision multimeter (used for calibration of pressure and temperature transducers and any other devices used for measurement), and the multiprogrammer with its interface that allows the transmission of digital signals received from or transmitted to the analog devices, switches, etc.

The multiprogrammer, which can be expanded to three times its present capacity, allows up to 15 specialized measurement or control cards to be selectively connected to the bus. While some of these cards are standard Hewlett-Packard equipment, most of them have been designed and built by our own personal to suit the specific purposes at hand (i.e., in Figure 19, the cards at A,B,C,D and F).

Of particular interest should be cards B,C and D which translate up to 7 multiplexed analog channels into digital information using a ramp-type A-to-D converter that was chosen to make these cards reasonably insensitive to extraneous noise. The signals measured by these cards, for instance, can be either resistance measurements (from thermistor temperature transducers), or voltage measurements (from pressure transducers).

Card F, a multiplexed card feeding directly into a high-speed A-to-D converter, is designed to provide high-speed voltage measurements of 8 channels in the range from 0 to 10 volts. The basic data transmission

rate of this "fast handshake" data transmission system is 300 microseconds. It has been incorporated for the acquisition of data during turbulent or transient flows.

Multiprogrammer cards M and N are output cards that selectively operate 24 relays, thereby controlling valves, motors, pumps, and other such devices under the action of the controller.

To enable the multiprogrammer to operate in the fast handshake mode, its electronics needed to be modified. This was accomplished by eliminating some unnecessary data transmission delays in the multiprogrammer interface and providing a trigger for the high-speed, A-to-D converter to advance the multiplex and start the next conversion just as soon as the previous signal is ready for transmission.

Use of the Facility

The facility has been operated for a period of four years to obtain temperature and pressure drop data in horizontal and vertical flows through a constant cross-sectional area pipe. Questions such as the existence of metastability in two phase flow and the effect of dimensionless parameters (Mach, Reynolds and Froude numbers) on the flow have been experimentally investigated [6-7].

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Figure 1: Schematic Plan of Experimental Facility

Figure 2a: Overview of Experimental Facility

Figure 2b: Elevation Section

Figure 3a: Horizontal Test Section Configuration

Figure 3b: Vertical Test Section Configuration

Figure 4:

Typical measuring station. Thermistor probe is at upper left, pressure probe is at right of Delrin insert. Note connecting flanges for glass pipe sections.

FIG. 5: THROTTLE PLATE AND HOLDER

Figure 6: ELEVATION SECTION

Figure 7: Temperature Transducer Mounting

Figure 7a: Sample Calibration Correlation for Temperature Transducers

scale: 3/4

Figure 8: Pressure Transducer Mounting

Figure 8a: Sample Calibration Correlation for Dif. Pressure Transducers

Figure 9: Venturi Design

Figure 9a: Venturi Calibration

Figure 9b: Venturi Calibration

FIG. 10: AUTOMATIC DATA ACQUISITION AND PROCESSING SYSTEM

APPENDIX B

PHOTO SERIES

April 18, 1985

Vertical flow through abrupt enlargement

Tri-X, 400ASA
Nikkor f/2, 50 mm lens w/skylight and polarizer
Setting: 1/125 s, f/5.6
Sunpak flash, autoflash yellow
Distance from subject to focal plane = 1.1 m

<u>Photo No.</u>	<u>Case No.</u>	<u>Description</u>
20,22,25	1	7 psi boost, gate valve closed at 110s.
13	2	6 psi boost, gate valve closed at 90s.
6-9	3	5 psi boost, gate valve closed at 60s.
27,28	5 (transient)	5-6 psi boost, gate valve fully open, initial flashing.
30	5	Same as 27, fully developed.