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Measurement of Local Void Fraction at Elevated Temperature and Pressure

D. Duncan and T. A. Trabold

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Nomenclature

C	capacitance
C_D	drag coefficient
D_b	bubble diameter
D_H	hydraulic diameter
E	energy
f	friction factor
F_I	interfacial shear coefficient
g	gravitational acceleration
G	conductance or mass flow
M	momentum flux
P	absolute pressure
ΔP	pressure drop
q	heat flux
U	phase velocity
U_r	relative velocity, i.e., U_g - U_l
Y	admittance
Z	axial (vertical) position

Greek symbols

α	void fraction
ε	capacitance
γ	conductivity
Θ	phase angle
ρ	density
σ	surface tension
ω	angular frequency

Subscripts

g	gas phase
l	liquid phase
m,mix	two-phase mixture

Abstract

Significant advances have recently been made in analytical and computational methods for the prediction of local thermal-hydraulic conditions in gas/liquid two-phase flows. There is, however, a need for extensive experimental data, for the dual purposes of constitutive relation development and code qualification. This is especially true of systems involving complicated geometries and/or extreme flow conditions for which little, if any, applicable information exists in the open literature. For the tests described in the present paper, a novel electrical probe has been applied to measure the void fraction in atmospheric pressure air/water flows, and steam/water mixtures at high temperature and pressure. The data acquired in the latter experiments are compared with the results of a one-dimensional two-fluid computational analysis.

Measurement of Local Void Fraction at Elevated Temperature and Pressure

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1. Introduction

Over the past several decades, much effort has been devoted to improving computational methods for the prediction of local thermal-hydraulic conditions in gas/liquid two-phase flow. Recent advances in computational capability have, however, resulted in an imbalance between our ability to solve the complicated conservation equations and our ability to measure physical parameters that describe interactions between the phases. It is now apparent that additional detailed experimental data are required, both for the purpose of formulating the required constitutive relations and for code qualification. General Electric is currently developing computational methods based on a rigorous two-fluid formulation. This has become the impetus behind a comprehensive program to develop two-phase flow measurement techniques for high-pressure steam/water applications. Of the various parameters that need to be measured, the local void fraction is of primary interest for defining the two-phase flow environment.

As documented in several excellent reviews (e.g., Brockett and Johnson, 1976; Hsu, 1977; Delhaye, 1986; Mayinger, 1988; Snoek, 1988; Yokobori *et al.*, 1991), a number of techniques for local void fraction measurement have been used with varying degrees of success. These techniques generally have limitations which make them unsuited for transient two-phase flows, and where the temperatures, pressures and water chemistries make them impossible to apply. For example, gamma densitometry is limited by long counting times and bulky, rather expensive equipment. Additionally, there are restrictions on the handling of this equipment due to the radiation source. Other methods such as the optical probe and hot-film anemometer have been used for local measurements (Cartellier and Achard, 1991), but are not suitable for high pressure and temperature conditions. This is especially true in applications in which the working fluid can be very corrosive to the active element of these types of devices.

Electrical instrumentation techniques are particularly attractive for local void fraction measurements, due to their ability to resolve rapid changes in the two-phase flow field. The general principle of operation of electrical void fraction probes is based on the difference in the electrical properties between the liquid and vapor phases. As outlined by Hardy and Hylton (1984), the admittance (inverse of impedance), Y, of a two-phase mixture can be described by a complex number:

$$Y_{mix} = G_{mix} + j\omega C_{mix} = |Y| e^{j\Theta} \tag{1}$$

whose real part is the conductance G and whose imaginary part is the susceptance ωC, where C is the capacitance, ω is the angular frequency of excitation, and Θ is the phase angle. The two-phase mixture conductance and capacitance for a fluid like water, where the conductivity and the dielectric constant of the liquid are much greater than those of the corresponding vapor phase, can be expressed as

$$G_{mix} = \frac{\gamma_m}{B} \tag{2}$$

$$C_{mix} = \frac{\varepsilon_m}{B} \tag{3}$$

where γ_m is the average mixture conductivity, ε_m is the average mixture capacitance, and B is a constant determined by the geometry of the electrode. In general, an electrical impedance-type probe measures the magnitude and phase of the admittance, which in turn permits the determination of γ_m and ε_m that can be related to void fraction through calibration.

A variety of probe geometries has been applied, including those in which the ground and emitter are placed in opposite test section walls, and those which are completely immersed in the two-phase flow. Depending on the system configuration, the impedance will be dominated by conductance (conductivity probe), capacitance (capacitance probe), or both (impedance probe). In general, it is desirable to operate at a high enough frequency to ensure the domination of the capacitance term because the liquid conductivity is a strong function of temperature and ion concentration while the capacitance is not significantly affected by these factors. Impedance-type probes can generally be used for both steady and transient measurements due to their virtually instantaneous response. Accuracy is adequate for low void fractions when the water chemistry is stable, but may be limited at extremely small vapor volume fractions when the mixture impedance is close to that of the pure liquid. The probe sensitivity can be expected to improve with increasing α, but, at very high void fractions, accuracy often decreases because the measured void fraction is dependent on the distribution of voids and entrained liquid in the neighborhood of the active element. The probe and signal processing costs are relatively moderate; however, application in a high- pressure steam/water environment is complicated by the required mechanical penetration and the fact that the electrical insulators that support the electrodes might not be able to survive for long-term measurements.

The impedance-type probes have been used extensively for void fraction measurement and a number of different electrode geometries have been investigated. General problems encountered with electrical sensors include phase distortion, electrochemical effects, non-representative conductive paths, nonlinear response due to the effect of flow regime, probe wettability and surface tension. To minimize these problems, it is required that the sensor and data acquisition technique be designed and calibrated specifically for the desired measurement. Also, most instruments lose their sensitivity when the sensing device is positioned at a significant distance from the signal acquisition hardware or when there is a change in the electrical properties of the fluid. This is primarily due to either the decrease in the signal-to-noise ratio caused by increasing the length of the transmission cable, or to significant changes in dielectric constant or resistance of the fluid, both of which decrease the ability to resolve the signal. A new proprietary method that overcomes these deficiencies, hereafter referred to as the Electric Field Perturbation (EFP) technique, has been developed by Mohr and Associates[1]. The probe can be used in a variety of applications in high-temperature and chemical (high conductivity, mildly corrosive) environments, permitting remote measurements to be made over extended periods of time. For purposes of the present study, several EFP probes have been adapted by Mohr and Associates to measure the local void fraction in various water chemistries at high temperature and pressure.

A brief description of the test facilities and some of the most significant results of experiments performed in an air/water flow loop and a pressurized autoclave system are given below. These results demonstrate the potential usefulness of the measurement technique in improving analytical models and computational methods, as well as offering insight into the physical behavior of two-phase flows under severe thermal-hydraulic conditions.

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1. An engineering and consulting firm located at 1440 Agnes Street, Richland, WA.

2. Air/Water Experiments

Test Facility and Measurement System

A series of preliminary tests was performed in an air/water flow loop (illustrated schematically in Figure 1), for the early qualification of the EFP probe. The loop consisted of a vertical transparent test section, a water pump, a heated water tank, and an air/water separator. The test section was separated into two modules by three fast-acting valves that were used to quickly (in about 0.1 sec) trap the two-phase flow mixture. A liquid-air mixing chamber was located at the inlet of the test section. For a given set of air and water flow rates, the two-phase flow field could be altered by varying the method of air injection. When the air was introduced by means of a manifold, the bubbles formed were generally larger, less frequent, and not uniformly distributed across the test section width. Conversely, with air injection through a soapstone, the smaller bubbles were rather uniform in both size and distribution. The latter configuration was considered to more closely model the expected two-phase flow structure in high-pressure steam/water applications. The loop instrumentation included rotameters to measure the air and water flows, and differential pressure (DP) cells and pressure gages to monitor both the absolute pressure and the pressure drop in the upper and lower parts of the test section. The EFP probe (2 in. long in the streamwise dimension) was positioned at the center plane of the upper section of the 0.25 x 2.5 in. cross-section rectangular flow duct, between fast-acting valves (FAVs) 2 and 3, approximately 65 in. downstream from the duct entrance. Although under the conditions used in these experiments the bubble diameter was significantly larger than what is expected in a pressurized water system, a roughly comparable two-phase flow environment was simulated by adding a small amount of soap to lower the water surface tension in all tests.

Results and Discussion

The validation of a new measurement technique requires the existence of a standard. However, it is generally difficult to qualify measurements made with a local void fraction device, because no convenient standard exists. The fast-acting valves permit, by measuring the relative lengths of the trapped gas and liquid columns, a direct measurement of the spatially averaged void fraction. A local measurement, such as that from the EFP probe, can be validated against a spatially averaged measurement only for flow conditions in which the vapor volumes are uniformly distributed in the test section. A second way to validate the results of the EFP probe is to compare them with the void fraction calculated from the differential pressure measurement. This comparison, however, can be made only for a limited range of flow conditions (low liquid and air flows) where buoyancy forces are predominant.

The EFP void fraction probe performed well in air/water mixtures for a wide range of flow rates (0 - 2000 lb/hr water flow and 0 - 11 SCFM - standard cubic ft/min air flow). As illustrated in Figure 2 for a single liquid mass flow rate, the variation of measured local void fraction with air volumetric flow rate follows the expected trend, and provides strong evidence that the EFP probe is capable of acquiring data in various flow regimes. However, the probe performance was validated only for a bubbly flow regime (0 - 40 lb/hr water flow; 0 - 0.12 SCFM air flow). This was the only test condition where a uniform, buoyancy-dominated flow could be obtained. The EFP probe qualification data for a water flow of 40 lb/hr are presented in Figure 3. The void fraction measured by the probe, fast-acting valves, and the DP cell are shown as a function of the air flow rate for both air inlet mixing configurations. The experiments were run by keeping the water flow constant and varying the gas flow from 0 to 0.1 SCFM. When air was introduced through the soapstone (smaller, well distributed bubbles), the void fraction measured by the EFP probe compares very well with the results obtained from both the fast-acting valves and DP cell; relatively good agreement was obtained even when the air was injected through the manifold. It is interesting that the EFP probe showed, as theoretically expected, a lower void fraction when larger bubbles were present due to the increased bubble rise velocity. For larger gas flows, the flow regime changed from bubbly to churn-turbulent. Under these conditions the local measurement could no longer be validated by a spatially averaged measurement from the fast-acting valves because the large unsteady bubbles were not uniformly distributed in the test section. Also, in this flow regime the friction forces are significant and the DP measurement cannot be used as a standard.

3. Steam/Water Experiments

The successful qualification of the EFP probe in the air/water bubbly flow did not guarantee that it would work in the intended high-pressure, high-temperature, high-pH steam/water application. As noted above, the electrical impedance-type devices work based on the difference between the dielectric properties of the liquid and gas phase; this difference decreases with increased mixture temperature. Therefore, by knowing the variation with temperature of the dielectric properties of the two phases, a theoretical temperature correction was developed and applied to the correlation between impedance and void fraction obtained from air/water data. An additional concern in the application of the EFP probe in steam/water environments was that the high electrical conductivity of the solution could result in loss of signal. It was therefore considered imperative to perform an additional series of tests to validate the EFP probe in a pressurized boiling autoclave.

Test Facility and Measurement System

The test facility used to evaluate the performance of the EFP probe in a pressurized steam/water environment is shown schematically in Figure 4. It consisted of an autoclave heated by a primary (high-pressure water) tube array. The total heat input was controlled by varying the primary side flow rate and inlet temperature. The autoclave basically is a heat exchanger with the secondary side in a pool boiling (low phase velocities) configuration. The interface between the two-phase mixture and pure steam was kept constant by a feedwater controller. This controller matched the subcooled feedwater flow introduced at the bottom of the autoclave with the outlet steam flow. The test facility was instrumented to monitor primary water inlet and outlet temperatures and flow rate, feedwater temperature and flow rate and two-phase mixture level. Additional instrumentation was installed to monitor steam flow rate and the steam and two-phase mixture temperatures on the secondary side. Experiments were performed using water (Solution A) with electrical conductivity of 8 μmho/cm and pH = 8.8, and Solution B with conductivity of 500 μmho/cm, and pH of approximately 10.8.

Five void fraction probes, 3 in. long in the vertical dimension, were mounted with equal spacing on a rod and inserted into the test cell as indicated in Figure 4. As the water level was varied, the position of the probes relative to the interface between two-phase mixture and pure steam changed, resulting in different local void fraction conditions and boiling characteristics. The probes were connected to a signal processing unit controlled by a host computer. Data acquisition and analysis software has been developed for IBM-clone 386 and 486 PC systems, as well as for HP workstations.

One-Dimensional Computational Analysis

In order to gain some insight as to how the void fraction can be expected to vary with axial (Z) position (along the EFP probe array) within the autoclave, a one-dimensional computational analysis was performed. This was considered to be an integral part of the void fraction probe data analysis because the variation of bubble size with chemical composition, which would be expected to affect the local thermal-hydraulic conditions, was not determined experimentally. Also, the elevated temperature and pressure conditions encountered in these experiments made it virtually impossible to perform a concomitant measurement that could provide a means for evaluating the probe's performance. A computer code was employed in which the following equations for conservation of mass, energy, and momentum, respectively, were solved:

$$\frac{dG}{dZ} = 0 \tag{4}$$

$$\frac{dE}{dZ} = q \tag{5}$$

$$\frac{1}{2}\alpha\rho_g\frac{d(U_g^2)}{dZ} = \alpha\frac{d\Delta P}{dZ} - \alpha\rho_g g - F_I U_r^2 \tag{6}$$

where the axial pressure drop gradient ($d\Delta P/dZ$) is a combination of contributions due to elevation (ΔP_{el}), acceleration (ΔP_{acc}), and friction (ΔP_{fr}):

$$\Delta P_{el} = \int_0^L \rho_m g dZ \tag{7}$$

$$\Delta P_{acc} = M_{out} - M_{in} \tag{8}$$

$$\Delta P_{fr} = \int_0^L \frac{U_l}{|U_l|}\frac{f}{2D_H}|M|dZ \tag{9}$$

Note that, since a one-dimensional formulation is used, the computed void fractions are actually spatial averages over horizontal "slices" of the modeled autoclave; no radial void fraction distributions are calculated. If the vapor phase is considered to consist of dispersed spherical bubbles, the interfacial shear coefficient (F_I) may be expressed as

$$F_I = \frac{3\alpha C_D\rho_l}{4D_b} \tag{10}$$

where ρ_l, C_D and D_b are, respectively, the liquid density, drag coefficient and bubble diameter. The drag coefficient was set equal to 0.44 for all computations, while the bubble diameter was treated as a variable parameter for the purpose of comparison between experimentally and computationally determined void fractions. To determine an approximate range over which the specified bubble diameter should be varied, the following correlations for bubble diameter at departure from a heated surface were applied:

Fritz (1935)

$$D_b = C\beta\left[\frac{2g_c\sigma}{g(\rho_l-\rho_g)}\right]^{1/2} \tag{11}$$

where C was found experimentally to be 0.0148 for water bubbles and β corresponds to the contact angle, which could vary from roughly 20 to 60 deg;

Borishanskiy et al. (1981)

$$D_b = \frac{0.00149}{P^{0.46}} \tag{12}$$

where D_b and P have units of meters and bars, respectively. For saturated components at a pressure of about 600 psia and over all contact angles, Equations 11 and 12 yielded bubble diameters from 10 to 92 mils. Since there was such a large variation in possible D_b values estimated from these two empirical correlations, it was apparent that the computations should be run using a wide range of bubble diameters. For purposes of the present analysis, this range was chosen to be 8 to 100 mils.

Results and Discussion

The objectives of these tests were to demonstrate that the void fraction probe could function in a high-pressure steam/water environment, to provide data that could be compared with prior calculations and help in the understanding of differences in the void fraction distribution in the autoclave as a function of heat flux and flow rates. Additionally, the performance of the EFP probe in a high-conductivity water solution was also investigated. To achieve these objectives, two types of tests were performed.

The first set of experiments maintained a constant liquid level while the heat input was varied by changing the primary water temperature and/or flow rate. For this test series, each data point was acquired at a constant heat input. In the second set of experiments, the primary water conditions (heat input) were held constant while the liquid level was varied. Typical results from these sets of experiments are illustrated in Figures 5 and 6, respectively. Figure 5 presents a comparison between the EFP probe measurements and a 1-D two-fluid model calculation in which the interfacial shear force (F_I) was changed by specifying different bubble sizes. The test was run in Solution B under saturated conditions at 665 psia (100% heat input) with the two-phase mixture level just barely contacting the bottom of void fraction Probe VF5. Generally, the local void fraction increases with vertical position, although some variation from this trend is observed due to differences in probe proximity to the primary water tube. Probe VF2 was located close to the heating surface and measures a higher than average void fraction. Probe VF3, yielding a relatively low void fraction measurement, is located opposite the array and is shielded from the heated surface by the supporting rod. A linear regression of the void fraction data from EFP probes VF1 through VF4 correlates well with the 1-D analysis using an interfacial shear force based on 16 mil average diameter bubbles. Probe VF5, which for this test resided mostly in the steam space above the two-phase mixture interface, yielded a void fraction measurement of about 98%. The measured 2% liquid volume fraction is likely due to the frothing behavior of the liquid/steam interface.

Figure 6 compares the data for two test points from the second set of experiments (Solution B at 665 psia and 100% heat input; Solution A at 770 psia and 50% heat input) run with the two-phase mixture interface located low in the autoclave, beneath Probe VF3. As expected, and as predicted by the 1-D model, the EFP probe data indicate that there is an increase in the local void fraction with increasing heat input. As mentioned above, the Probe VF2 is located near the heating surface and will tend to measure a higher than average local void fraction. The measurements also show a distinct change in void fraction at the interface between two-phase mixture and steam. In fact, the froth level near the interface at EFP Probe VF3 could easily be detected by the dynamic change in local void fraction indicated by the probe. Another very important finding was that the probes were able to detect slight differences in moisture carryover at the three highest measurement locations. For example, for the Solution A test at 50% heat input, Probes VF3, VF4, and VF5 yielded local void fraction measurements of 98.0, 98.3, and 99.0%, respectively, indicating that the moisture carryover decreases away from the interface. As expected, there are no significant differences in data for 50 and 100% power in the steam space.

4. Conclusions

A novel electrical technique, the Electric Field Perturbation probe, has been applied to measure the local void fraction in various gas-liquid two-phase environments. For testing in vertical air/water flows through a rectangular duct, the data acquired with this device were validated with spatially averaged results obtained using fast-acting valve and differential pressure methods at low liquid flow rates in the bubbly flow regime. Also, results obtained over the full range of gas and liquid flow rates indicate that the probe can potentially be used in all flow regimes. In the case of pressurized water two-phase flow, which is the actual physical environment for which the present study was undertaken, the EFP probe was able to detect small variations in void fraction over the entire range studied. At very high void fractions, subtle differences between pure saturated steam and slight amounts of moisture carryover near the two-phase mixture interface were measured. Also, for the lower void fraction region near the bottom of the autoclave, differences in the local void fraction due to heat input and probe proximity to the nucleate boiling source were detected.

From a practical standpoint, the measurement technique described in this paper holds a great deal of promise since it was successfully applied at temperatures and pressures up to about 520°F and 770 psia, and maintained its mechanical integrity in a pH = 10.8 environment. Also, the fact that the signal processing equipment was placed at an appreciable distance (12 to 15 ft) from the active element of the probe indicates that its use in demanding research and industrial applications is possible. Future work is planned to perform a rigorous validation of the EFP void fraction probe under various flow conditions, using standard instrumentation such as the hot-wire anemometer and gamma densitometer. Also, the application of this device for flow regime identification through analysis of the output signal will be thoroughly investigated.

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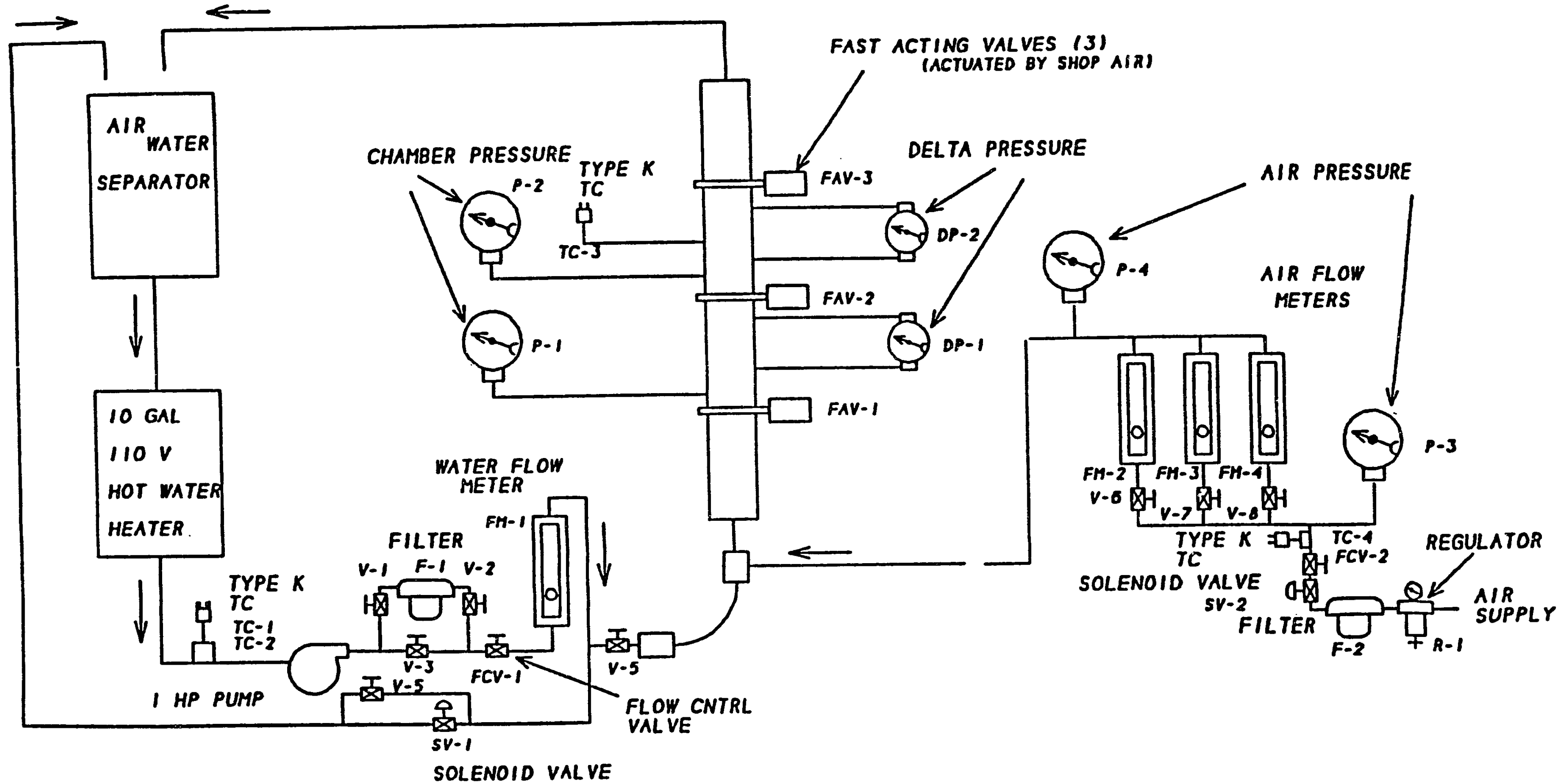

Figure 1 - Air/Water Loop Schematic

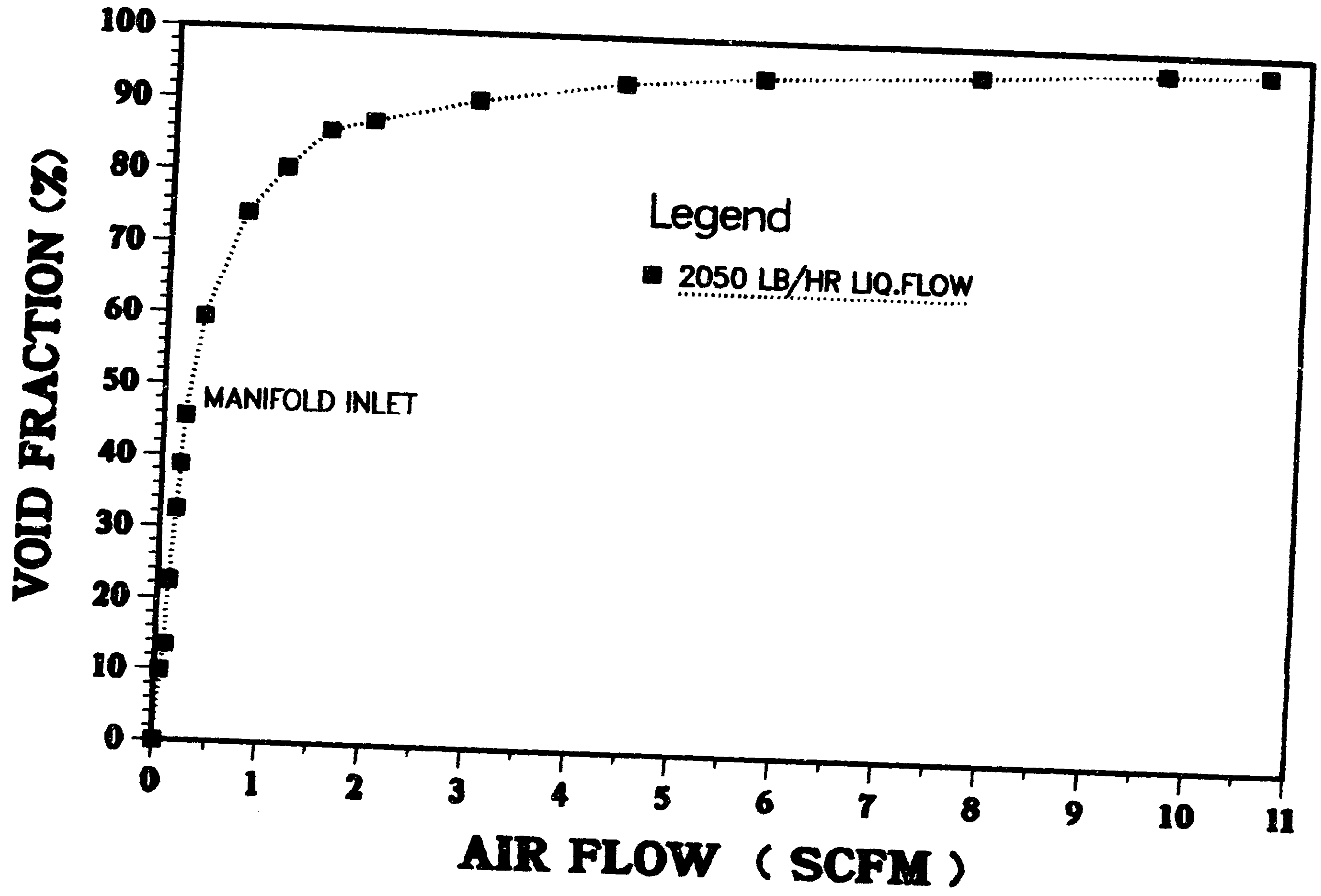

Figure 2 - Air/Water Test Results (Various Flow Regimes)

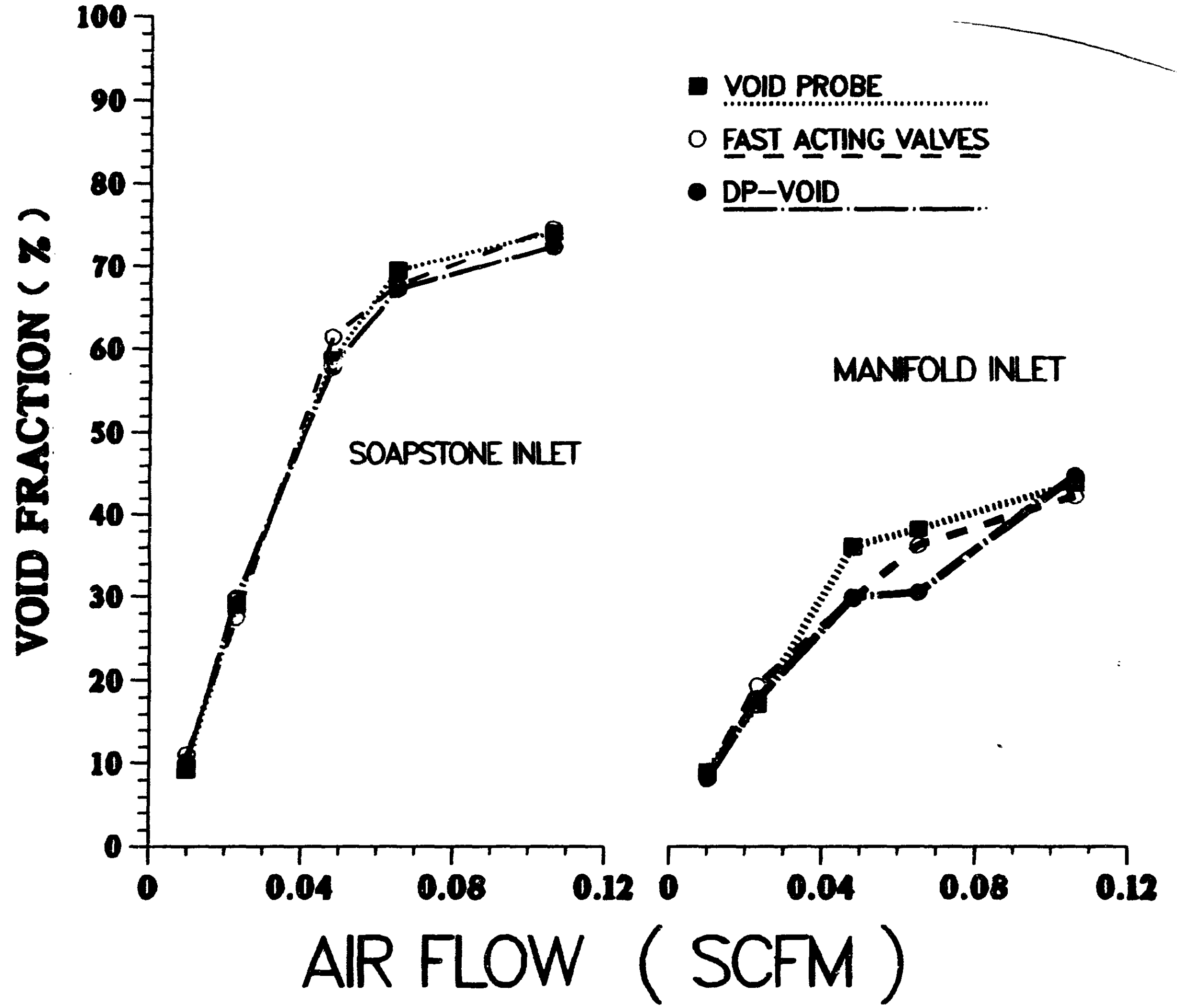

Figure 3 - Air/Water Test Results (Low Liquid Flow)

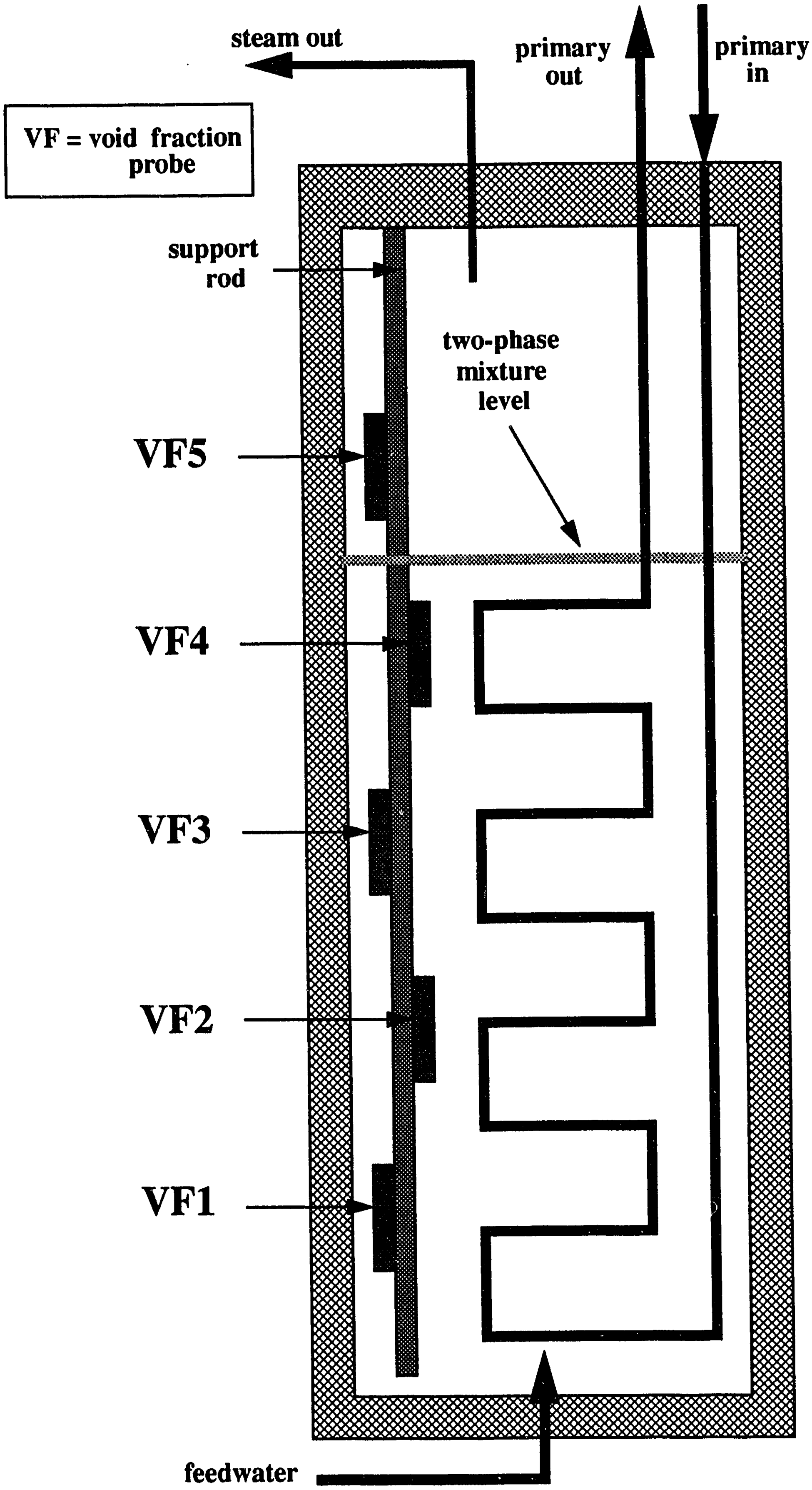

Figure 4 - Pressurized Water Test Cell

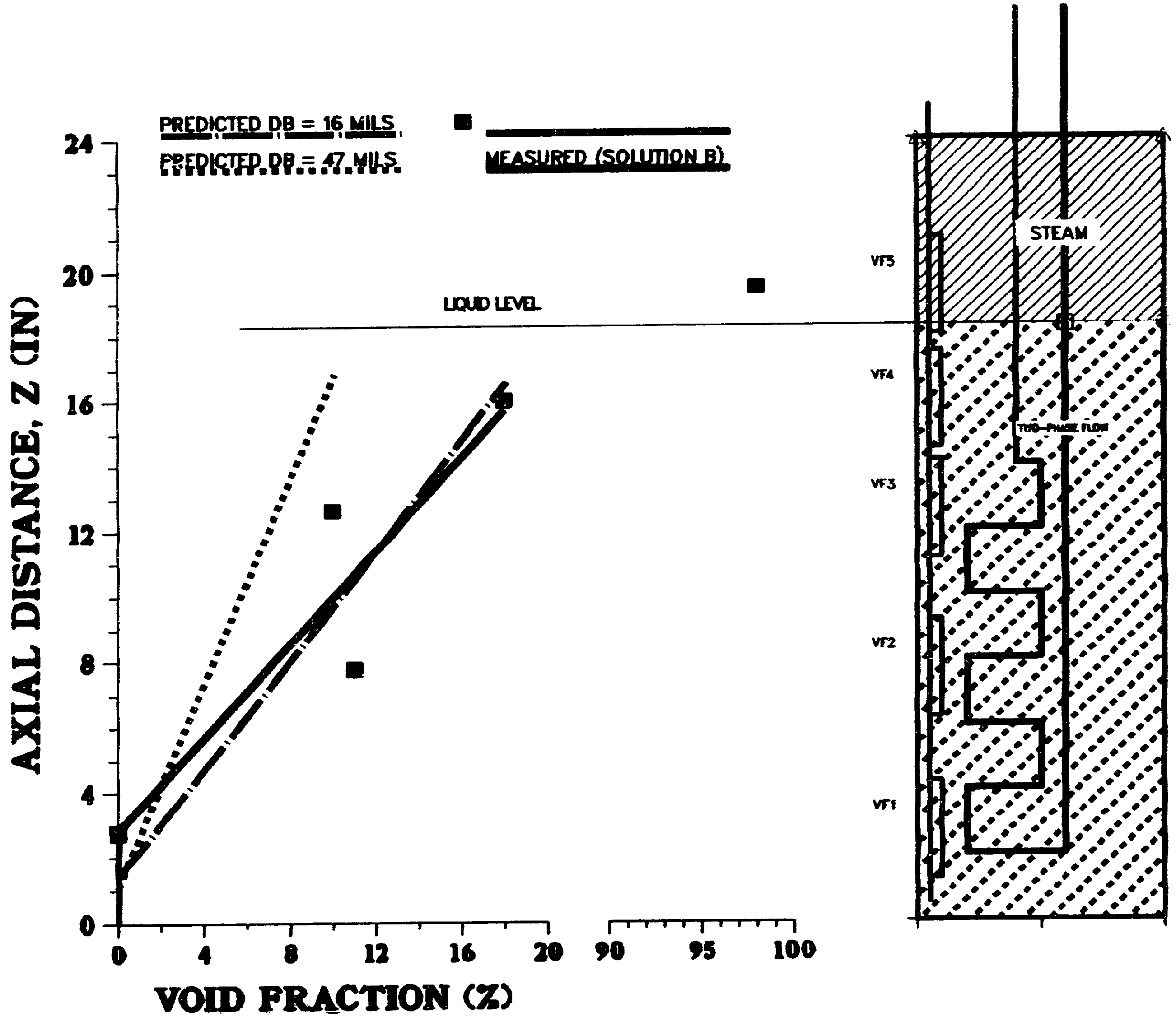

Figure 5 - Steam/Water Test Results (High Interface Level; P = 665 psia)

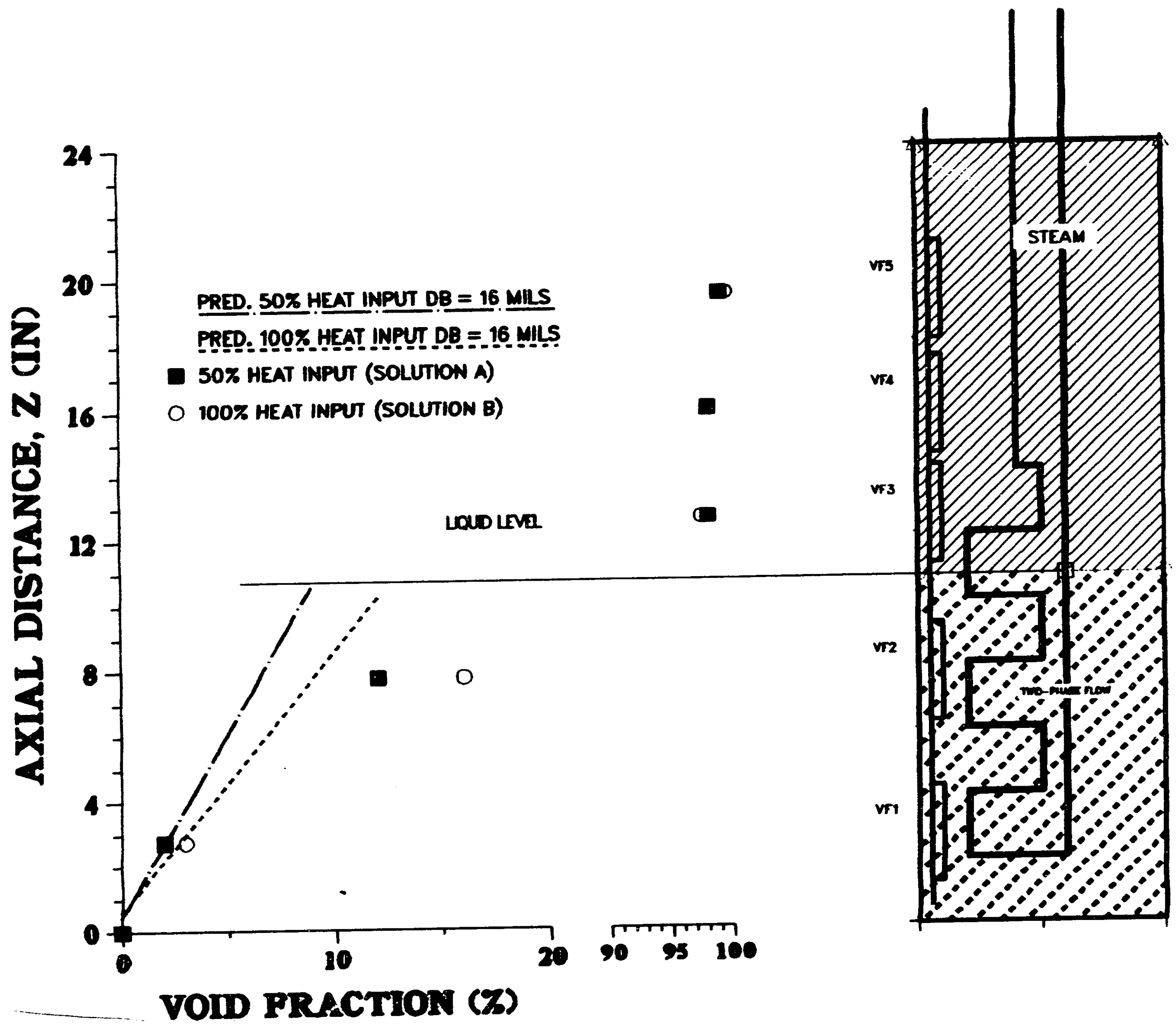

Figure 6 - Steam/Water Test Results (Low Interface Level)

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