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INTERNAL TECHNICAL REPORT

Title: MEASUREMENT OF VELOCITY VECTORS IN TWO-PHASE FLOWS USING FIVE HOLE STAGNATION PROBE

Organization: Advanced Instrumentation Branch

Author: V. A. Deason/J. R. Fincke

Checked By: S. A. Naff

Approved By: S. A Naff

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LOFT TECHNICAL REPORT

Title MEASUREMENT OF VELOCITY VECTORS IN TWO-PHASE FLOWS USING A FIVE HOLE STAGNATION PROBE	LTR No. LO-00-80-117
Author V. A. Deason/J. R. Fincke	Released By LOFT CDCS
Performing Organization Advanced Instrumentaion Branch	Date June 6, 1980
LOFT Review and Approval	Project System Engineer NA

LPD Mgr

DISPOSITION OF RECOMMENDATIONS

No disposition required.

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ABSTRACT

A flow mapping technique has been developed using a prototype five-point stagnation probe. The five-point probe produces five separate differential pressure measurements which can be combined with a density determination to resolve the three-dimensional fluid velocity vector at the probe tip. Modeling and calibration techniques for determining the local velocity vector, and data from a single-phase calibration are presented. Extension of the technique to two-phase flow calibration is discussed and two-phase data are evaluated.

This probe can be used to map two phase flow fields in complex piping configurations where bends and obstructions strongly influence flow patterns. Such information is useful in understanding instrumentation readings in PWR experiments or in associated reference loops.

NOMENCLATURE

CP_{yaw}	A calibration coefficient derived from stagnation pressures in the pitch plane (eq. 1).
CP_{pitch}	A calibration coefficient derived from stagnation pressures in the pitch plane (eq. 2).
CP_{total}	A calibration coefficient derived from stagnation pressures due to flow at zero pitch and yaw angle (eq. 3).
ΔP_i	Differential stagnation pressure for hole i (Fig. 1).
$\overline{\Delta P}$	Average differential stagnation pressures.
P_{total}	Differential stagnation pressure P_1 for pitch = yaw = 0°.
$\overline{V}$	Magnitude of fluid velocity at probe.
$\overline{\rho}$	Average fluid density
θ	Probe orientation relative to fluid velocity in pitch plane, degrees
ϕ	Probe orientation in yaw plane, degrees.

Primed quantities are values derived from calibration plots.

CONTENTS

FIGURES

1. INTRODUCTION

A composite stagnation probe consisting of five specially prepared Pitot tubes (Fig. 1) has been constructed and tested at the INEL. The geometry of the device permits the measurement of both local speed and direction of fluid flows. The principle need for such measurements arises because complex piping and associated devices such as pumps, mixers, and bends, cause severe distortion of two phase flow fields. Stagnation probes have been employed to map momentum and mass flux profiles in two phase flows. However, these devices give little information concerning velocity vectors. Hot wire and hot film anemometers have been used to determine local velocity vectors, but such devices are fragile, and difficult to use and interpret in two phase flow. Five hole probes, however, are inherently simple and sturdy. The five hole probe produces five separate differential pressure measurements which can be combined to resolve the three dimensional velocity vector at the probe tip. The tips of the outer Pitot tubes are angled to increase their sensitivity to off-axial flows and the pressure transducers recording the Pitot tube stagnation pressure can be located outside the probe environment. The probes must be individually calibrated due to the difficulty of producing identical probe tip geometries. Calibration is accomplished by mounting the probe in a known flow field and then varying the probe orientation (pitch and yaw) through ± 30^0 relative to the flow direction. Treatment of the data is discussed in the Section 5 MODEL.

Previous applications of five hole probes to single phase flows have included mapping of single phase velocity fields near walls and objects in wind tunnels, combustors, wiers, etc. Probes have been constructed in various geometries including spherical and hemispherical(1), prism and tubular(2). The probe described in this report has been shown to exhibit greater directional sensitivity than other devices relying on the same principle(2).

In this report, modeling for the five-point probe data is discussed and the single-phase calibration data are presented. The two-phase flow calibrations were evaluated over a void fraction range of 0 to 0.5, the limitations of the measurements in two-phase flows are explained.

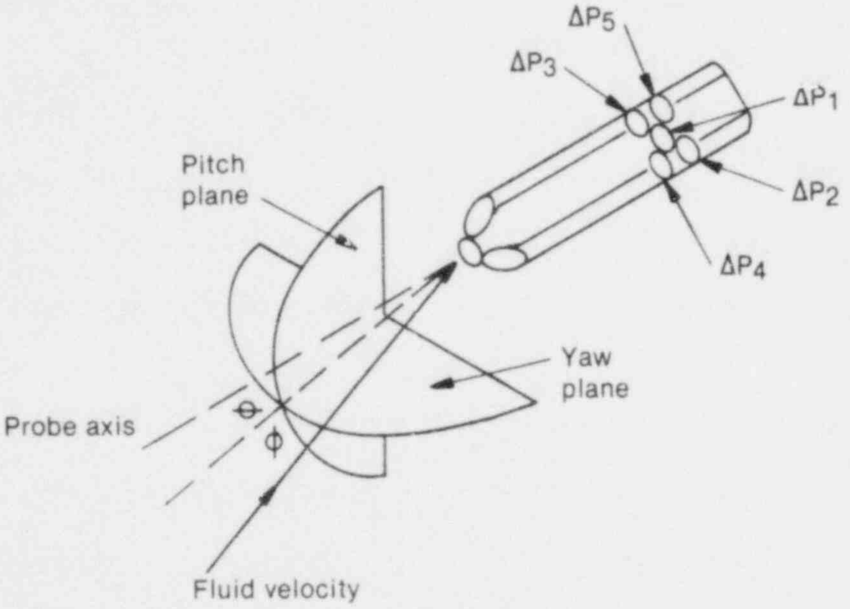

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Fig. 1 Five-Point Probe Geometry.

2. MEASUREMENT CONSIDERATIONS

The problems encountered in applying stagnation probes to measurements in two phase flows have been fully discussed by the authors(3). The major requirement is that the pressure sensing lines be kept full of a single phase fluid, either gas or liquid. Partial filling can cause both pressure offsets due to unknown liquid heads in the lines and loss of frequency response due to the damping effect of alternating plugs of differing phase. In general, the authors use water full tubes due to the faster response times characteristic of this medium. A further difficulty with two phase flow is a pumping action which tends to trap gas plugs in the probe. To alleviate this difficulty, a constant water purge is provided to each pressure line with drainage into the test section. The purge is adjusted with a fine metering valve on each pressure sensing line so that a slow steady drip occurs at the probe tip. The slight overpressure introduced by this procedure can normally be zeroed out at the pressure transducer signal conditioning electronics. To compute velocities, the density at the probe must be known. The density measurements reported here were obtained from a low energy gamma densitometer with a Cd^{109} source and a LN_2 cooled semiconductor detector.(4) The density measurement was made just upstream of the probe tip and resulted in a line average density along a horizontal pipe diameter. For horizontal flows downstream of long straight runs the major variation in density is in the vertical direction with only slight changes horizontally.

The general procedure in both single and two phase measurements was to establish a stable flow, set the pitch angle, and then vary the yaw angle in steps of ± 10° while recording pressures and density. The angles could be set to better than ± 0.5°.

3. TEST FACILITY

The two component flow experiments were performed in the National Engineering Laboratory (INEL) Fluids Laboratory air-water loop. Briefly, the facility consists of a centrifugal pump, separation tank, mixer, heat exchanger, and associated valves and piping. Process instrumentation include turbine meters and temperature and pressure transducers necessary to calculate mass flow rates of air and water before mixing. Density was determined by a single beam low energy gamma (Cd^{109}) densitometer just upstream from the five hole probe. Loop operating parameters are 0.379 MPa and 38°C nominal. The maximum water flow is 0.0221 m^3/s, and the maximum airflow is 0.0425 m^3/s at 0.379 MPa. All tests were conducted in horizontal piping. Data acquisition was provided by a Hewlett-Packard 2100 computer.

The probe was mounted in a 6.7 cm ID x 1 m long clear plastic test section which allowed observation of flow effects during the measurements. A straight section of pipe of the same internal diameter approximately 100 pipe diameters in length was located between the mixer and the test section. This pipe section ensured that velocity profiles were well established and not affected by bends or blockages near the probe.

4. INSTRUMENTATION

The five hole probe consists of five 0.16-cm-OD stainless steel tubes with 0.02-cm walls. These tubes are assembled into a bundle as shown in Figure 2 and soldered in place. The probe was mounted in a calibration holder shown in Figure 3. This holder allowed the probe to be rotated $\pm 30^{0}$ in both the yaw and pitch plane and then locked in place. The stagnation pressure at each probe hole was monitored by a separate validyne DP15TL differential pressure transducer referenced to a common static pressure tap in the wall of the test section.

A low energy gamma densitometer provided a line average density on a horizontal diameter just upstream of the probe tip. The gamma source was CD^{109} and the detector was a LN_2 cooled semiconductor device. The density measurement has an uncertainty of ± 5%. Flow loop parameters including pressure, temperature, and air and water flow rates were provided by the standard Fluids Laboratory instrumentation.

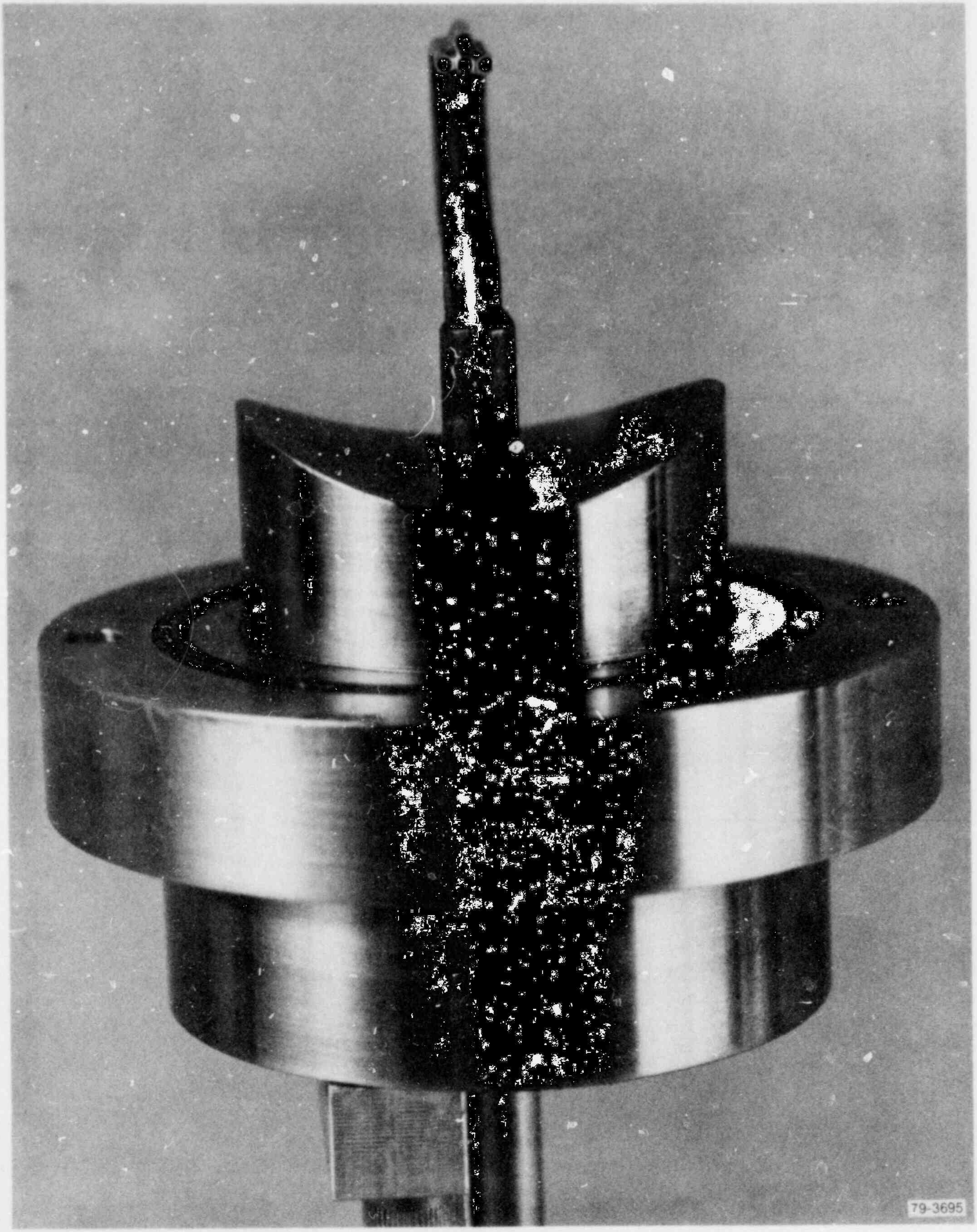

Fig. 2 Five-Point Stagnation Probe.

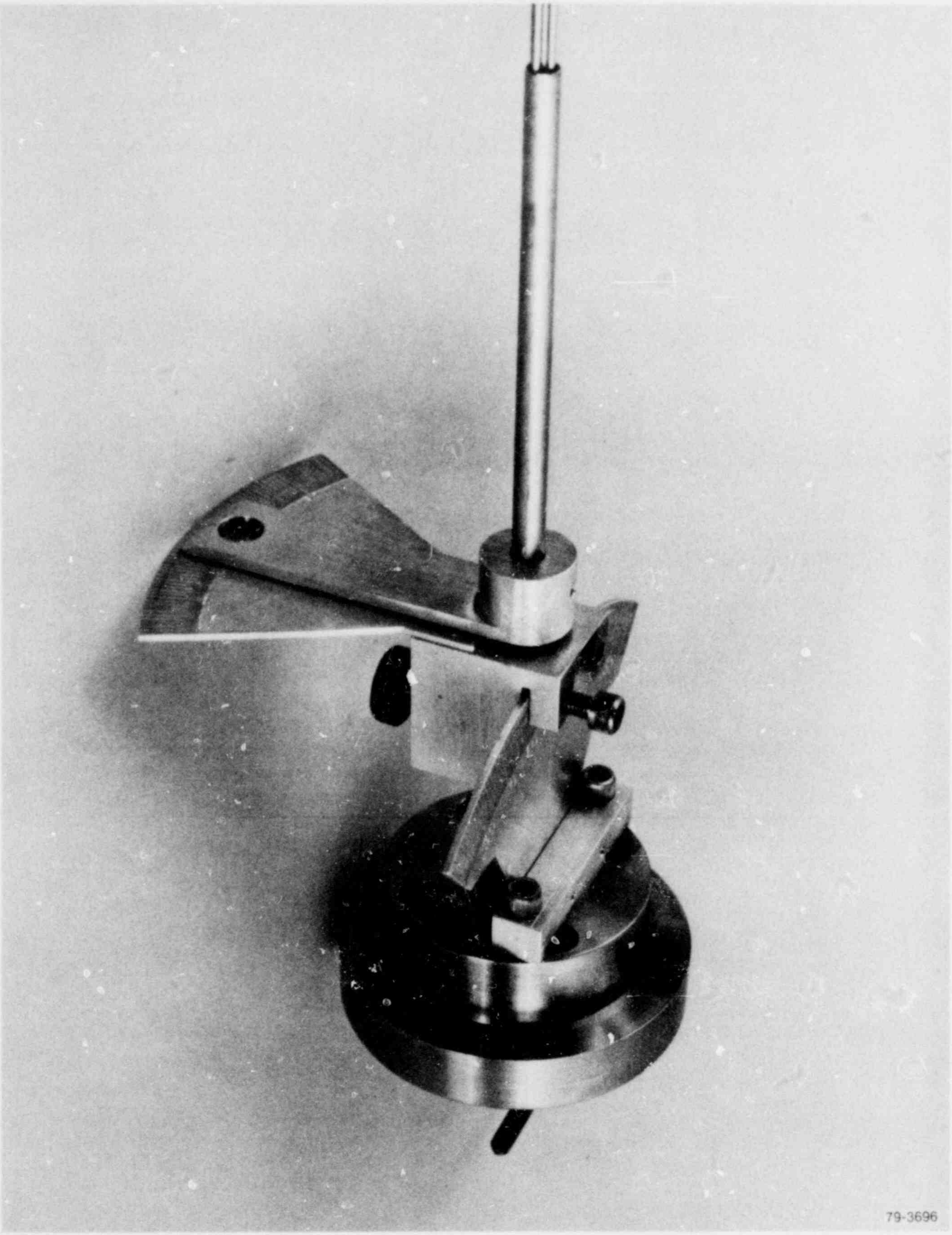

Fig. 3 Five-Point Probe Mounted in Calibration Fixture.

5. MODEL

This probe design has been shown to exhibit greater directional sensitivity than other devices relying on the same principle. Pien(1) proved that for spherical probe geometry, three dynamic pressure measurements in any plane are sufficient to determine the fluid flow velocity component in that plane. For nonspherical probe geometries, the mathematical difficulty both of obtaining theoretical calibration curves and of producing identical probes makes it necessary to provide empirical calibrations. The probe geometry, evaluated by the authors, was shown in Figure 1. During calibration or use, measurements of differential pressure between each tube and a common wall pressure tap located near the probe are made. These differential pressures are used to calculate three separate coefficients as defined by Treaster and Yocum(2). Equations (1), (2), and (3) show the three coeficients.

$$CP_{yaw} = \frac{\Delta P_2 - \Delta P_3}{\Delta P_1 - \overline{\Delta P}} \qquad (1)$$

$$CP_{pitch} = \frac{\Delta P_4 - \Delta P_5}{\Delta P_1 - \overline{\Delta P}} \qquad (2)$$

$$CP_{total} = \frac{\Delta P_1 - \Delta P_{total}}{\Delta P_1 - \overline{\Delta P}} \qquad (3)$$

where ΔP_i are the differential pressures from the corresponding probe tube to a static pressure wall tap.

$\Delta P_{total} = \Delta P_1$ for pitch = yaw = 0^0 which is the total stagnation pressure where the probe faces directly into the fluid flow.

Also

$$\overline{\Delta P} = \frac{\Delta P_2 + \Delta P_3 + \Delta P_4 + \Delta P_5}{4}$$

The pitch and yaw planes shown in Figure 1 are defined relative to the probe. The orientation of the flow direction relative to the probe is defined by the pitch and yaw angles θ and ϕ, respectively.

From calibration data, a plot of CP_{yaw} versus CP_{pitch} is constructed and curves of constant pitch and yaw are drawn. Also, the calibration data are used to construct a plot of CP_{total} versus pitch angle on which curves of constant yaw are drawn. When the probe is inserted in an unknown flow, experimental values of CP_{pitch} and CP_{yaw} are determined. These experimental values are used with the calibration curve, to determine the experimental pitch and yaw angles, θ and ϕ. These angles are then applied to the calibration plot of CP_{total} versus θ, to determine the experimental value CP'_{total}. This quantity can be combined with Bernoulli's equation to determine the velocity: for this purpose, Bernoulli's equation is expressed in the form.

$$\bar{v} = \left[\frac{2}{\bar{\rho}} \left(\Delta P_{total} \right)\right]^{1/2} \qquad (5)$$

where

$\bar{v}$ = average velocity

$\bar{\rho}$ = average density

From Equation (3)

$$\Delta P_{total} = \Delta P_1 - CP'_{total} \left(\Delta P_1 - \overline{\Delta P} \right). \qquad (6)$$

Combining Equations (5) and (6):

$$\bar{v} = \left[\frac{2}{\bar{\rho}}\left(\Delta P_1 - CP'_{total} \left[\Delta P_1 - \overline{\Delta P}\right]\right)\right]^{1/2} \qquad (7)$$

where everything under the square root is experimentally measured except for CP'_{total} which comes from the calibration plot. Therefore, from the output of a five-point probe and a density measurement at the probe, fluid speed v and its direction θ and ϕ can be calculated.

The authors(3) have shown that Pitot tubes may be used to deduce velocity in two-phase flows. The preceding analysis leading to Equation (7) holds for two-phase flow if $\overline{\rho}$ is defined as the local time average density, the local slip ratio is assumed to be unity, and the void fraction is less than 0.90. For void fractions greater than 0.90 more sophisticated analysis is required[5].

6. RESULTS OF TESTING

The five point probe has been fully calibrated in single phase (water) flow. A partial calibration in air-water flows was also performed to evaluate two phase effects on the single phase calibration plots. Sections 3 and 4 have detailed the experimental arrangement.

6.1 CALIBRATION IN SINGLE-PHASE FLOW

Prior to use, the five-point probe must be calibrated in a known flow field - typically a single-phase flow.

Calibration data for the five-point probe in a water flow of 3.5 m/s and various pitch and yaw angles between ± 30 degrees are presented in Figure 4 as CP_{pitch} versus CP_{yaw}. CP_{total} is plotted versus pitch angle in Figure 5. The asymmetric form of these calibration curves is due to slight asymmetries in the shape of the probe. Such unavoidable asymmetries are the principal reason for developing experimental rather than theoretical calibration curves.

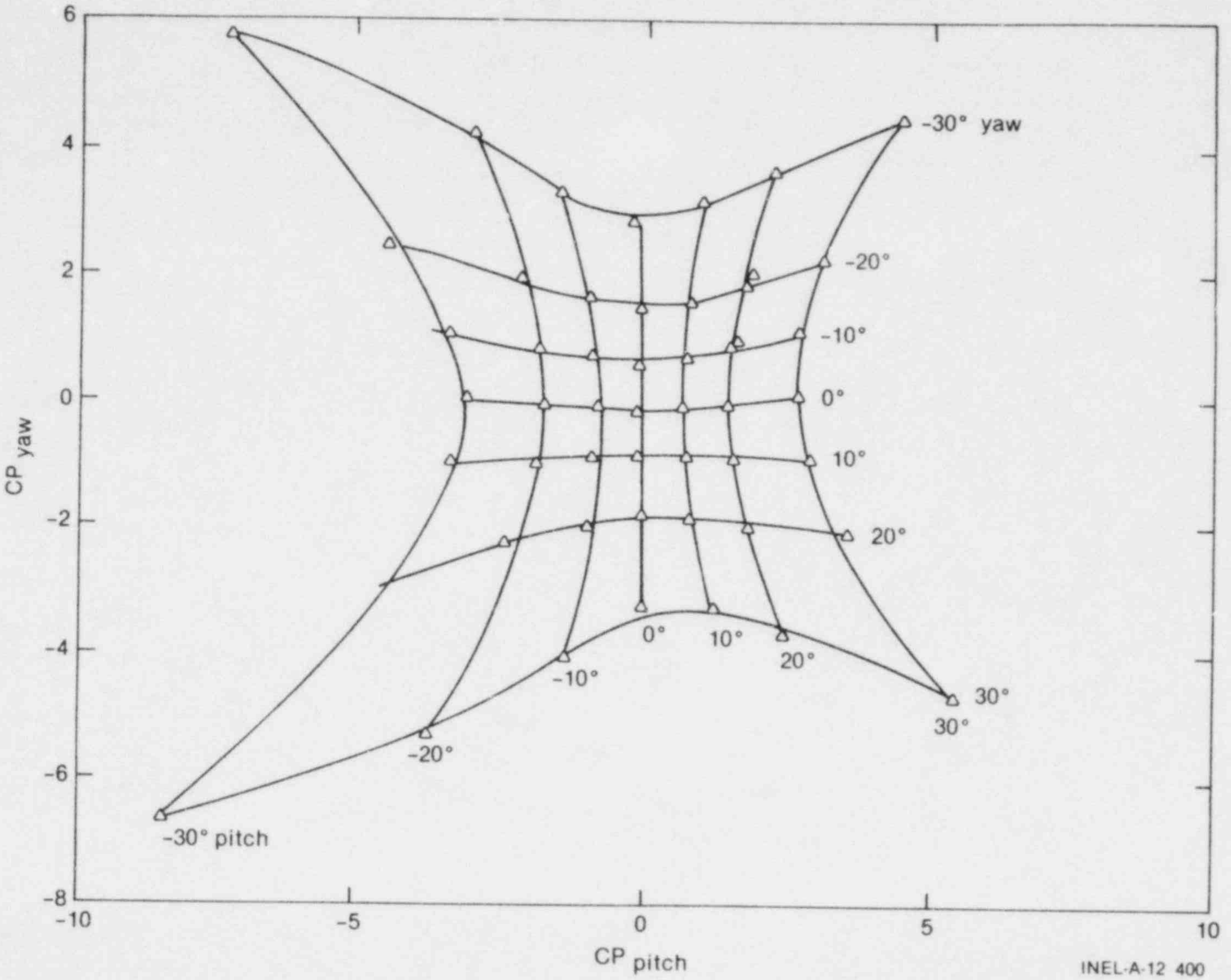

Fig. 4 CP_{yaw} vs CP_{pitch} Calibration Data for Single Phase Water Flow.

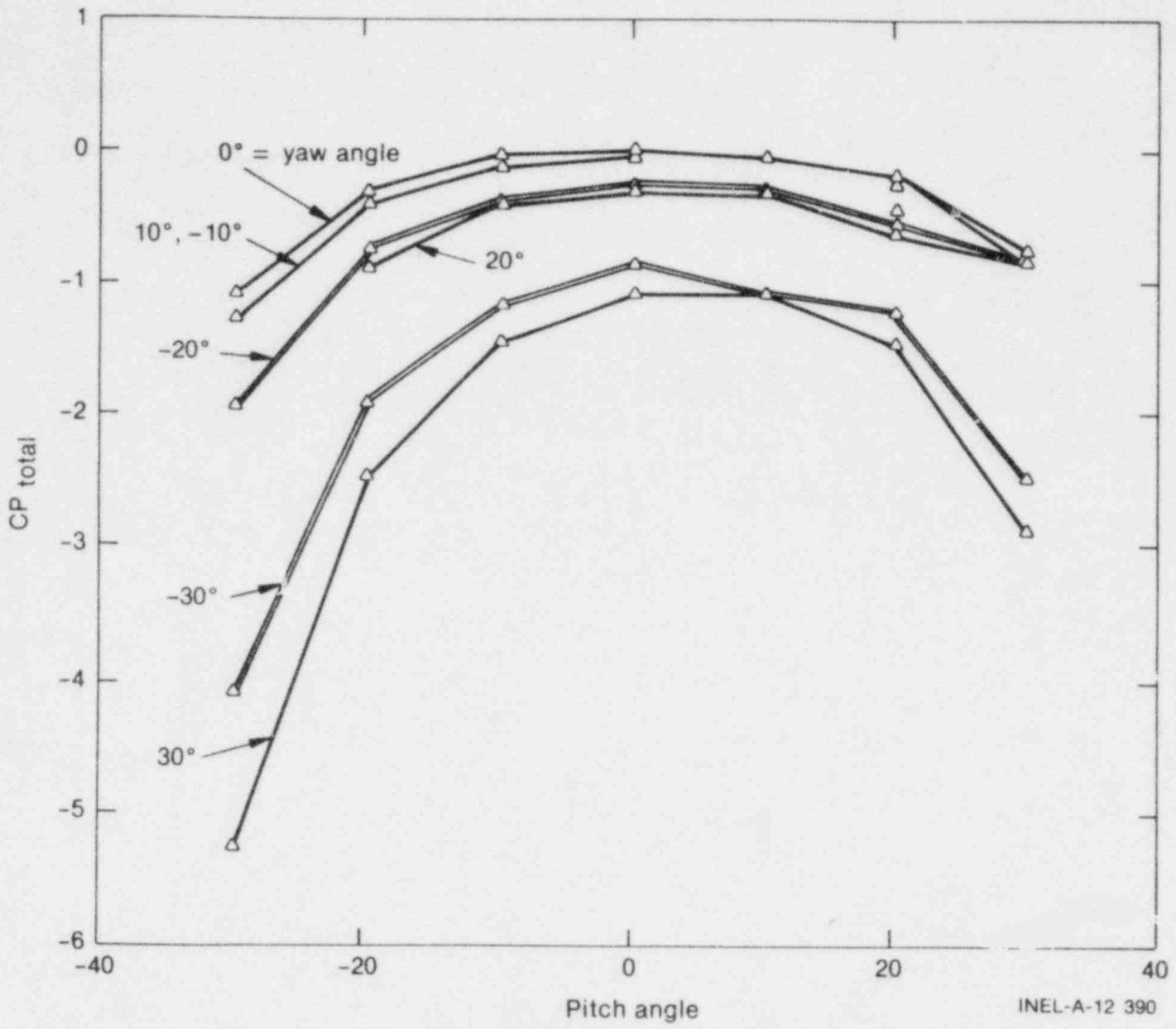

Fig. 5 CP_{total} Versus Calibration Data for Single Phase Water Flow.

6.2 CALIBRATION IN TWO-PHASE FLOW

The results of a two-phase (air-water) calibration for the quadrant pitch = 0 to + 30 degrees and yaw = 0 to +30 degrees is shown in Figure 6. For comparison, the corresponding all water calibration points are also plotted. There is an offset between the two sets of data which increases with increasing probe angle. These differences are probably due to pseudo-cavitation at the probe tip which also becomes more pronounced at the more extreme probe positions. The results of pseudo-cavitation is to trap an air bubble in the recirculation zone on the downstream side of the probe. Thus, the downstream probe ports sense a different environment than the upstream, unlike the case in single-phase flow.

In Figure 7, CP_{yaw} is plotted against CP_{pitch} for a variety of flow regimes and pitch = yaw = 0 degrees. The root-mean-square (rms) variation in these data due to two-phase effects is 0.3 (5% of full scale). Thus, there is only a small two-phase effect for small flow angles relative to the probe. Figure 8 is a similar plot for pitch = yaw = 20 degrees. The scatter due to two phase effects is greater at the more extreme angles.

Figure 9 shows the effect of void fraction variations on CP_{pitch} for pitch = 20 degrees and yaw = 0, 10, 20, and 30 degrees. For all yaw angles up to 20 degrees, the experimentally determined correction for void

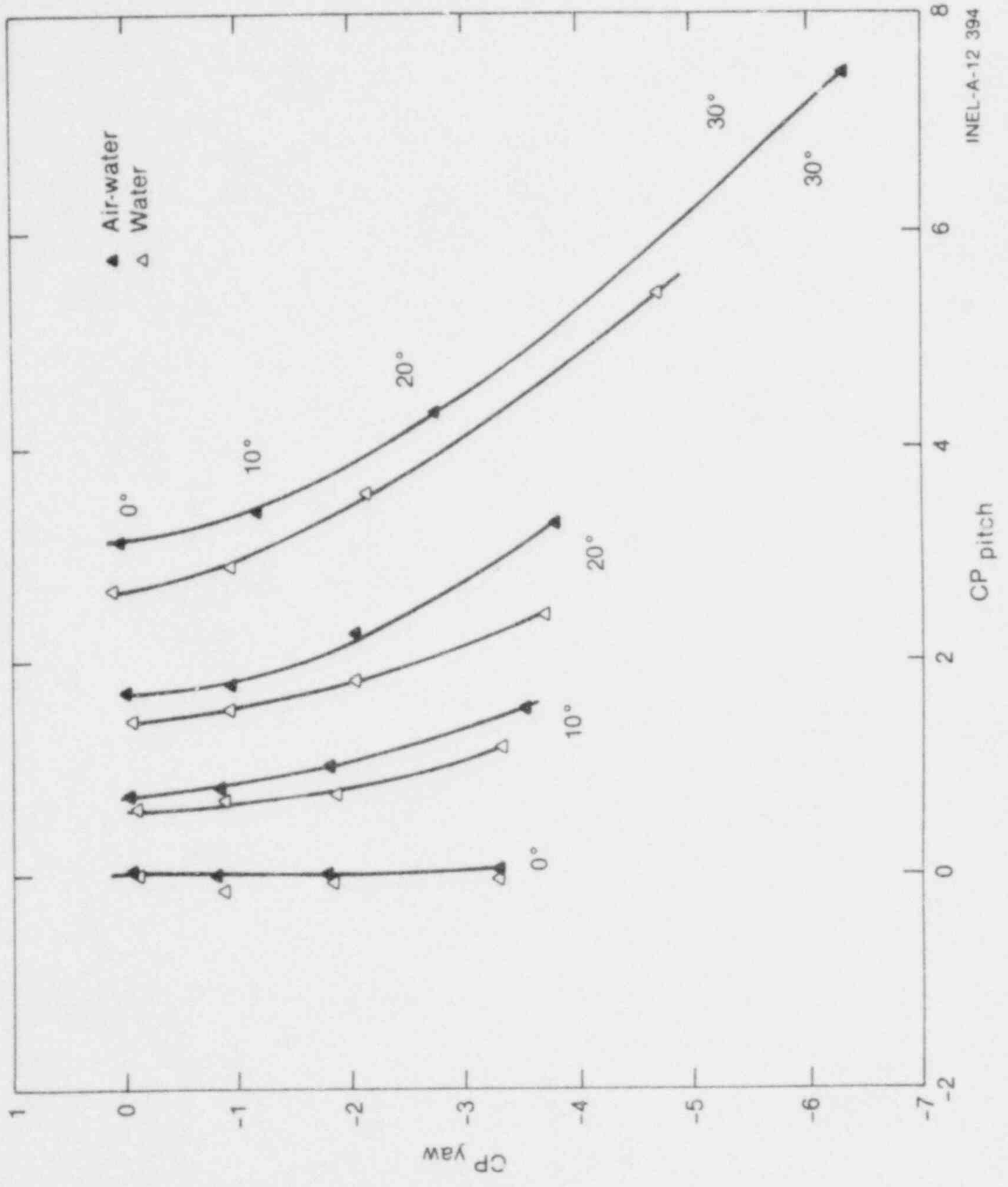

Fig. 6 Two-Phase Effects.

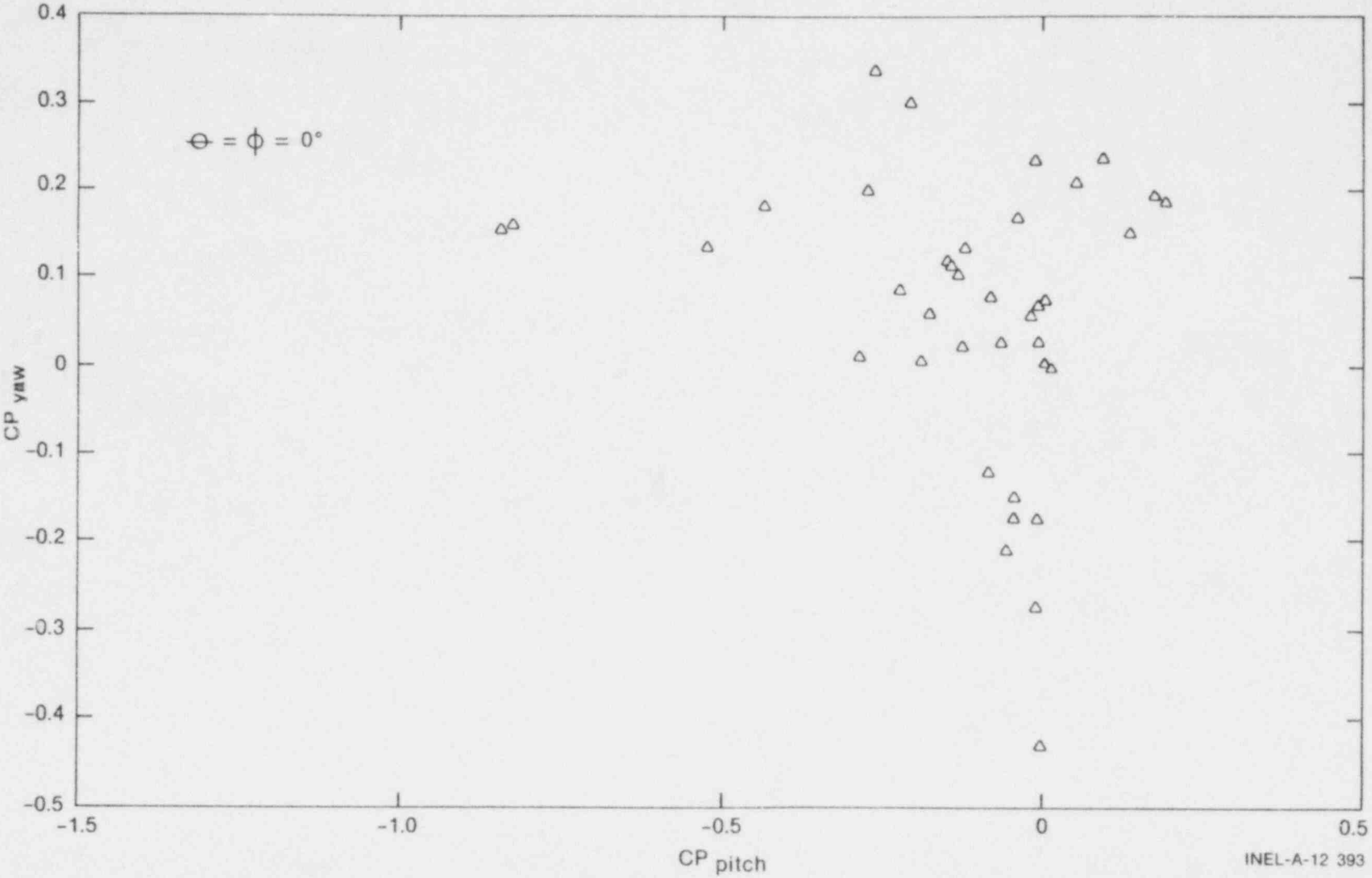

Fig. 7 Two-Phase Flow Effects for Pitch = yaw = 0°.

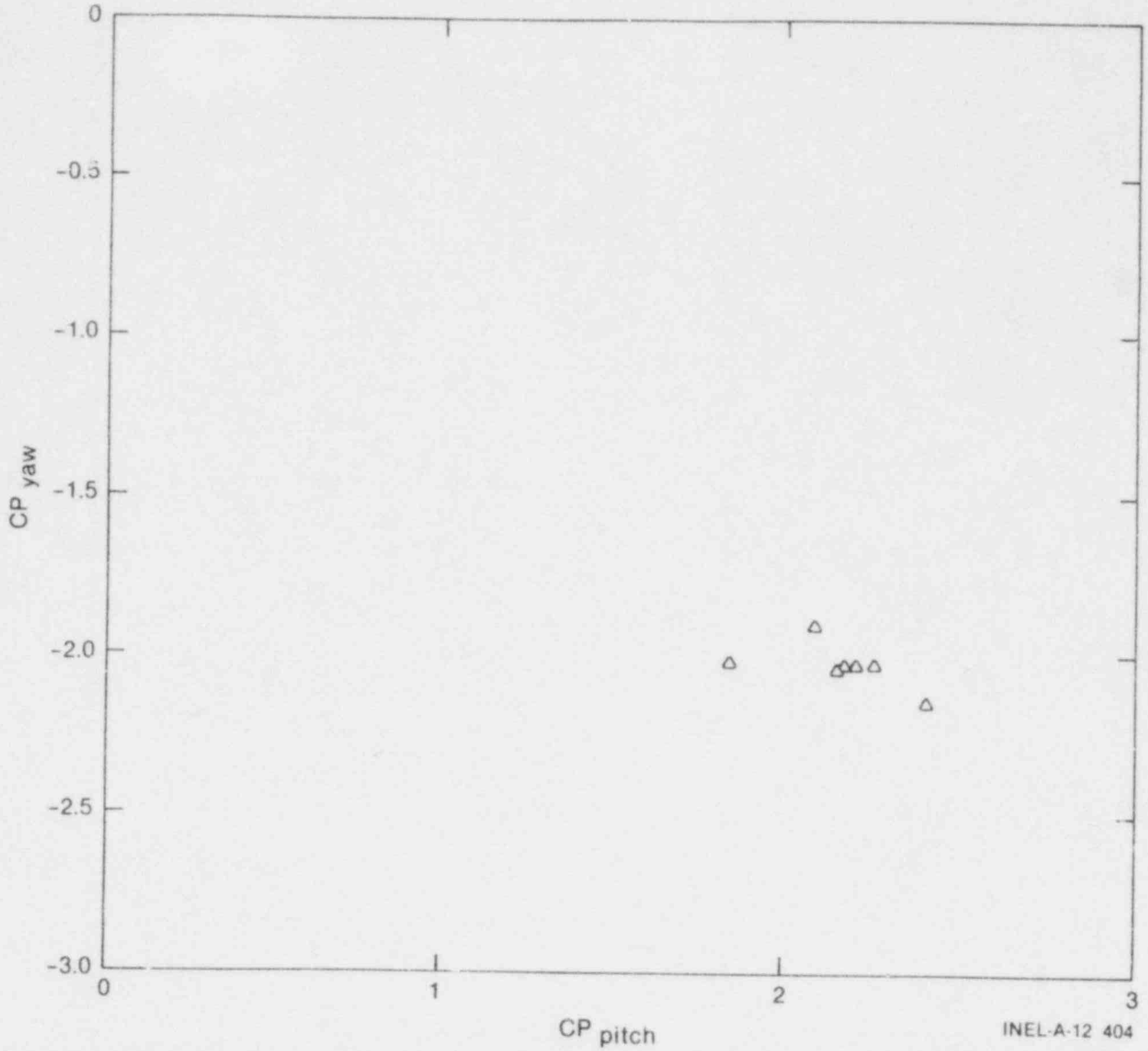

Fig. 8 Effect of Two-Phase Flows for Pitch = yaw = 20^0.

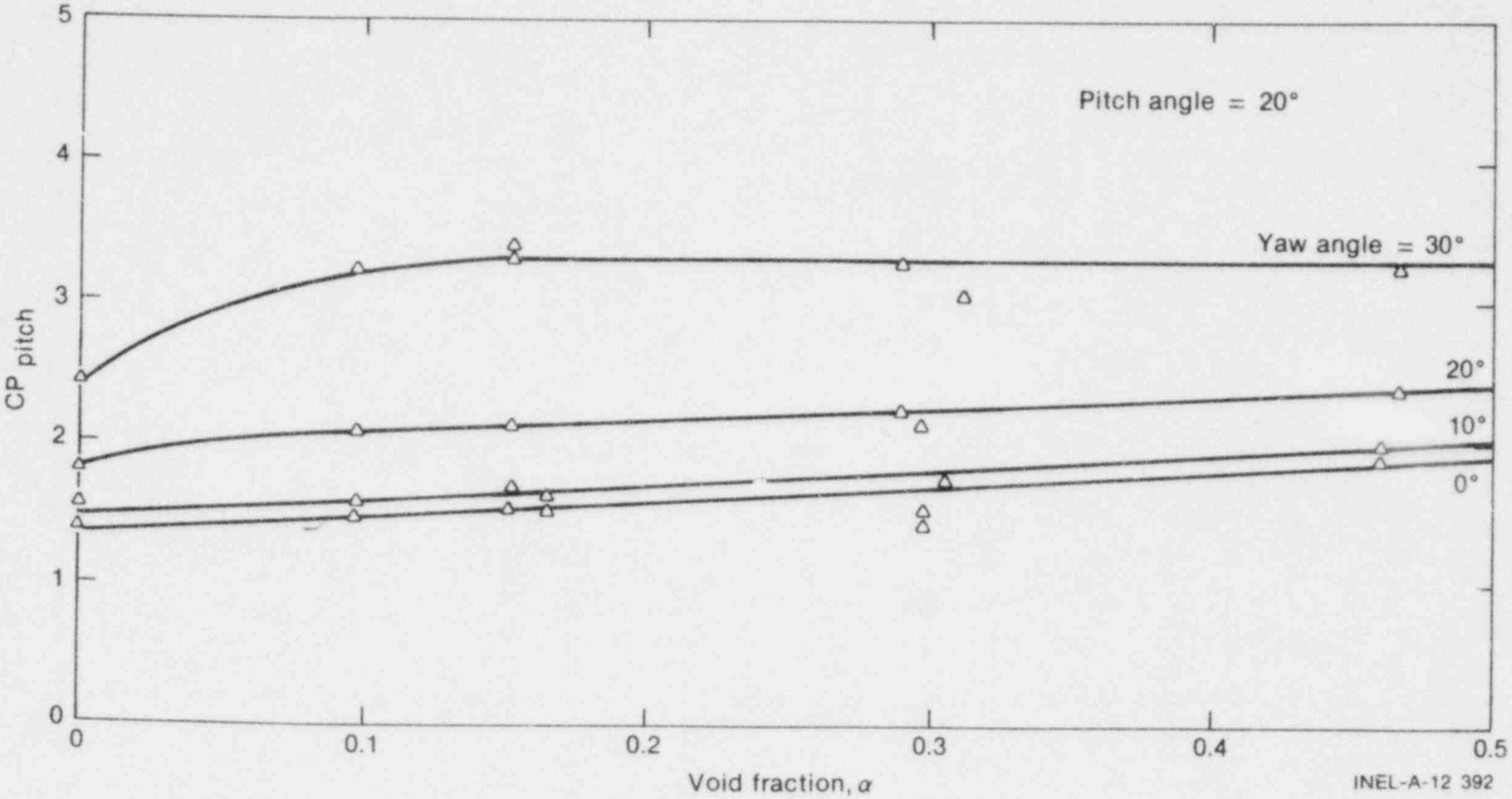

Fig. 9 Void Fraction Effects.

fraction between 0 and 0.5 is approximately linear and can be represented by $CP_{pitch} = CP'_{pitch} - 0.097\ \overline{\alpha}$, where CP'_{pitch} is the experimentally determined value.

Figure 10 shows superimposed data for various air-water flows in the sluggy and sluggy-stratified regimes (air flow of 7×10^{-2} m^3/s and water flows from 4.7×10^{-4} to 2.1×10^{-2} m^3/s). Considerable scatter is present in the data, and little correlation is possible with the all water calibration data. Some improvement in the data for slug flows probably could be accomplished by analyzing the data from water slugs separately from those for air slugs rather than taking average values over both. However, the time constant of the gamma densitometer which provided the only means of distinguishing between regions of differing void fraction is too large to allow the instantaneous flow condition at the probe to be determined. The problem of interpretation encountered in slug flows is illustrated in Figures 11 and 12, where the density and stagnation pressure records for a typical data point are shown. The data show a quasi-steadiness with density maximums occurring in frothy water slugs and minimums in droplet laden air slugs. The stagnation pressure record mirrors this fluctuation.

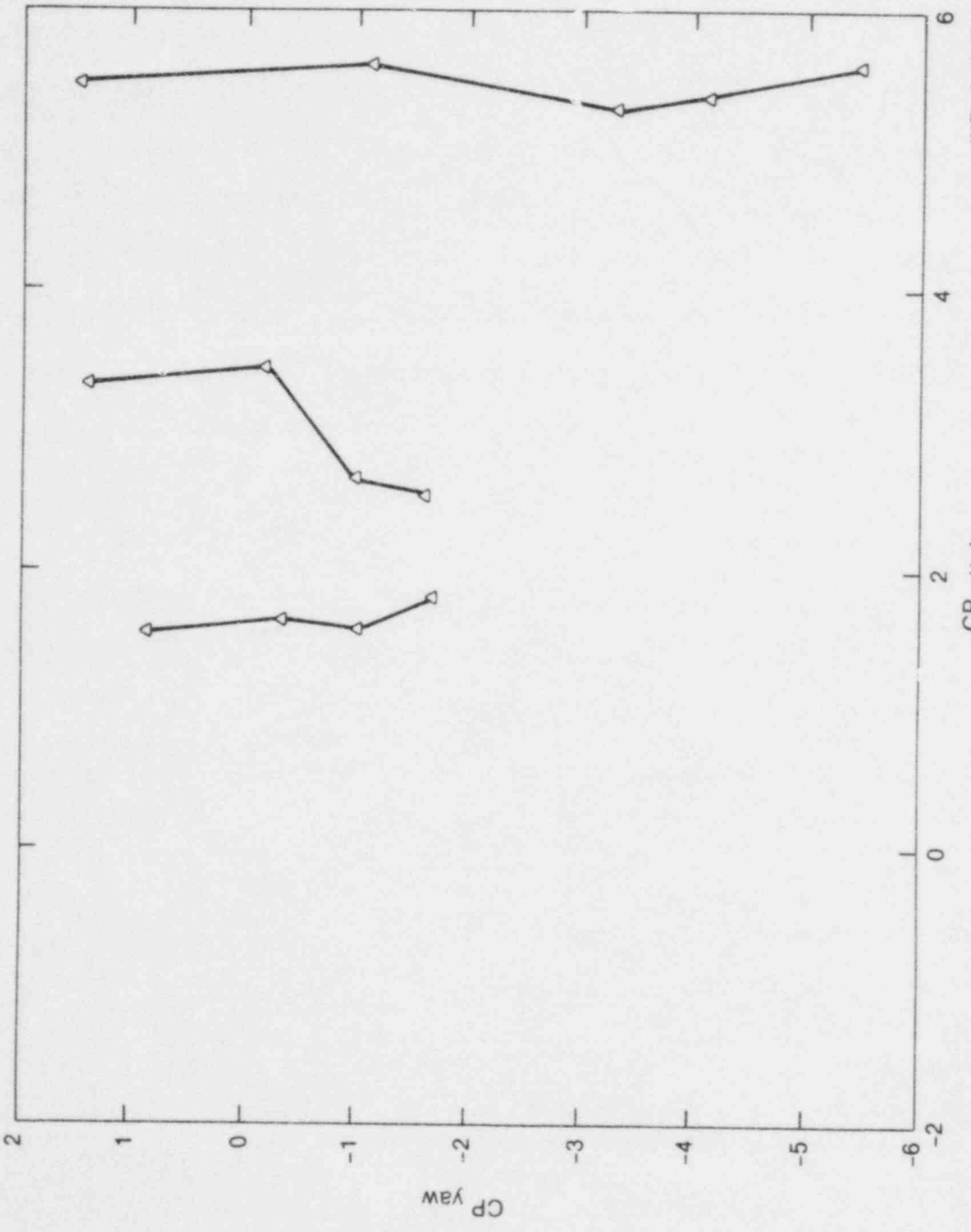

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Fig. 10 Two-Phase Data for Slug Flows.

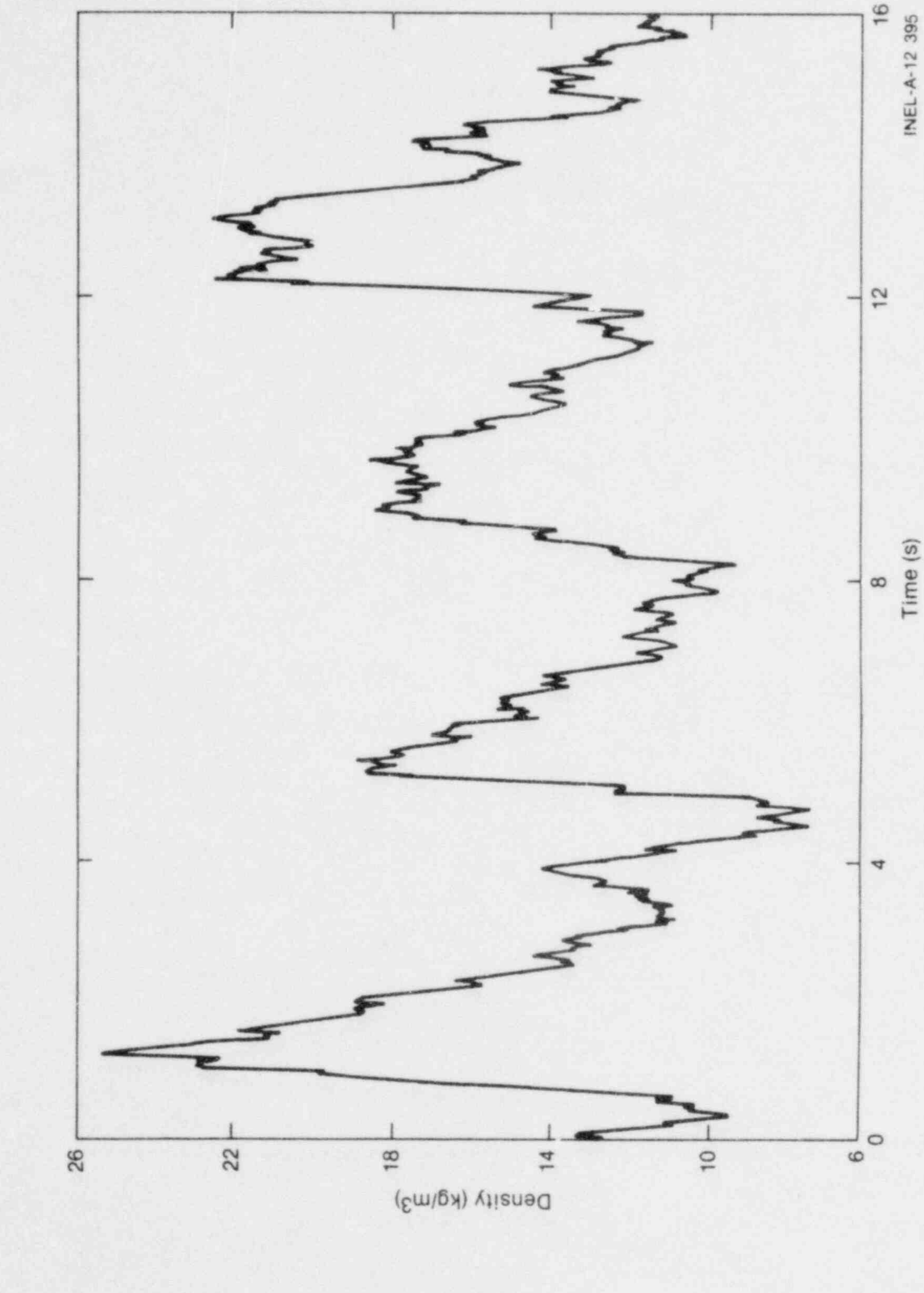

Fig. 11 Slug Flow.

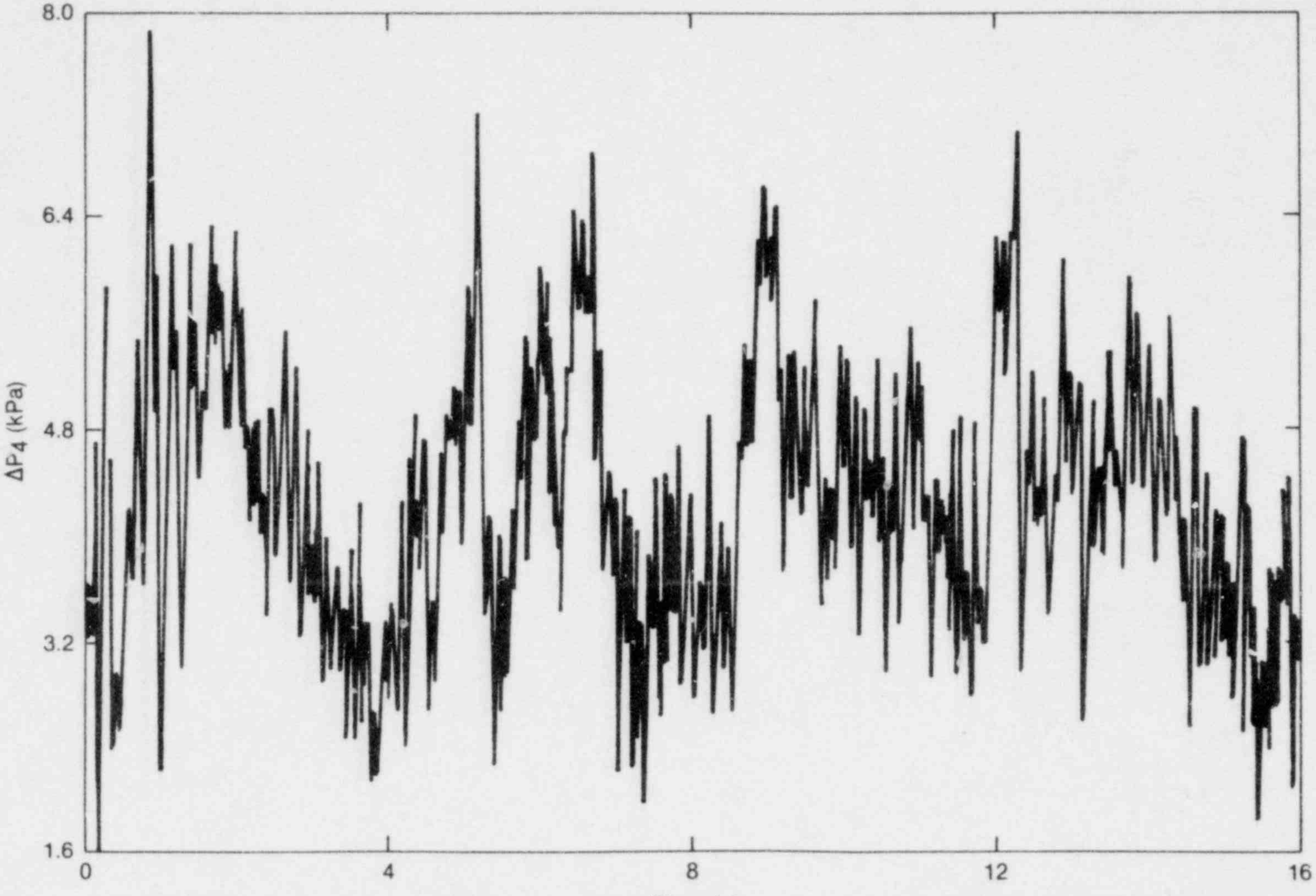

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Fig. 12 Slug Flows.

7. CONCLUSIONS

The five-point probe, which has a long history of application to single-phase velocity measurements, can be used for velocity determination in two-phase flows. The probe performs well in homogeneous bubbly flows; however, more accurate density measurements and a more sophisticated model are required before the measurement technique can be applied to the mist flow regime. The slug regime also presents problems. Data analysis on a point-by-point basis rather than with time averages, would greatly improve the scatter encountered in slug flow data. Stratified flows may be treated as two contiguous homogeneous flows.

Five point probes provide an effectual tool for mapping velocity fields to determine the effects of pipe geometry and instrusions into the flow upon the flow profiles downstream.

8. REFERENCES

1. P. C. Pien, "Five-Hole Spherical Pitot Tube", David Taylor Model Basin Report 1229 (May 1958).

2. A. L. Treaster and A. M. Yocum, "The Calibration and Application of Five-Hole Probes", 1978 ISA Meeting, Albuquerque ISBM 86674-403-5M, p 255.

3. J. R. Fincke and V. A. Deason, "Fluid Dynamic Measurements in Air-Water Mixtures Using a Pitot Tube and Gamma Densitometer", Proceedings of Twenty-Fourth International Instrumentation Symposium: Albuquerque, New Mexico, May 1978.

4. A. G. Stephens, M. A. Emery, L. E. Hochrelter, "Local Density Measurements in a Steam-Water Mixing Zone Using the Photon Attenuation Technique, Topics in two-phase Heat Transfer and Flow, ASME Winter Annual Meeting, San Francisco, Calif., Dec. 1978

5. J. R. Fincke and V. A. Deason, "The Measurement of Phase Velocities in Mist Flows Using Stagnation Probes", NUREG/CR-6048, TREE-1350, March, 1979