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A CALIBRATION OF THE PRESTON TUBE IN LIQUID FLOW SYSTEMS.(U)
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A CALIBRATION OF THE PRESTON TUBE IN LIQUID FLOW SYSTEMS

THESIS

AFIT/GAE/AA/79D-10

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AFIT/GAE/AA/79D-10

A CALIBRATION OF THE PRESTON TUBE IN LIQUID FLOW SYSTEMS

Master's THESIS

Presented to the Faculty of the School of Engineering of

the Air Force Institute of Technology

Air University

in Partial Fulfillment of the

Requirements for the Degree of

Master of Science

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by

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Preface

The measurement of skin friction on a body or a wall can be a time consuming and complicated process. In 1954, Dr J.H. Preston introduced a means of measuring wall shear stress through a small total pressure probe mounted directly on a surface. This theory has undergone repeated revision and verification until it is now a well established procedure for air. Nothing, however, has been postulated on its validity or usage in any other working medium. The basic intent of this study is to explore the validity of this method in other fluids of practical use to the engineer.

I would like to thank the technicians of the AFIT Fabrication Shop especially Mr Jack Tiffany for the wood venturi model and Mr Rus Murrey for the Preston tubes and depth measurement system. Their quality work and helpful advice made this area a trouble free part of this study.

The precise results of the water tunnel experiment would not have been possible without the assistance of Mr Parker Buckley of the Propulsion Laboratory. His knowledge of manometer performance and his previous computation of test section velocity profiles saved many futile hours and helped focus on the real objective of this study.

Lastly, I wish to extend my sincere appreciation to my wife, Chris, for her enthusiastic and unreserved efforts in proofreading and typing this thesis.

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<u>List of Symbols</u>

A	area, ft^2
d	Preston tube diameter, in
D	pipe diameter or channel depth, ft
h	height of a liquid column, in
ℓ	length associated with boundary layer calculation
L	length of pipe or channel, ft
$\dot{m}$	mass flow rate, lbm/sec
ΔP_p	Preston tube dynamic pressure - difference between tube pressure and local static pressure, lbf/in^2
P_s	static pressure, lbf/in^2
Q	flow rate, ft^3/sec
R	radius, in
Re	Reynolds number
R_h	hydraulic radius, in
SG	specific gravity
T	temperature, F
u	local velocity, ft/sec
U	free stream velocity, ft/sec
U_τ	Friction velocity, ft/sec
W	specific weight, lbm/ft^3

δ boundary layer thickness, in

τ_o wall shear stress, lbf/in^2

ρ fluid density, lbf-sec^2/ft^4

ν kinematic viscosity, ft^2/sec

$$X^* = \log_{10}\left[\frac{\Delta P_p\ d^2}{4\rho\nu^2}\right]$$

$$Y^* = \log_{10}\left[\frac{\tau_o\ d^2}{4\rho\nu^2}\right]$$

Abstract

The justification of Preston tube usage is based on a universal similarity law that relates the velocity profile in fully developed pipe flow to that of a boundary layer associated with external flow. The Preston tube measures these velocities at the wall and when calibrated for flow in a pipe, provides a means of determining the local wall shear stress. This study is intended to extend the validity of this method to other working fluids such as liquids.

Four separate size Preston tubes are used in three different experiments. The oil pipe provided a unique fluid in a narrow bore pipe and encompassed Reynolds numbers from just turbulent flow to 11600. Results indicated a calibration for oil that closely matched established air data. In the water tunnel experiment some difficulty was encountered for low speed flow but results above Re = 12800 precisely matched that for air. Each tube tested provided similar data and effectively proved the validity of Preston's method for water.

A two dimensional experiment was designed to initially calibrate the tubes and to demonstrate practical usage in a venturi model. The calibration failed largely from insufficient precision of the measuring equipment. The model analysis provided an indication of flow separation but failed to specify trend information.

A CALIBRATION OF THE PRESTON TUBE IN LIQUID FLOW SYSTEMS

I. Introduction

The measurement of turbulent skin friction directly at a surface or a wall is often a fundamental and desireable element in many experimental tests. This skin friction parameter, or wall shear stress, can precise y specify such flow characteristics as boundary layer growth, regions of stall, and tendencies toward flow separation from a body or wall. Mechanical measurement of this parameter, while accurate, is invariably a complicated and time consuming process that is beyond the capability of many test facilities. This real need for skin friction measurement was addressed by Dr J.H. Preston of Cambridge University who put forth a simple, yet effective measuring procedure in air.

Preston's method makes use of a thin, total pressure type probe that is mounted directly on the surface of the body being analyzed. Its use for flow measurement is predicated upon the assumption of a universal inner law (or law of the wall) common to both boundary layers and fully developed pipe flow. By mounting such a probe at varying locations in a model, adverse effects in the boundary layer can be accurately determined. Several experiments to this date have substantiated this simplified method and proven its versatility.

History

Preston first introduced his method of measuring skin friction in a turbulent boundary layer in 1954. Through the use of a round pitot tube resting on the surface (hereafter called a Preston tube), he attempted to establish a universal relation between the pressure recorded by the tube, its accompaning static pressure, and the local skin friction. Soon after publishing his results, the National Physical Laboratory (NPL) of England attempted to check the procedure's claimed accuracy for flow over a flat plate. This study conflicted with Preston's calibration by some 14 percent. Since this cast considerable doubt upon Preston's method, Head and Rechenberg (Ref 3) of Cambridge University attempted to reestablish justification for Preston's method and the assumption of universal wall similarity, or to provide clear evidence against such. They, in fact, provided convincing proof of the soundness of the method and its assumptions, but their experiments indicated that Preston's original calibration was somewhat in error. In 1964, Dr V.C. Patel, also of Cambridge, provided an accurate calibration of the Preston tube and defined the pressure gradient limitations on its use (Ref 6).

Objective

To this date, the literature indicates that all calibrations of Preston tubes have been in air. The primary objective of this study is to expand upon this limited use of Preston tubes and analyze their potential in other fluids and configurations. Specifically, calibrations will be determined for oil in pipe flow and for water in both pipe flow and a two dimensional configuration. A secondary objective is to demonstrate practical application of the Preston tube through a brief analysis of flow conditions leading to separation in a venturi's diffuser section.

Approach

The calibration of the Preston tube requires a fully developed pipe flow in order for the similarity law to be upheld. Such pipe test installations are available in the Air Force Aero Propulsion Laboratory's (AFAPL) Water Tunnel and the Air Force Institute of Technology's Oil Pipe facility. Wall shear stress is easily calculated in these facilities so that a correlation may be obtained between the installed Preston tube reading and the wall shear stress. Experimental curves are plotted that uniquely relate these two parameters and thereby establish a calibration curve that may be applied to other boundary layer problems requiring wall shear stress analysis.

In addition to the axisymmetric flow conditions of the pipe experiments, it is also desirable to demonstrate the Preston tube in a restricted environment such as a two dimensional flow. The pipe calibration procedures are applied to a channel flow using a water table facility. The two dimensional aspects of this flow required substantially different measurement techniques and several limitations not present in the pipe experiments were considered.

In conjunction with the 2-D calibration, a unique flow channel was utilized to demonstrate the practical application of the Preston tube. Such a channel was modeled directly after a Universal Venturi meter that is being installed in the AFAPL's Compressor Research Facility. This recently designed venturi employs a shortened overall length which increases its susceptability to boundary layer separation in its diffuser section. This adverse effect is a function of wall shear stress and thus may be detected and analyzed through strategic mounting of Preston tubes in this section.

Several size Preston tubes will be compared in each experiment to further establish the validity of results. All data taken is compared to the established calibration curve for air. Appropriate conclusions are then made on the extension of Preston's method to other fluids and configurations.

II. Theory

The accurate measurement of turbulent skin friction directly at a surface or wall is invariably a complicated and time consuming process. Several experiments to this date have substantiated a simplified method by Dr Preston of a pitot tube measuring procedure in air. The following discussion analyzes briefly the theoretical justification of this unique method. The application of this procedure to a two dimensional configuration and extension of the basic theory to other fluids such as oil and water are also considered.

Justification

The Preston tube method of measuring turbulent skin friction depends upon the assumption of a universal law of the wall. This "inner law" as it is also called, postulates that close to the wall there exists a region of velocity distribution that is common to both boundary layers associated with external flow and fully developed pipe flow (Ref 6:185). It is further postulated that a flow is substantially determined by the wall shear stress and properties of the fluid and remains independent of the nature of the outer turbulent flow and such quantities as pressure gradient and surface curvature (Ref 3:1). This law commonly has the form

$$\frac{u}{U_\tau} = f\left(\frac{U_\tau \cdot y}{\nu}\right) \qquad (1)$$

where U_τ is the friction velocity and u is the local velocity at the point of measurement*. The function f is determined by experiment although it can be shown to be a logarithmic function outside the linear sublayer (Ref 8).

The equation as it appears above is largely unusable so the following non-dimensional form was put forth by Patel and forms the basis of this study:

$$\frac{\tau_0 d^2}{4\rho\nu^2} = F\left(\frac{\Delta P_p \cdot d^2}{4\rho\nu^2}\right) \qquad (2)$$

This expression relates the Preston tube measurement, ΔP_p, to the wall shear stress, τ_0, through the new function F. This function is determined experimentally in pipe flow where the shear stress is known from the relationship:

$$\tau_0 = \frac{\Delta P_s \cdot R}{2 \cdot L}$$

F then forms the Preston tube calibration which allows direct calculation of an unknown wall shear stress for similar type flows. Values of ρ and ν are those corresponding to the free stream temperature and pressure at the measuring point.

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* Schlichting derived this same universal law from Prandtl's mixing length theory and Von Karman's similarity rule as they apply to a flat plate and extends the law to pipe flow (Ref 8:586-604).

Extensive experiments were conducted by Patel in air using several sized pipes and 13 different Preston tubes. These results are plotted in Fig 1 as a single curve and substantiate that:

1. The law of the wall exists and relates directly the velocity profiles of a turbulent boundary layer in external flow to that of fully developed turbulent pipe flow.

2. Various diameter Preston tubes specify given portions of this profile and their readings form a unique curve.

3. The Preston tube measurement precisely specifies the wall shear stress of any surface through this unique calibration curve and basis in the law of the wall.

Schlichting assigns no upper limit to the validity of the law of the wall. In fact, he states that the laws derivation may be extrapolated to arbitrarily large Reynolds numbers (Ref 8:611). Patel's analysis agrees with this approach and shows accurate data agreement to values of $U_\tau d/\nu = 1270$. To reduce ambiguity in forming the calibration, Patel suggests that several size Preston tubes be correlated to assure it is sized correctly for the flow conditions and will lie within this defined limit.

Two-Dimensional Application

The calibration of Preston tubes has been defined only for an axisymmetric, three dimensional flow and no analysis

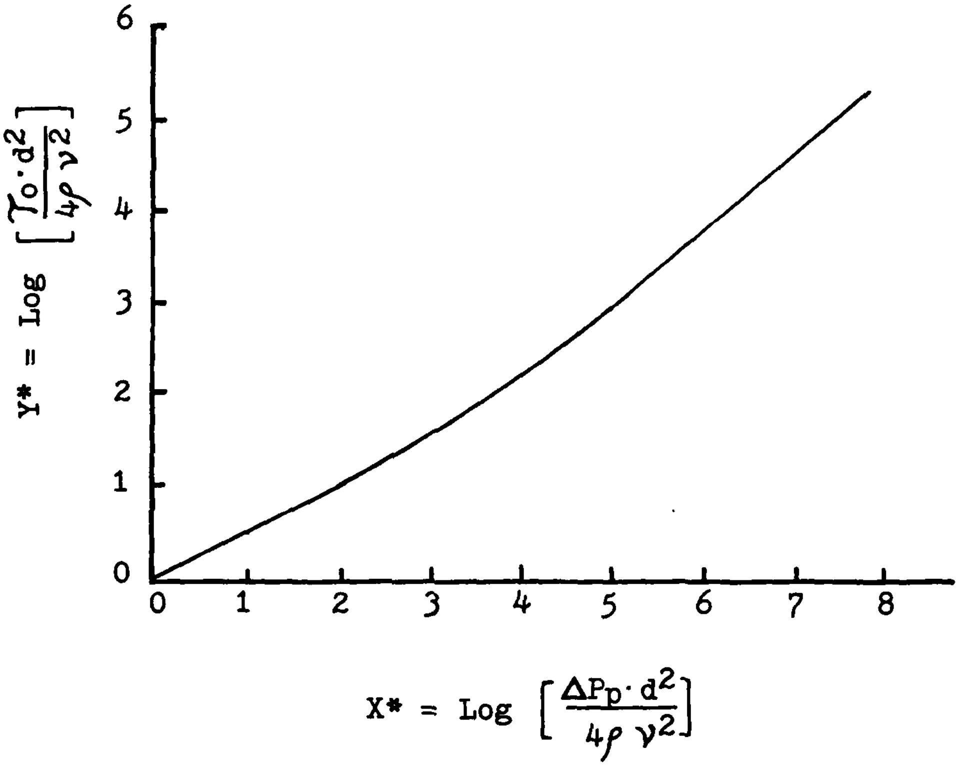

Fig 1. Patel's Calibration Curve - Air

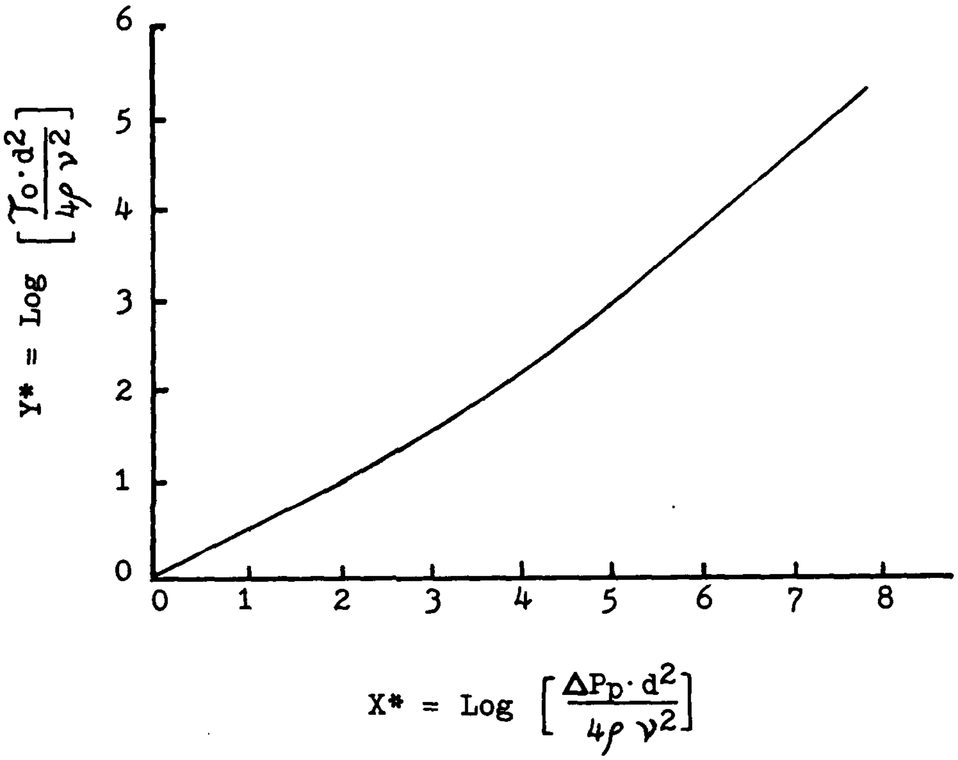

Fig 1. Patel's Calibration Curve - Air

is provided on its applicability to a more restrictive regime. The objective of this section will be to evaluate the correspondence of Preston's method of measuring skin friction to a particular two dimensional test facility, namely, the water table. Governing portions of the water analogy are now considered along with the unique boundary layer problems and the overall suitability of the two dimensional model within the framework of Preston's theory.

Hydraulic Assumptions. The basis of water table usage is found in the Hydraulic Analogy. A detailed account of this hypothesis is available in several publications (Refs 4, 5 and 12) and will not be covered in this report. However, the analogy is derived from three basic assumptions that are important. These are:

1. Vertical accelerations are negligible.
2. Flow is irrotational.
3. Viscosity effects are zero.

Additionally, it is assumed that the gas flow be considered isentropic and perfect which restipulates an inviscid flow condition. While these conditions are quite reasonable for ordinary water table modeling, the inviscid assumption does not describe a flow ideally suited to Preston tube measurement.

Specifically, any assumption of inviscid flow tends to negate the necessary conditions for the law of the wall to hold. Simply put, the use of Preston's method requires a boundary layer profile to develop, while the water analogy seeks to minimize any boundary layer effects. It is commonly regarded that the water analogy is better modeled for sufficiently high Reynolds numbers. Eventually an upper limit will be reached where the inviscid assumption holds and the range of Preston tube validity (law of the wall) will be surpassed.

The definition of Reynolds number for the open channel is

$$Re = \frac{U \cdot R_h}{\nu} \tag{3}$$

where R_h is the channel hydraulic radius defined in Appendix C. Several factors tend to limit this parameter in the water table. The viscosity has the greatest variability due to its significant dependency upon fluid temperature. While its nominal value is sixty times greater than air at room temperatures, increasing the temperature only 10 F can produce a 10-15 percent increase in Reynolds number. This viscosity factor can, therefore, play a significant modeling role. Restrictions arise when attempting to adjust either the mean velocity, U, or the hydraulic radius. These interdependent variables (at constant flow rate) are primarily limited by the capacity of the water table itself and its flow capability. Due to the usual low values of both compared to air facilities, the overall Reynolds numbers tend to remain relatively low (less than 10000 at U = 1.0 ft per sec). This leads to a limitation of the water analogy that inviscid fluid properties can never be fully attained and thus other similarity parameters must be considered for accurate modeling. For this study, some median Reynolds numbers must be considered that balance the viscous properties necessary for the law of the wall against the basic assumptions necessary for water analogy modeling.

Boundary Layer Considerations. Directly related to the above discussion are the two dimensional boundary layer considerations. While viscous effects will always be present, dominance is found with decreasing Reynolds number. If the limitations of the preceeding section combine to keep the Reynolds number low, boundary layer effects take on increasing importance. These effects are felt on the water table's floor and on the model's walls and must be considered in the analysis. By far the most serious effect is felt from the floor's contribution due to its large area compared to the wetted perimeter. This effect is felt not only in influencing the overall channel flow but also of interacting with the wall boundary layer and thus negating Preston tube correlation.

From flat plate theory, Schlichting puts forth the following relationships for boundary layer growth per length.

Laminar Flow: $$\frac{\delta}{\ell} = \frac{5}{(Re)^{0.5}} \qquad (4)$$

Turbulent Flow: $$\frac{\delta}{\ell} = \frac{0.37}{(Re)^{0.2}} \qquad (5)$$

Given sufficient channel width the bottom surface of the water table may be considered a flat plate. Then the boundary layer dominance can be determined approximately by these functions. Clearly, as Reynolds number increases, these considerations diminish. Yet another problem exists in increasing Reynolds number for a given channel size. The depth may need to be decreased in order to increase velocity which can arise if operating near the maximum table flow rate. A trade-off between depth and velocity will have to be made to insure that the floor boundary layer remains as small as possible.

This leads to the final boundary layer consideration, that of interaction of the floor and wall boundary layers. If the depth of the water is sufficiently deep, the wall boundary layer growth may also be modeled as a flat plate for portions away from the floor. In this region, the Preston tube's pipe calibration should be representative of the boundary layer profile* if the flow is turbulent.

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* Schlichting presents an argument for proof of the similarity between a two dimensional and an axially symmetric pipe velocity profile (Ref 8:608).

This means ensuring that the Preston tube remain sufficiently far from the area of intersection of the wall and floor boundary layers for accurate measurement. This region would form a complicated interaction area that could not be modeled effectively with the simplifying assumptions previously made. The possibility remains that any data collected in the water table will be influenced by this interaction and further reduces quantitative accuracy.

Similarity

Due to the several fluids involved in this study, including Patel's analysis in air, a means must be established to relate the results of each experiment to one another. Investigating Patel's modification of the law of the wall (Eq 2), one finds that only density and viscosity are fluid dependent. While these variables differ for various fluids and depend greatly upon fluid temperature, their impact is minimal in the Preston analysis. Close scrutiny of Eq 2 reveals that the combination of these terms in the parameter $\rho \nu^2$ serves only to non-dimensionalize the expressions. By modifying both the Preston tube term and the shear stress term, it functions only to scale the expressions and does not alter the validity of the results.

As a scale factor it should effect the calibration range in each fluid. This effect is seen in the Reynolds number relationship (Eq 3) and the various limits assigned by Schlichting or Patel to the individual sections of the law of the wall (Appendix D). These equations contain a viscosity term which dominates the overall expression's magnitude. As degree of viscosity varies between fluids so also should the effective ranges vary and cause the various data to be in different segments of the overall calibration curve. Because the oil used in this report is approximately 20 times more viscous than water and considering roughly equivalent flow parameters, (e.g velocity, radius), the oil calibration should occur over a lower range of Reynolds number than water. Although water is about 60 times more viscous than air, this same comparision can not be made due to the wider range of available flow conditions for air (such as mean velocity or temperature). Thus, given sufficient flexibility in establishing flow parameters, one can calibrate a single curve that consists of data points from each of the three fluids. With limited flexibility, the range of calibration will be correspondingly limited but still remain as segments on the same curve.

III. Experimental Equipment and Procedures

Preston Tubes

Fundamental to each of the experiments is the design and installation of the Preston tubes themselves. These tubes were made in the AFIT fabrication shop of stainless steel tubing and are depicted in Fig 2. They were selected from standard thin wall tubing and conform to the specifications of Table I with outside diameter the primary distinction between tubes. This is to provide a wide comparitive base for the variation in boundary layer thickness of each test pipe.

The only critical specification was the end of the Preston tube itself where great care was taken to insure a symmetrical bore and a surface free of irregularities. Each tube was placed into a stem shaft of 0.11 in. to standardize the mounting devices. Tube #4 (not shown) has the same dimensions as tube #1 but without the probe sheath. Tube #5 was the smallest practical size tube due to its relatively slow reaction time. Its use in the oil pipe was essential due to that pipe's extremely narrow cross section. Its reaction time was on the order of five minutes so it was not considered for the 6 in. water tunnel where the estimated response time exceeded ten minutes.

Oil Pipe

The Air Force Institute of Technology's Oil Pipe facility

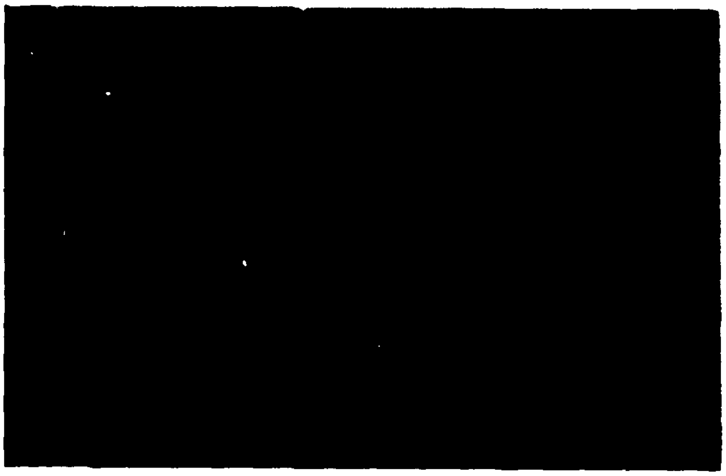


Fig 2. Preston Tubes

TABLE I

Preston Tube Specifications

TUBE #	OUTSIDE DIAMETER (INCH)	INNER DIAMETER (INCH)	DIAMETER RATIO (ID/OD)	PROBE LENGTH (INCH)
1	.050	.033	.660	1.0
2	.072	.055	.764	2.0
3	.110	.086	.781	2.0
4	.050	.033	.660	2.0
5	.036	.0225	.625	2.0

presented an ideal system for Preston tube experiments. The pipe itself is slightly over 24 ft long and has an extremely narrow bore of 0.81 in. Due to this relatively small diameter, only Preston tubes #4 and #5 were used in this experiment. Jet 1010 standard engine oil is recirculated through the pipe to a collection tank and then via a return duct to the electric pump as depicted in Fig 3. Various flow rates and conditions can be selected by adjusting the fluid temperature and the pump output capacity. The pipe's internal smoothness is indicated by its proven capability to exceed Reynolds numbers of 11000 while maintaining laminar flow. Flow conditions can also be adjusted with a thin metal fence located at the pipe's inlet.

Along the pipe are located ten static pressure ports connected to a 40 in. mercury manometer bank. Two total pressure probe installations are available, with one located at the extreme outflow end of the pipe and the other approximately 24 in. forward of this end. The end position was selected for mounting of the Preston tubes and for determining pipe velocity profiles. The Preston tube was mounted on the pipe's wall at the top and extended 1 3/4 in. into the pipe. This installation proved the most versatile and assured both good probe alignment to the flow and negligible probe interference effects. The probe was connected to a single 30 in. mercury manometer which gave readings accurate to .05 in. Hg as did the 40 in. manometer bank.

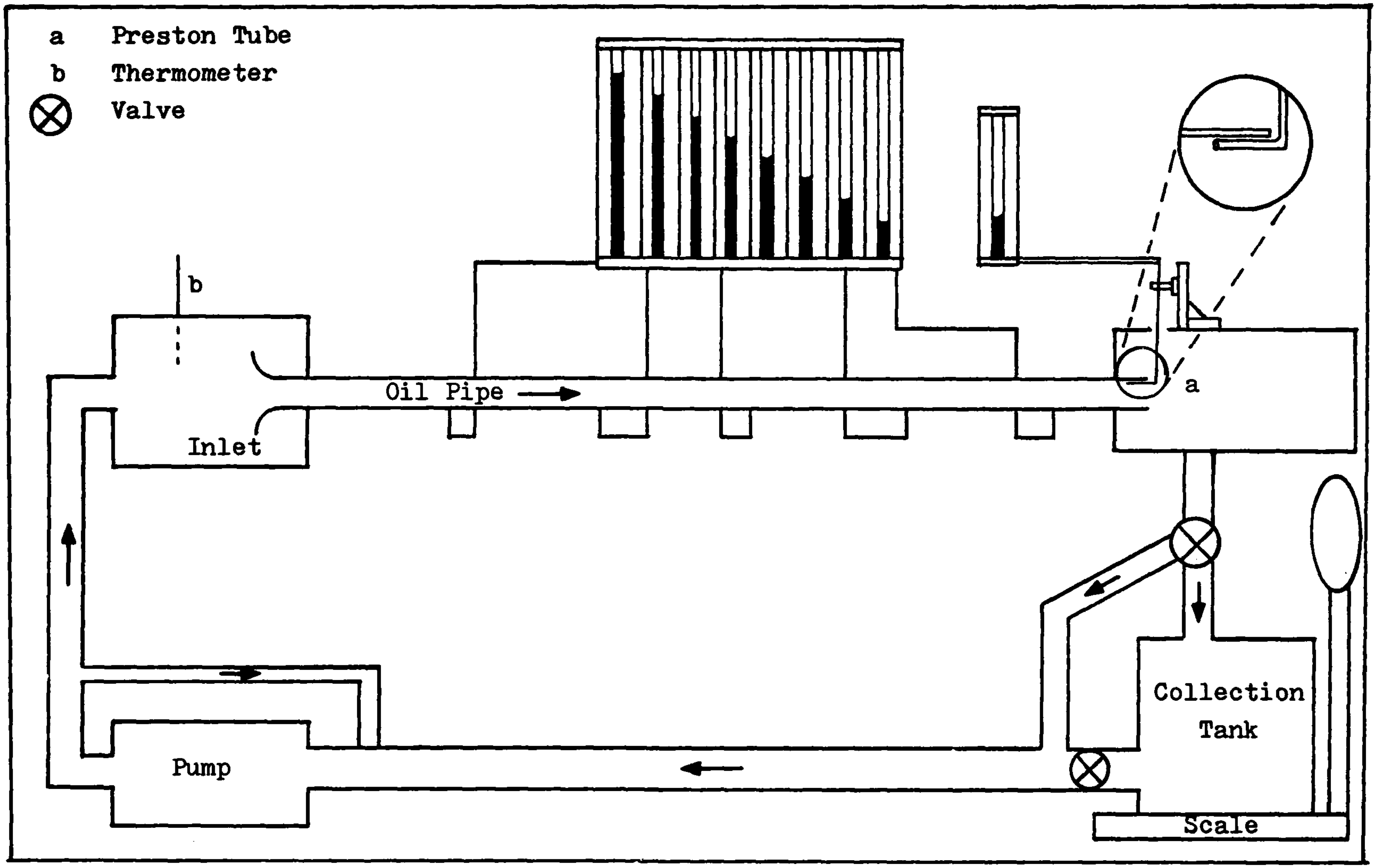


Fig 3. Oil Pipe Experiment

Additional features of the oil pipe are two thermometers and a return duct heating element. Mass flow was determined via a collection tank positioned at the outlet end. By timing the flow diverted to this tank for a specific period and weighing the collected fluid, the precise pipe flow can be determined accurate to 1 lbm/sec.

Water Tunnel

Description. The Air Force Aero Propulsion Laboratory's Water Tunnel was another facility ideally suited to this study. Its 6 in. inside diameter test section contrasted nicely to the small dimensions of the oil pipe and allowed a broader selection of Preston tubes. Tubes 2, 3 and 4 were considered most suitable for the velocity profiles anticipated. Directly upstream of the test section is a 14.25 ft length of straight pipe that establishes the test section profile. Figure 4 depicts a dual duct arrangement just prior to this straight section through which a wide range of flows may be selected. Normally, the system can be run from 15 to 1500 gal/min although the present facility instrumentation limits operation to approximately 825 gal/min.

Temperature is measured in the pump output duct. Normal recirculation of the water will gradually raise the water temperature on the order of 10 F per hour. A constant head pressure is maintained over the length of the test section by use of a downstream holding tank whose fluid level is maintained at a designated height above the section. This also keeps the pipe completely full and free of air pockets or bubbles.

Pressure Measurement. The test section is a 29 in. cylindrical piece of clear plexiglass. Care was exercised to insure smooth connections at all forward joints in order to attain as smooth and continuous a internal surface as possible. Static ports of 1/8 in. diameter were bored in the test section at the four positions shown in Fig 4. Each pair of these holes was connected to opposite sides of an inverted U type manometer. Water was used as the manometer fluid with a continuous water connection between it and the test section. A valve arrangement at the top of the U tube allowed balancing the columns and setting a reference level. Due to the small ΔP expected, these manometers were inclined to yield a 10 to 1 ratio. This permitted readings in increments of 0.01 in. H_2O.

A similar arrangement was constructed for the Preston tube and its accompanying static pressure port. One of these was located on either side of the pipes circumference at a position 45° from the bottom centerline. This insured the maximum correlation of these two pressures while completely minimizing mutual interference effects. Quarter inch diameter, clear tubing was used for all manometer connections which allowed frequent inspections for air bubbles.

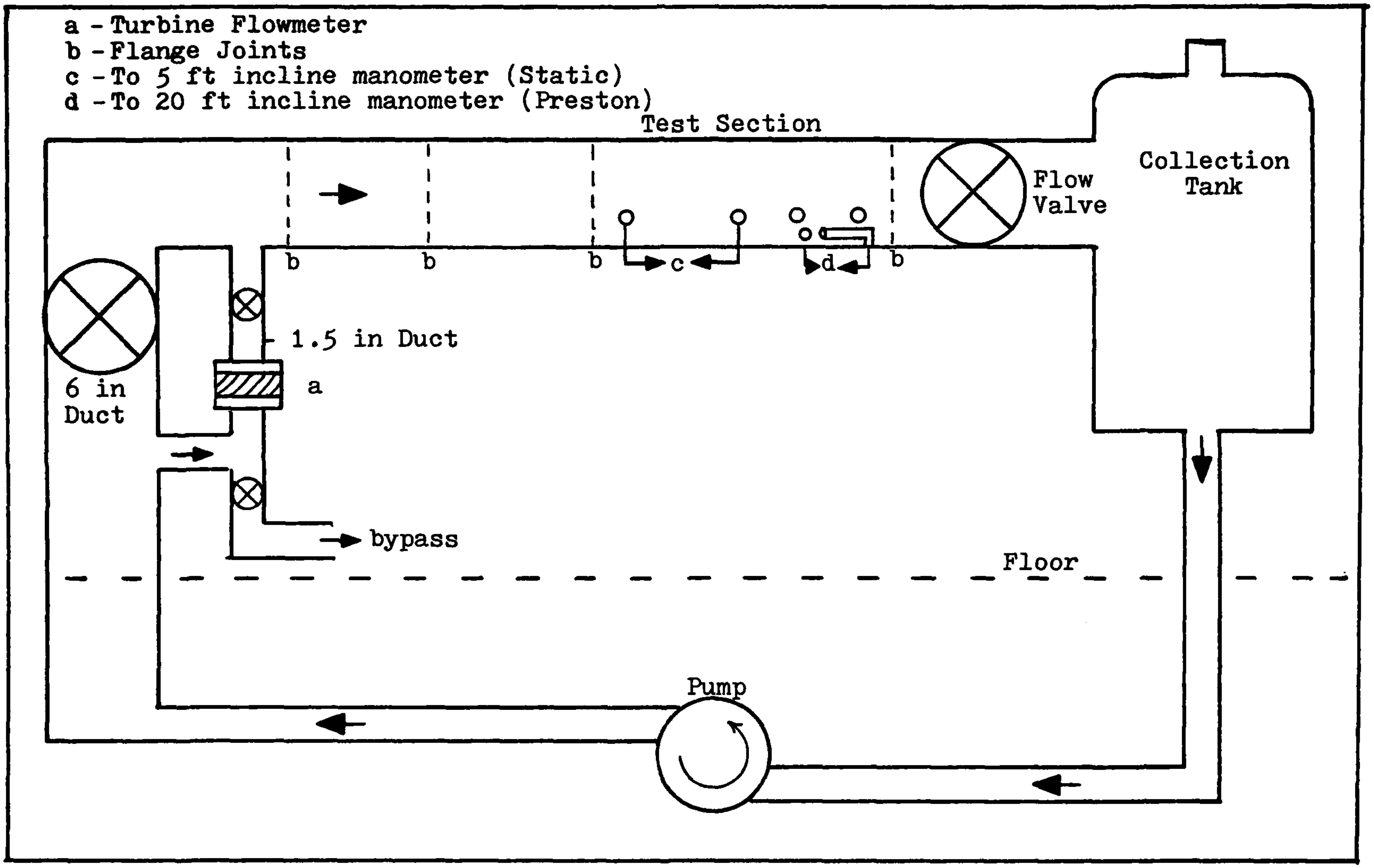


Fig 4. Water Tunnel Experiment

Flow Rate Measurement. The test pipe inlet consists of a dual duct arrangement. The smaller 1.5 in. duct is used for flows of less than 150 gal/min while the 6 in. pipe handles flows at higher rates. When using the small pipe exclusively, flow rate is measured by an inline, turbine type, flowmeter whose output is frequency. Actual flow rate is calculated from the expression

$$Q \text{ (gal/min)} = 0.1310 \, f$$

where f is the frequency in Hertz. Several readings were averaged due to slight pump fluxuations. A pitot-static probe is used for larger flows. It is connected to a direct reading gauge that measures height differential in inches H_2O. The gauge reading is related to the flow rate directly by the expression

$$Q \text{ (gal/min)} = 165.011\sqrt{h}$$

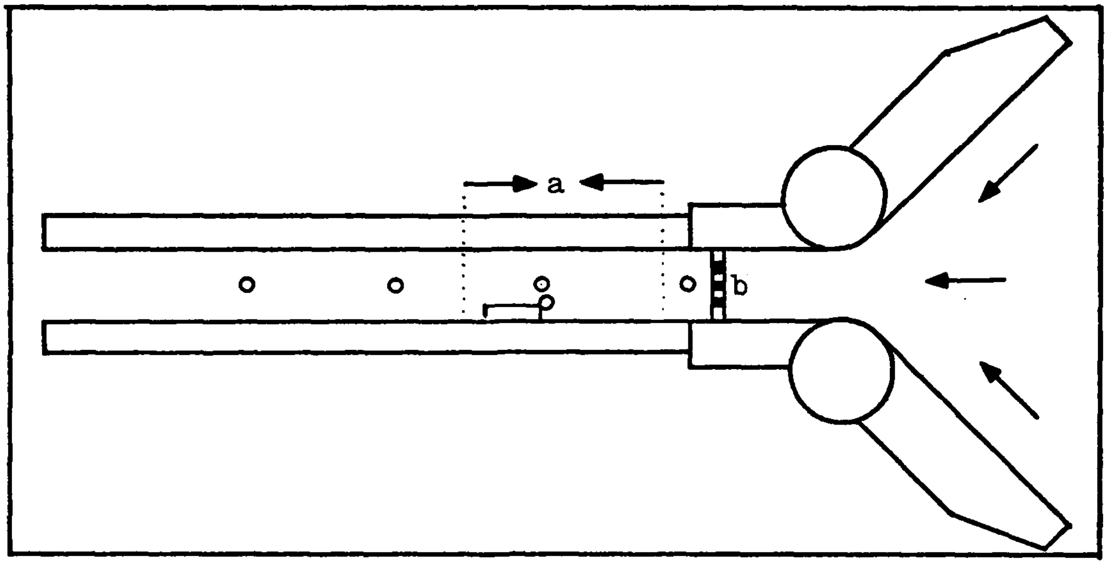
where h is the height in inches.

Water Table

Description. The two dimensional tests were conducted at AFIT's water table facility which provides an 8 ft by 4 ft test section surface. This large surface is of a high quality glass that helps maintain laminar flow and thus reduces boundary layer buildup (Ref 5). Water is pumped into a calming reservoir at the table's head. As the water rises, it flows in a fairly uniform sheet over the glass surface into a collection tank at the opposite end. From here it is recirculated at a maximum rate of 26 gal/min through a series of control valves back to the reservoir. Depth control is accomplished by the vertical movement of a weir at the foot of the test bed. Velocity of the water can be controlled by adjusting both depth and flow rate or by constricting the channel's width by use of inserts.

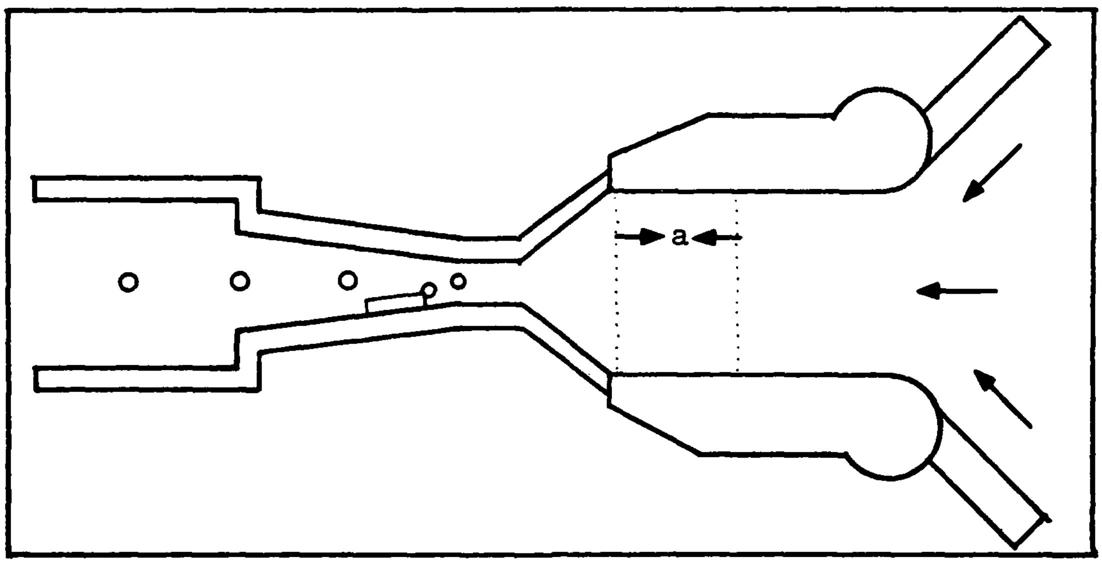
Due to the precise measurements required of the water depth, the test section's general degree of levelness was tested. Results indicate variations to approximately .01 in. per foot near the center and were determined to be uncorrectable by leveling the table. Rather, a map of the various differences was developed and the models positioned to minimize the glass slope error.

Test Procedures. Two models were used in this experiment; one for the Preston tube calibration and the other for the venturi analysis. Both were made of wood with a marine type varnish applied to the exterior to increase smoothness and prevent water absorption. The arrangement of the models on the test surface is pictured in Figs 5 and 6. Flow was channeled into each model via a gradually tapered inlet that conditioned the flow and eliminated non-uniformities. The models were placed as close to the stilling reservoir as possible to minimize boundary layer buildup.



o Static Pressure Measurement
▭ Preston Tube
a Velocity Measurement
b Turbulence Generator

Fig 5. Water Table Calibration Duct



o Static Pressure Measurement
▭ Preston Tube
a Velocity Measurement

Fig 6. Water Table Venturi Model

Velocity measurement is accomplished by timing a wooden float over a 6-12 in. section of the channel. Water temperature measurements were made with an ordinary thermometer suspended in the reservoir tank. Temperature variations were made by filling the table with hot tap water and allowing it to cool down as subsequent runs were made. A maximum of 120 F was then possible which greatly added to the Reynolds number range capability.

Preston tubes were mounted to the walls of the models by a clamp positioned on top of the wall. The tube shaft extended vertically through the clamp and into the flow stream. No interference was expected at the limited velocities planned, due to the long probe length compared to stem diameter. With a probe length of over 18 stem diameters between opening and stem centerline, it was felt that this mounting system would not limit the experiment (Ref 9).

Pressure Measurements. Due to the near total dependency of the calibration equation (Eq 2) upon pressure, and its predicted small variation per unit length, a precise method was needed to measure water depth. With water depth directly related to static pressure and Preston tube measurement to velocity head through the water analogy, these terms shall be used interchangably. A desired accuracy of 0.001 in. was estimated from mathematical analysis. A simple bridge supports resting on the table's surface. A screw type arrangement was used as both the probe and an indicator of vertical position. An ohmmeter was connected to the probe and to a ground positioned in the water. This gave a positive indication of water contact. However, readings differed by approximately .025 in. when either lowered to, or raised from, the water due primarily to surface tension effects. Comparisions with visual observation indicated a more consistant reading when raising the probe after first contact. On turbulent surfaces, water contact was estimated when the ohmmeter reading returned to within 20% of its "no contact" reading and remained in this range.

The location of static pressure depth measurements is indicated on Figs 5 and 6. Due to the slight variation in the table surface, these points were selected with the minimal spacing that would allow a measureable difference. Three or more points were measured so that comparisions could be made in pressure profile versus length. For the Preston tube static pressure the depth was measured at the stem opening at about an inch from the wall. This was necessary to avoid any surface tension effects at the surface-wall interface.

Preston tube pressure was also determined by this depth measuring system due to the equally small velocity head expected at the wall. A brass well with a 1 in. diameter was connected via a clear tube directly to the Preston tube shaft. Water completely filled the line and constant checks were made for air bubbles. The well acted as a small manometer with its measured depth indicating directly the probe pressure in inches H_2O. Both this and the static pressure depth are then combined to form the Preston tube term, ΔP_p.

Table surface variations were accounted for by comparing well depth versus channel depth in a no-flow situation. Three separate trials were made for each of these readings with the bridge located identically for each trial. The difference in readings determined a surface correction factor and remained valid as long as the bridge was positioned exactly as during the trials. The well further served as the bridge ground and functioned as such for both static and Preston tube measurements.

IV. Discussion of Results

The results of this study are discussed separately for each experiment. Although anticipated results are similar, the actual outcomes vary for each facility and are covered in depth in its associated section. Water table results are further subdivided into the calibration and venturi tests. Overall comparisions are delayed until Section V, Conclusions.

Oil Pipe Experiment

Data was collected during four separate runs using the #4 and #5 Preston tubes. More emphasis was placed on testing with tube #5 due to its narrow diameter and therefore, good correlation with the 0.81 in. wide oil pipe. The widest possible spread of data points was attempted within facility capability. Test conditions were started at the minimum that would permit turbulent flow. The flow rate variation was from 2.6 lbm/sec to 4.25 lbm/sec. Fluid heating was used to effect variations in viscosity and extend the limits of Reynolds numbers. The valid range for the data taken is

$$4.11 \times 10^3 \leq Re \leq 1.16 \times 10^4$$

with it being necessary to position the fence over the inlet to establish turbulent flow at the lower limits.

All data is recorded in Appendix A for this experiment.

For the calculation of the wall shear stress and to analyze flow quality more completely, static pressure was recorded over the entire length of the pipe. The results are plotted in Appendix A and show a consistently linear relationship for this pressure versus length. This permitted exact calculation of the static pressure at the Preston tube inlet through interpolation and indicates the turbulent quality of the flow throughout the pipe. The consistency of these results and the large number of data points available (ten to every one Preston tube reading) give high confidence to the shear stress values.

Care was taken to assure proper alignment of the Preston tube in the flow and to allow sufficient time for reading and flow stabilization. Results of the various runs are plotted in Fig 7 as is the corresponding air data (solid line) for this range. The data points for each tube used show excellent agreement with one another and form a correspondence that is similar to Patel's air data. However, the relationship (dashed line) formed by each tube's data points differs slightly from the air data. This result was not expected but the high level of point correlation seems to establish the curves as valid.

The distinct curves for each size Preston tube indicates a disparity in the velocity profiles each tube measures. A possible explanation of this is found in the trend of the

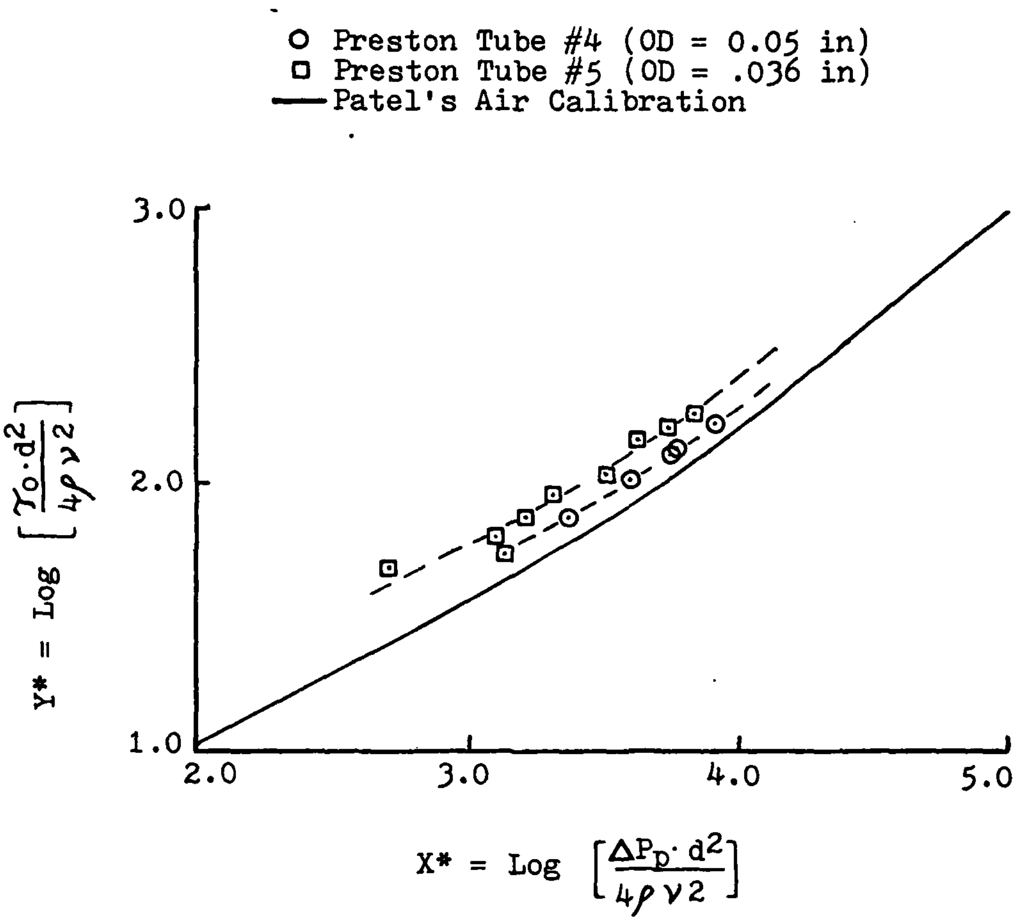


Fig 7. Preston Tube Calibration - Oil Pipe

data of tube #5 noted at low x* values. Here a slight leveling of the curve occurs. While sufficient data is not available in this range to accurately specify conditions, this effect could indicate a tendency of the velocity profile to revert to a laminar condition or that the flow has not achieved fully turbulent properties yet. The long pipe length and smooth walls could cause the flow to be in a transition stage to or from laminar flow by the time it reached the Preston tube. The velocity readings near the wall would be smaller for a laminar profile compared to a turbulent one and may account for a lag[#] in X* values. The larger tube would see more of the transition profile and therefore have a closer profile to that of turbulent flow. This possibly accounts for the seemingly better correlation of tube #4 with Patel's air data.

As a crosscheck of Preston tube readings, a velocity profile was taken for two separate flows at the oil pipe's outlet. Five symmetric positions were sampled and results of these profiles are depicted in Fig 8. This profile was made to generally characterize the flow with no attempt to precisely depict a complete velocity profile. Several previous Preston tube measurements in similar flows were used for the data points near the wall. It was found that the Preston tube readings fit into the profiles

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This considers that Y* values are correct due to previous arguments and, therefore, only the absissa (X*) is subject to variation and lies to the left of its expected position.

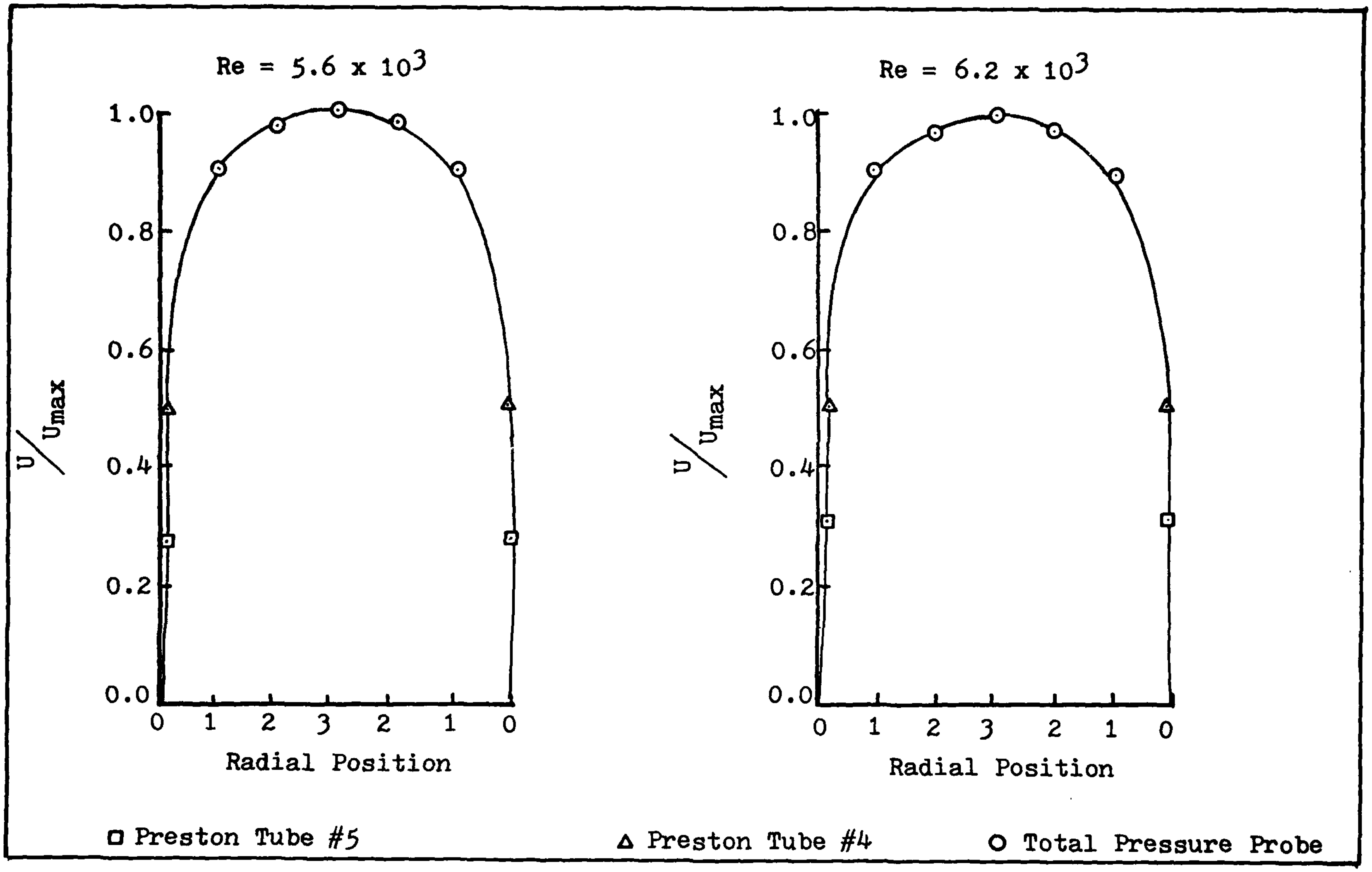

Fig 8. Oil Pipe Velocity Profile

extremely well and correspond to approximately 30% and 50% of the maximum velocity for each tube used. Profile characteristics support the previous postulation that the flow is neither fully laminar nor fully turbulent by its semi-parabolic shape. Additionally, for both flows sampled, U (mean)/U (max) calculates to 78.4% and 78.8% respectively, further indicating a flow that is in a transition region. This correlation is valid only at the tested Reynolds numbers and further testing would be necessary to generalize this result over the entire range of data points.

Water Tunnel Experiment

While the oil pipe experiment tended toward the laminar or lower flow limits, the Water Tunnel provided data near the higher values of Patel's analysis. Due to the wider diameter test pipe, three different Preston tubes were compared, each yielding a full range of data. Flow rates were varied from 125 gal/min to almost 900 gal/min with associated mean velocities ranging from 1.4 ft/sec to 10.2 ft/sec. Although instrumentation primarily limited flow regimes, a broad range of data was encompassed, specifically delineated by

$$4.55 \times 10^4 \leq Re \leq 6.25 \times 10^5$$

Data for this experiment is found in Appendix B.

Static pressure analysis was not as elaborate as for the oil pipe, however, it was felt adequate. Two independent measurements were taken and results compared to each other. Correlation was good and this parameter remains a high confidence value.

Velocity profiles were obtained for several Reynolds numbers using the 6 in. pipe. These are presented in Fig 10 and clearly establish the turbulent flow condition at the cited Reynolds numbers. These profiles were taken at a position just upstream of the test section and can be considered characteristic of the test section's profile. Average velocity was calculated at 89% of U(max) which further indicates the flow's turbulent nature. Preston tube measurements were not included on this figure due to the uncertain test conditions of the profiles plotted. The velocity profiles themselves, together with the Preston tube data plotted, combine to instill a high level of confidence in the calibration curve in this range.

The results of the four test runs are plotted on Fig 9 along with associated air data. At lower flows established with the 1.5 in. supply pipe, the data is random with wide scattering noted, while at higher flow values, correlation is almost perfect. The abrupt break between these two conditions is due to the piping arrangement at the entrance to the test section. During operation at low flow rates, visible swirl was noted in the water with numerous air bubbles and air pockets present. Manometer readings are very erratic and occasionally indicate negative

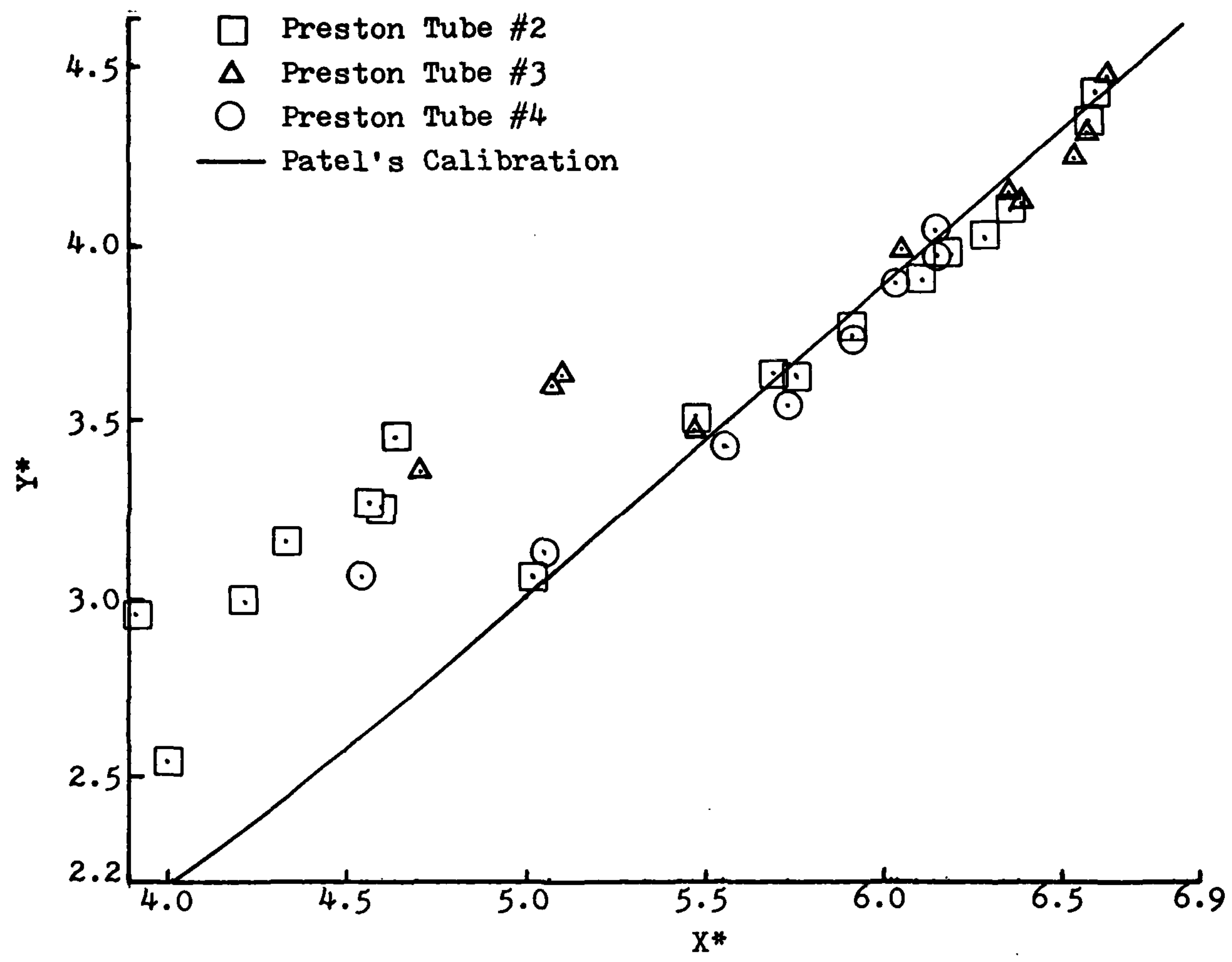

Fig 9 . Preston Tube Calibration - Water Tunnel

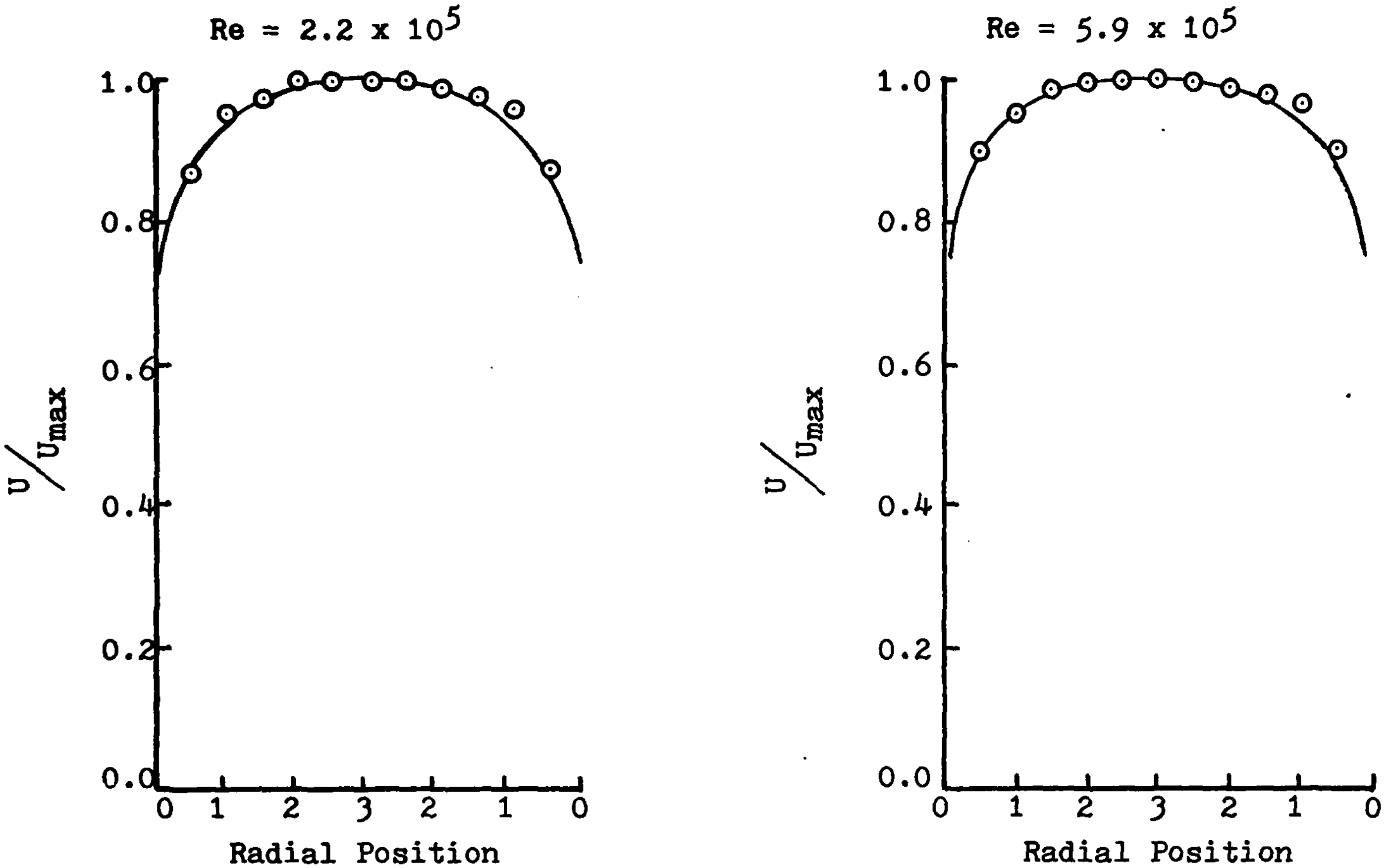

Fig 10. Water Tunnel Velocity Profile

(suction) readings for intense swirl. This unstable and non-uniform condition results in an unpredictable and highly varient flow and accounts for the data scattering below X* = 5.10.

Data for flow rates requiring the use of the 6 in. entrance pipe show a high degree of correlation with the air data and with each other. Each Preston tube used indicates a wide range of validity and high association with the air data. These results present a clear calibration of the tubes in water and establish the validity of Preston tube usage beyond a single fluid.

Water Table Experiment

Calibration. The collection of data in the water table was a tedious process that required the utmost in care and precision. Five tests were conducted on the calibration duct of Fig 5 using the #2 and #3 Preston tubes. These results are plotted in Fig 11 and indicate a high degree of randomness and scatter.

Preliminary tests and calculations indicated that a 6 in. wide channel was the most versatile and closely simulated the pipe experiments conducted in the Water Tunnel. This configuration was used throughout and provided free stream velocities of approximately 0.2 ft/sec to 1.2 ft/sec. In order to attain this range of flows, depths were varied from 0.75 in. to 1.70 in. The tubes were mounted at varying depths as determined by the free stream depth and predicted thickness of the glass surface boundary layer. Boundary layer calculations were checked by visually estimating the boundary layer through dye injection.

Flow quality was uniform and well behaved with the general tendency to quickly revert to laminar conditions if disturbed. A turbulence generating fence was placed upstream of the Preston tube location. Its actual distance was varied as the rate of transition of flow characteristics varied in order to maintain maximum separation between it and the Preston tube. The range of Reynolds numbers tested was

$$855 \leq Re \leq 12590$$

The range $Re \geq 6000$ generally required adding hot tap water to the reservoir.

Static pressure was sampled at four equally spaced points and results are plotted in Appendix C. Correlation is good with most runs forming a linear or near linear relationship. Due to the expected constant slope of the free stream depth, these plots show high confidence in the static pressure measurement. However, due to measurement limitations previously discussed, a generalization of flow character based upon these graphs would not be justified.

Water table results lie on the upper side of the air data curve with the larger tube showing more correspondence than the smaller. This is the identical situation to that

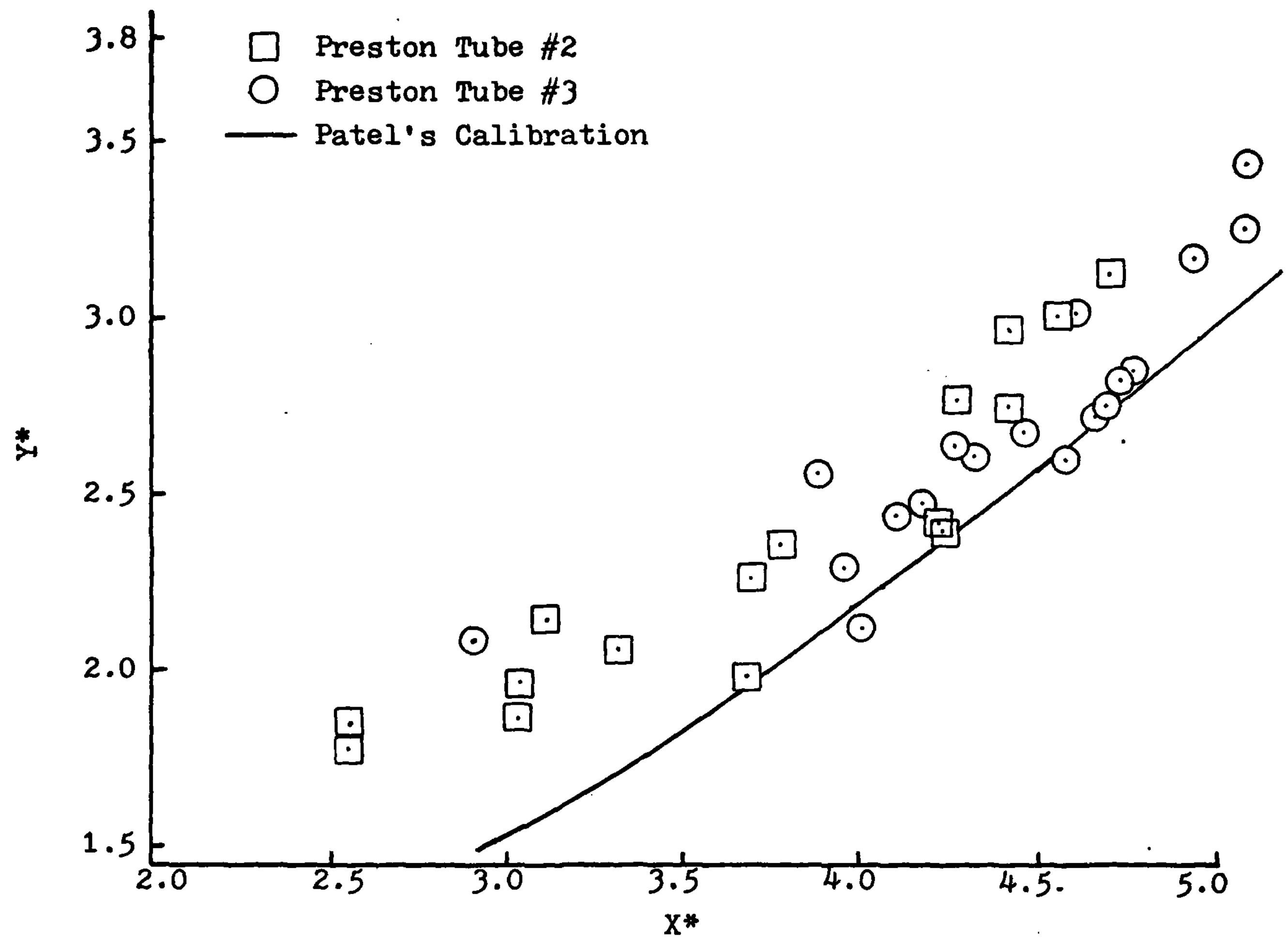

Fig 11. Preston Tube Calibration - Water Table

outlined for the oil tests. Further analogy, however, does not exist due to the high level of randomness obtained for the water table data. With this tendency toward point scatter, it is difficult to specify y specific correlation between points of a given tube or identify a single calibration curve. While scatter is as much as 25% for the X* values, this tendency to follow the air data may indicate that the basic approach is sound. Some characteristic of the flow (such as a larger than predicted bottom surface boundary layer) was not completely accounted for and its effects are felt on each point plotted.

Venturi Model. The second phase of the water table was conducted similarly to the calibration phase, with the addition of the universal venturi model. Preston tubes were mounted at two distinct locations in the diffuser section with all static pressure readings taken aft of the throat. Entry duct Reynolds numbers lay within the range

$$2150 \leq Re \leq 6600$$

Depths varied from 1.0 to 1.5 in. and no turbulence generator was used. Conditions were simulated to duplicate ideal flow so that the venturi itself could be analyzed.

Although the 2-D calibration data was unreliable, Preston tube measurements were taken and compared to the air data and water tunnel calibration curves. These measurements were supported by visually checking for separation of the flow at the wall through dye injection into the boundary layer. No attempt was made to estimate the wall shear stress although a pressure profile was made of the venturi aft of the throat.

The flow regimes tested can be divided into three areas that displayed distinct characteristics:

1. Re > 5000. Flow was very turbulent with a pronounced shock pattern originating in the throat area. Flow experienced a distinct hydraulic jump aft of the throat and areas of separation were indicated. Measurements extremely imprecise.

2. 4000 < Re < 5000. Some turbulence noted but measurements not greatly affected. Weak shocks and slight separation are characteristics.

3. Re < 4000. Smooth, uniform flow with almost linear pressure profiles. No shocks or separation areas noted.

For the regions of slight to no turbulence, Preston tube readings varied as Reynolds numbers varied. No indication of separated flow was provided by the probe although some separation was visually observed forward of the probe. In one case the area of separation surrounded the probe yet probe response was consistent with an attached boundary layer.

At the higher, very turbulent flows, separation was very dependent upon location of the hydraulic jump. When the Preston tube was positioned outside of the separated region, a reading similar to those mentioned above was made. However, when the Preston tube was specifically placed in a region of separation, an extremely low value (outside the limit of equipment accuracy) was obtained. This indicates a loss of wall shear stress and thus positively identifies the fact that the flow has separated. While this demonstrates the designed usage of the Preston tube, it is only the extreme case where total separation has occurred. In order to be effective, it must also predict the trend values as separation starts to occur.

V. Conclusions

The conclusions of this study are formulated for each of the experiments undertaken and are listed below. These individual conclusions are then combined in a general statement of the effectiveness in meeting the study's stated objective.

Oil Pipe Experiment

The results of this phase of the study indicate a unique function for each Preston tube tested. These functions are closely related and indicate a close correspondence with the established air data. This is clear indication of the soundness of the similarity rule and Preston tube usage as they apply to oil. An exact proof, however, is lacking and therefore the use of this method remains limited to further experimental testing.

The resulting functions for each tube tested, while similar, are not sufficiently accounted for in the experiment. This factor may be an incompletely developed turbulent velocity profile. These considerations limit the usefulness of the Preston tube in oil and require clarification before an exact calibration may be specified.

Water Tunnel Experiment

This experiment establishes the validity of the law of the wall for water and expands the application of the

Preston tube to this fluid. This was accomplished through the determination of a single calibration function for all tubes tested that precisely matched the established air calibration. Test results limit this precise correlation to the range

$$1.28 \times 10^5 < Re < 6.25 \times 10^5 \quad .$$

however, similarity should extend to the limits of the air data, provided fully developed turbulent flow is maintained.

Water Table

Calibration. The numerous limitations of the water table make it an inferior device in which to calibrate the Preston tube or attempt to prove the similarity law. The high scatter of plotted data and the randomness of tube correlation suggests a lack of correspondence between the proven pipe flow and a two dimensional simulation. While an accurate two dimensional model is possible, the extraordinary measures necessary to collect the data would not be justified over a simple pipe calibration.

Venturi. The venturi model clearly demonstrated the design usage of the Preston tube in locating areas of flow separation. This was only accomplished for an extreme case and the tube was unable to identify lesser degrees of this condition. This was not seen as a limitation of the Preston tube but rather supports its lack of validity for the two dimensional water table. The separation started at $Re \geq 4000$, in a range that as separation tendencies increased so also did precision measurement difficulties. Thus only the extreme case where equipment accuracy was exceeded could be discriminated by the tube.

In general, this study demonstrated the potential of the Preston tube in incompressible working fluids other than air. Results of the water tunnel prove the similarity with established air data while oil pipe results indicate a slight deviation from this data by only a constant. Although correspondence is shown only for specific ranges of Reynolds numbers, there is no theoretical limitation why a unique calibration curve could not be established over the entire range of proven air data.

VI. Recommendations

The validity of the Preston tube calibration for water flow in a pipe is established. However, its scope is limited to a narrow range of flow conditions which needlessly restricts its usage. This range of validity could easily be expanded and precision increased through the following modifcations to the water tunnel apparatus:

1. Increase the stability of the low Reynolds number flow by installing flow straighteners downstream of the 1.5 in. inlet duct.

2. Improved static pressure measurement capability is required with longer lengths over which measurements are taken in order to increase readability.

Due to the proven validity of the Preston tube in water and the desired accuracy of water tunnel measurements, it is further recommended that the venturi model be tested in this facility. This would eliminate much of the uncertainty of the two dimensional analysis and provide an accurate appraisal of the venturi over a much broader range of flow conditions. Additionally, it would provide a clear demonstration of the practical usage of the Preston tube and establish its capability in determining areas of flow separation.

In order to achieve a more universal extension of Prestons method to other fluids, the following procedures should be considered in further experiments in this area:

1. Use of a single Preston tube in each fluid tested including air. This will provide a direct comparision of this single tube in all mediums.

2. Conduct experiments in several different fluids in a single test facility. Such a facility is the AFIT Oil Pipe which may be converted to usage of a variety of oil type liquids.

These recommendations will provide the greatest degree of flexibility yet establish a clear relationship of the Preston tube in a variety of flow situations. This should form a precise and universal calibration of the tube for all working fluids.

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Appendix A

Oil Pipe Data Reduction

The purpose of this appendix is to present the useful data derived from the Oil Pipe tests. The applicable equations used to reduce the test measurements to graphical form are provided. This is followed by pipe static pressure profiles and then the data itself.

Pressure:

$$P\left[\frac{lbf}{in^2}\right] = \frac{SG \cdot h\,[inHg] \cdot W\,[lb/ft^3]}{12^3\,[in^3/ft^3]}$$

Shear Stress:

$$\tau_o\left[\frac{lbf}{in^2}\right] = \frac{\Delta P \cdot R\,[in]}{2 \cdot L\,[in]}$$

Mean Velocity:

$$V_m\left[\frac{ft}{sec}\right] = \frac{\dot{m}\,[lbm/sec]}{SG_{oil} \cdot W\left[\frac{lbm}{ft^2}\right] \cdot A\left[ft^2\right]}$$

Y*:

$$Y^* = \log_{10}\left(\frac{\tau_o\, d^2}{4\rho\nu^2}\right)$$

X*:

$$X^* = \log_{10}\left(\frac{\Delta P_p\, d^2}{4\rho\nu^2}\right)$$

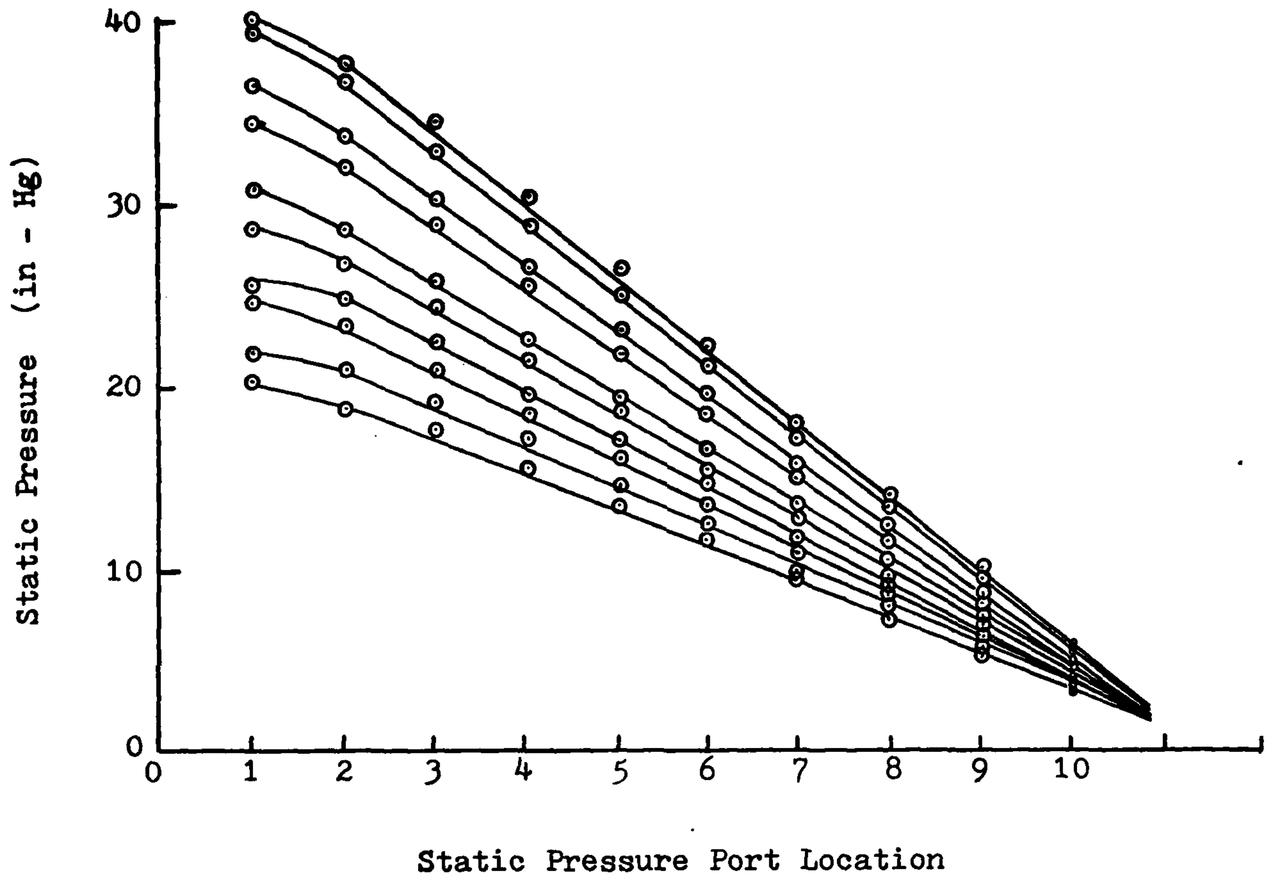

Fig 12. Oil Pipe Static Pressure Profile

Data Reduction - Oil Pipe Experiment

Calibration Tests: #'s 1,2,3 — Probes: As Indicated

L = 24 in — D = 0.81 in — d_p = 0.050 in (#4), 0.036 in (#5)

T	$W(H_2O)$	ΔP_s	τ_o	ΔP_p	$\dot{m}$	SG(oil)	V_m	$\nu x10^{-4}$	$Rex10^3$	Y*	X*
76	62.265	1.124	0.0095	0.317	2.633	.891	13.262	2.17	4.11	1.86	3.38
78	62.239	1.295	0.0109	0.447	2.90	.890	14.630	2.00	4.92	1.99	3.60
80	62.220	1.490	0.0126	0.569	3.18	.889	16.065	1.89	5.73	2.11	3.76
81	62.210	1.758	0.0148	0.758	3.52	.888	17.806	1.84	6.54	2.20	3.91
73	62.274	2.005	0.0169	0.785	3.70	.891	18.634	2.23	5.63	2.09	3.75
Probe #4 used for above data. All other data taken with Probe #5.											
78	62.239	1.222	0.0103	0.107	2.916	.890	14.71	1.98	5.02	1.69	2.71
79	62.220	1.417	0.0119	0.234	3.116	.889	15.74	1.89	5.62	1.79	3.09
80	62.220	1.685	0.0142	0.303	3.460	.889	17.48	1.89	6.24	1.87	3.20
82	62.210	1.929	0.0162	0.371	3.760	.888	19.02	1.86	6.88	1.94	3.30
83	62.191	1.001	0.0084	0.225	2.616	.888	13.24	1.75	5.11	1.71	3.14
92	62.093	1.853	0.0156	0.458	4.04	.885	20.54	1.43	9.66	2.15	3.62
97	62.033	1.826	0.0154	0.579	4.10	.883	20.91	1.29	10.91	2.24	3.82
97	62.033	1.096	0.0092	0.283	3.16	.883	16.12	1.29	8.42	2.02	3.50
97	62.033	1.558	0.0131	0.466	3.78	.882	19.31	1.26	10.30	2.19	3.74

Appendix B

Water Tunnel Data Reduction

The purpose of this appendix is to present the useful data derived from the water tunnel tests. The applicable equations used to reduce the test measurements to graphical form are also provided. Equations that remain the same as in Appendix A are not repeated.

Pressure:

$$\Delta P \left[\frac{\text{lbf}}{\text{in}^2}\right] = \frac{\Delta h\ (\text{inH}_2\text{O}) \cdot W\ (\text{lb/ft}^3)}{12^3\ (\text{in}^3/\text{ft}^3)}$$

Flow Rate:

$$Q \left[\frac{\text{ft}^3}{\text{sec}}\right] = \frac{165.011 \sqrt{h\ (\text{inH}_2\text{O})} \cdot 0.1337 \left[\text{ft}^3\right]}{60\ (\text{sec/min}) \cdot \left[\text{gal}\right]}$$

Mean Velocity:

$$V_m \left[\frac{\text{ft}}{\text{sec}}\right] = \frac{Q\ (\text{ft}^3/\text{sec})}{A\ (\text{ft}^2)}$$

Data Reduction - Water Tunnel Experiment

Calibration Test: #1 — Probe: #3

L = 22 in — D = 6 in — d_p = 0.11 in

T	W	ΔP_s	τ_o	ΔP_p	$\nu x10^{-5}$	Q	Vm	Rex10^5	Y*	X*
61	62.365	0.0032	0.00021	0.0047	1.20	0.197	1.003	0.417	3.35	4.17
62	62.359	0.0051	0.00034	0.0105	1.18	0.275	1.400	0.593	3.58	5.07
64	62.347	0.0051	0.00034	0.0105	1.15	0.337	1.716	0.746	3.60	5.09
65	62.341	0.0036	0.00024	0.0238	1.13	0.569	2.897	1.280	3.46	5.46
66	62.334	0.0112	0.00076	0.0891	1.12	1.072	5.459	2.430	3.97	6.04
68	62.320	0.0155	0.00105	0.1648	1.08	1.356	6.906	3.19	4.14	6.34
69	62.313	0.0227	0.00154	0.2647	1.07	1.740	8.863	4.14	4.32	6.55
72	62.290	0.0299	0.00204	0.2721	1.03	2.000	10.188	4.94	4.47	6.60
74	62.274	0.0165	0.00112	0.2097	1.00	1.507	7.675	3.83	4.24	6.51
75	62.265	0.0119	0.00081	0.1509	0.98	1.219	6.310	3.16	4.12	6.39

Data Reduction - Water Tunnel Experiment

Calibration Test: #2 | Probe: #2

L = 22 in | D = 6 in | d_p = 0.072 in

T	W	ΔP_s	τ_o	ΔP_p	$\nu x10^{-5}$	Q	Vm	Rex10^5	Y*	X*
67	62.327	0.0025	0.00017	0.0014	1.10	0.197	1.003	0.455	2.97	3.88
67	62.327	0.0039	0.00026	0.0039	1.10	0.274	1.395	0.634	3.15	4.33
69	62.313	0.0046	0.00031	0.0068	1.07	0.335	1.709	0.798	3.25	4.60
70	62.305	0.0028	0.00019	0.0176	1.06	0.557	2.84	1.330	3.05	5.02
72	62.290	0.0093	0.00063	0.080	1.03	1.052	5.35	2.590	3.60	5.70
74	62.274	0.0126	0.00086	0.1196	1.00	1.246	6.34	3.17	3.76	5.90
75	62.265	0.0162	0.0011	0.1783	0.98	1.498	7.63	3.89	3.88	6.09
78	62.239	0.0176	0.0012	0.2074	0.95	1.581	8.05	4.23	3.95	6.18
79	62.229	0.0205	0.0014	0.2438	0.94	1.716	8.74	4.64	4.02	6.26
81	62.210	0.0223	0.0015	0.2854	0.92	1.816	9.24	5.02	4.07	6.35
83	62.191	0.0057	0.0019	0.3336	0.89	1.993	10.15	5.70	4.20	6.45

Data Reduction - Water Tunnel Experiment

Calibration Test: #'s 3,4 | Probe: #'s 2,4

L = 22 in | D = 6 in | d_p = 0.072 in, 0.05 in

T	W	ΔP_s	τ_o	ΔP_p	$\nu \times 10^{-5}$	Q	Vm	Rex10^5	Y*	X*
76	62.256	0.00036	0.00006	0.0014	0.98	0.144	0.73	0.374	2.54	4.00
77	62.248	0.0014	0.00014	0.0023	0.97	0.190	0.96	0.498	2.99	4.21
78	62.239	0.0018	0.00025	0.0050	0.96	0.281	1.43	0.745	3.26	4.56
81	62.210	0.0010	0.00034	0.0054	0.92	0.333	1.69	0.921	3.43	4.63
86	62.159	0.0025	0.00036	0.0323	0.87	0.706	3.59	2.06	3.50	5.45
87	62.149	0.0028	0.00046	0.0611	0.86	0.929	4.73	2.75	3.62	5.74
92	62.093	0.0154	0.00218	0.3438	0.81	1.99	10.13	6.25	4.35	6.54
95	62.058	0.0147	0.00217	0.3250	0.78	1.93	9.83	6.30	4.38	6.55
	Test #4									
82	62.201	0.0043	0.00029	0.0089	0.91	0.351	1.79	0.983	3.06	4.54
85	62.170	0.0046	0.00032	0.0082	0.87	0.626	3.19	1.83	3.13	5.05
102	61.970	0.0064	0.00044	0.0595	0.73	0.854	4.35	2.97	3.42	5.55
100	61.996	0.0086	0.00058	0.0915	0.74	0.979	4.99	3.37	3.53	5.73
97	62.033	0.0150	0.00102	0.1414	0.76	1.325	6.75	4.44	3.75	5.90
95	62.058	0.022	0.0015	0.197	0.78	1.69	8.16	5.23	3.90	6.02
93	62.081	0.027	0.0018	0.266	0.79	1.79	9.15	5.79	3.97	6.14
91	62.104	0.032	0.0021	0.291	0.82	1.99	10.17	6.20	4.00	6.15

Appendix C

Water Table Data Reduction

The purpose of this appendix is to present the useful data derived from the Water Table tests. Reduction equations not previously defined are provided. Static depth profiles are included along with data for both the calibration duct and the venturi model.

Hydraulic Radius:

$$R_h(\text{in}) = \frac{CW\ (\text{in}) \times D\ (\text{in})}{2 \times D\ (\text{in}) + CW\ (\text{in})}$$

where CW is the Channel width
and D is the Channel depth.

Shear Stress:

$$\tau_o = \frac{R_h\,\Delta P}{2 \cdot L}$$

Reynolds Number:

$$Re = \frac{R_h\ V_m}{12\ \nu}$$

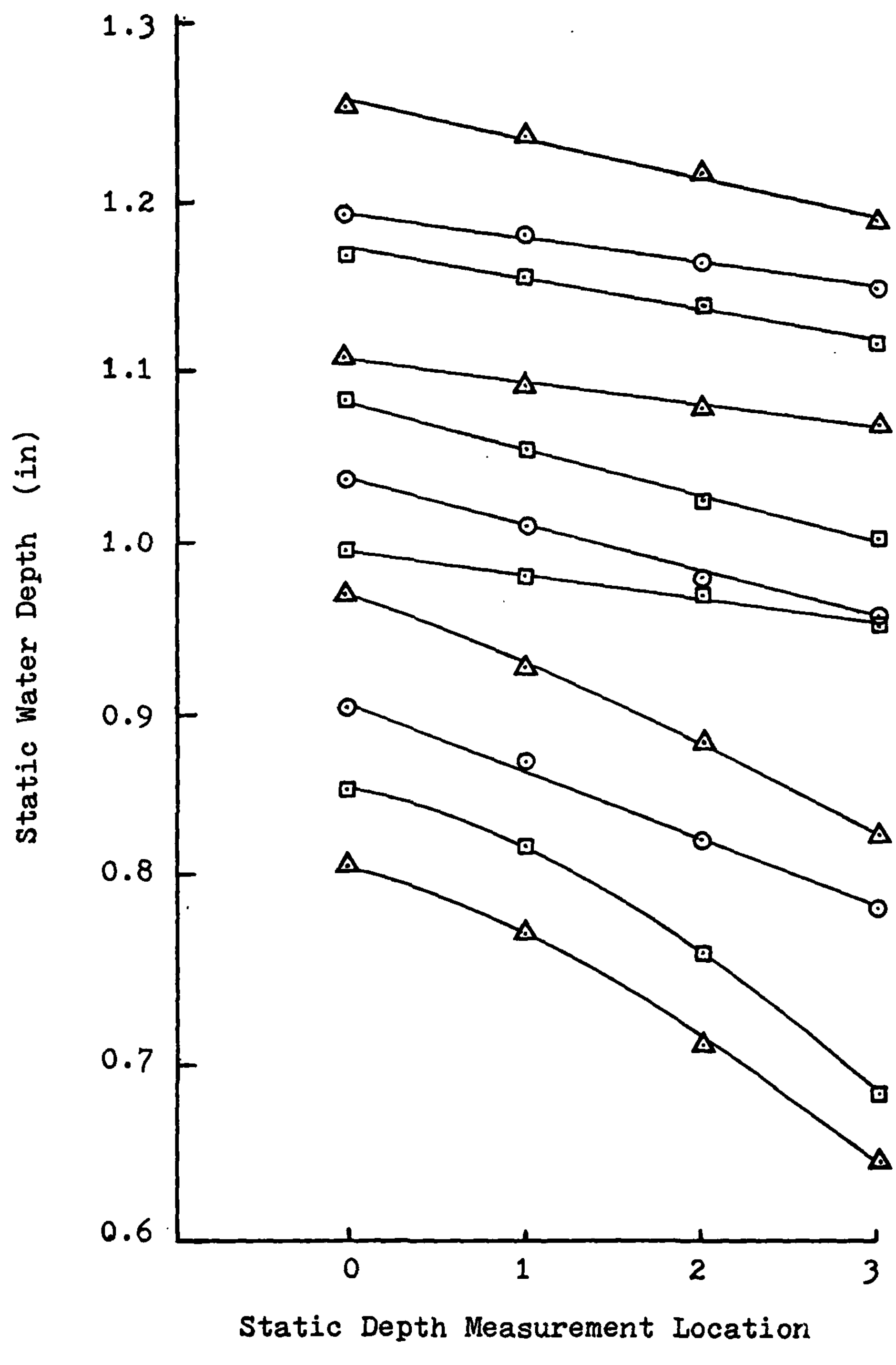

Fig 13. Water Table Static Depth Profiles

Data Reduction - Water Table Experiment

Calibration Tests: #'s 1,2,5 Probe: #2

L = 12 in CW = 6 in d_p = 0.072 in

T	R_h	W	ΔP_s	τ_o	ΔP_p	$\nu \times 10^{-5}$	V_m	$Re \times 10^3$	Y*	X*
62	0.995	62.359	.00036	1.49x10-5	.000072	1.18	0.217	1.52	1.85	2.54
63	0.995	62.353	.000469	1.94 "	.000036	1.16	0.192	1.37	1.98	2.25
64	1.041	62.347	.000433	1.87 "	.000216	1.15	0.312	2.35	1.97	3.03
64	1.093	62.347	.000613	2.79 "	.000253	1.15	0.435	3.44	2.15	3.10
62	0.799	62.359	.000469	1.26 "	.000072	1.18	0.151	0.85	1.78	2.54
63	0.764	62.353	.000469	1.50 "	.000216	1.17	0.416	2.26	1.86	3.02
64	0.804	62.347	.000685	2.30 "	.000397	1.15	0.555	3.23	2.06	3.30
64	0.846	62.347	.000541	1.91 "	.000938	1.15	0.714	4.38	1.98	3.67
64	0.709	62.347	.001551	4.58 "	.001154	1.15	0.833	4.28	2.36	3.76
64	0.611	62.347	.002056	4.83 "	.003174	1.15	0.950	4.17	2.40	4.22
65	0.595	62.341	.001950	5.24 "	.003211	1.13	0.909	4.03	2.42	4.21
120	0.796	61.712	.002392	7.94 "	.002785	0.62	1.176	12.59	3.14	4.69
115	0.756	61.778	.002038	6.43 "	.002109	0.64	1.000	9.85	3.02	4.54
112	0.727	61.832	.001252	3.79 "	.001145	0.65	0.869	8.10	2.78	4.26
110	0.782	61.861	.001217	3.97 "	.000429	0.67	0.740	7.19	2.77	3.80
106	0.766	61.917	.000860	1.37 "	.000358	0.71	0.666	5.98	2.26	3.68
95	0.814	62.058	.002585	8.87 "	.002298	0.78	1.176	10.23	2.98	4.40
94	0.726	62.070	.001796	5.43 "	.002370	0.79	1.000	7.66	2.76	4.40

Data Reduction - Water Table Experiment

Calibration Tests: #'s 3,4 — Probe #: 3

$L = 12$ in — $CW = 6$ in — $d_p = 0.11$ in

T	R_h	W	ΔP_s	τ_o	ΔP_p	$\nu \times 10^{-5}$	V_m	$Re_x 10^3$	Y*	X*
62	0.738	62.359	.00036	1.11×10^{-5}	.000072	1.18	0.294	1.53	2.09	2.90
62	0.786	"	.00036	1.18 "	.000902	"	0.476	2.64	2.12	4.00
62	0.792	"	.000541	1.79 "	.000794	"	0.555	3.10	2.30	3.95
62	0.835	"	.000721	2.51 "	.001154	"	0.625	3.49	2.45	4.11
62	0.841	"	.000794	2.78 "	.001371	"	0.714	4.24	2.49	4.18
62	0.875	"	.001010	3.68 "	.001876	"	0.770	4.75	2.61	4.32
64	0.710	62.347	.001695	5.01 "	.004258	1.15	1.000	5.14	2.77	4.70
64	0.676	"	.001587	4.47 "	.004005	"	0.909	4.45	2.72	4.67
64	0.663	"	.001263	3.49 "	.003356	"	0.833	4.00	2.61	4.59
64	0.647	"	.002273	6.13 "	.004980	"	1.050	4.92	2.86	4.77
64	0.647	"	.002201	5.93 "	.004691	"	1.050	4.92	2.84	4.74
120	0.804	61.712	.001357	4.54 "	.002999	0.62	0.909	9.82	3.27	5.09
115	0.720	61.788	.002467	7.40 "	.003254	0.64	1.111	10.42	3.45	5.10
110	0.753	61.861	.000966	3.03 "	.001181	0.67	0.769	7.20	3.02	4.61
110	0.738	"	.000895	1.38 "	.000859	"	0.606	5.56	2.68	4.47
107	0.701	61.903	.000465	1.36 "	.000573	0.69	0.500	4.23	2.65	4.27
105	0.686	61.931	.000430	1.23 "	.000250	0.72	0.400	3.17	2.57	3.88
98	0.624	62.021	.002153	5.60 "	.003338	0.76	1.000	6.85	3.18	4.95

Data Reduction - Water Table Experiment

Venturi Tests: #'s 1,2 Probe: #2

L = 10 in CW = 16 in d_p = 0.072 in

T	R_h	W	ΔP_s	τ_o	ΔP_p	$\nu \times 10^{-5}$	V_m	$Re \times 10^3$	Y*	X*
110	1.326	61.861	.0087	N/A	.0023	0.67	0.40	6.59	N/A	4.53
108	1.220	61.888	.0093	"	.0008	0.68	0.33	4.97	"	4.06
102	1.147	61.969	.0033	"	.0007	0.73	0.27	3.53	"	3.94
100	1.081	61.996	.0004	"	.00007	0.74	0.18	2.16	"	2.93
96	1.263	62.046	.0098	"	.0010	0.77	0.37	5.05	"	4.05
95	1.326	62.058	.0090	"	.0042	0.78	0.34	4.87	"	4.66
83	1.415	62.191	.0086	"	-.00003	0.89	0.42	5.51	"	2.48*
82	1.329	62.201	.0122	"	.00129	0.91	0.35	4.34	"	4.02
80	1.372	62.220	.0090	"	.00136	0.93	0.38	4.72	"	4.02
78	1.263	62.239	.0100	"	.00090	0.96	0.33	3.65	"	3.81

* indicates separation

Appendix D

A Verification of the Law of the Wall

Due to this study's established basis in the validity of the law of the wall, a brief argument of its existence is presented in this section. This justification is largely derived from the experiments of Patel (Ref 6) and similar theoretical works of Schlichting (Ref 8).

Patel's experiments resulted in the establishment of a single calibration curve for all tubes tested in three different pipes. This curve was developed from data in the form of Eq 2 and, therefore, establishes a unique function F that is postulated as the law of the wall. The curve, however, is not a straight line and Patel segments it into three individual empirical equations valid over distinct ranges. These equations are listed by range in the generalized variables of Eq 2 (see Fig 1).

$y^* < 1.5$:

$$y^* = \tfrac{1}{2}x^* + 0.037 \qquad \text{D-1}$$

$1.5 < y^* < 3.5$:

$$y^* = 0.8287 - 0.1381x^* + 0.1437x^{*2} - 0.0060x^{*3} \qquad \text{D-2}$$

$3.5 < y^* < 5.3$:

$$x^* = y^* + 2 \log (1.95y^* + 4.10) \qquad \text{D-3}$$

A parallel development is now made by Patel that starts with the unmodified law of the wall (Eq 1). Both Patel and Schlichting have further defined this law into two distinct regions and a transition zone. The resulting regions that make up the law are:

a. a linear sublayer region, where

$$\frac{u}{U_\tau} = \frac{U_\tau y}{\nu} \qquad \text{D-4}$$

b. a transition area, where

$$\frac{u}{U_\tau} = A \log_{10}\left(\frac{U_\tau y}{\nu} + C\right) + B \qquad \text{D-5}$$

c. a fully turbulent region, where

$$\frac{u}{U_\tau} = A \log_{10}\left(\frac{U_\tau y}{\nu}\right) + B \qquad \text{D-6}$$

Patel combines these resulting equations with a pitot tube centerline correction term such that the effective center of a round tube is specified at $y \approx \frac{1}{2}Kd$. Using this correction and by transforming these equations in a manner similar to the Eq 1 to Eq 2 derivation, he develops the following forms written in the generalized variables.

a. In the sublayer,

$$y^* = \tfrac{1}{2}x^* - \tfrac{1}{2}\log\left(\tfrac{1}{2}k^2\right) \qquad \text{D-7}$$

where the sublayer is defined as $(yU_\tau/\nu) < 5$. This establishes validity of Eq D-7 over the region $y^* < 1.40$.

b. In the transition zone,

$$x^* = y^* + 2 \log\left[\frac{A}{\sqrt{2}} \log (K\,10^{\frac{1}{2}y^*} + C) + \frac{B}{\sqrt{2}}\right] \qquad \text{D-8}$$

The range of validity is given by Patel as $5 < (yU_\tau/\nu) < 60$ and leads to a y* range of 1.4 to 3.56.

c. The fully turbulent region yields

$$x^* = y^* + 2 \log\left[\frac{A}{2\sqrt{2}}\left(y^* + 2 \log K\right) + \frac{B}{\sqrt{2}}\right] \qquad \text{D-9}$$

and occurs for values of $y^* > 3.56$.

It is now noted that the valid ranges of equations D-7, D-8 and D-9 correspond almost exactly to the empirical equations D-1, D-2 and D-3. By equating the corresponding regions equations, the constants A, B and C can be determined. Patel shows that the values obtained agree very closely with other experimenter's values thus an independent verification is made on the law of the wall.

Vita

Brian A. Maher was born in Brooklyn, New York on September 10, 1948. He graduated from Bishop Ford High School in Brooklyn in 1966 and entered the United States Air Force Academy in the same year. It was from here that he received a Bachelor of Science degree in Aeronautical Engineering and a regular commission in the U.S. Air Force. Upon graduation in 1970, he attended pilot training at Laredo Air Force Base, Texas and received his pilot wings. His first operational assignment was to fly the WC-130B for the "Hurricane Hunters" at Ramey Air Force Base, Puerto Rico. This was followed by a tour in Southeast Asia in the AC-130H Gunship. Prior to entering the Air Force Institute of Technology in 1978, he served as a Flight Commander and Instructor Pilot in the T-38 at Vance Air Force Base, Oklahoma. He is married to the former Christine S. Marzo, also of Brooklyn, and has two children, Pamela and Matthew.

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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER AFIT/GAE/AA/79D-10	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) A CALIBRATION OF THE PRESTON TUBE IN LIQUID FLOW SYSTEMS		5. TYPE OF REPORT & PERIOD COVERED 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Brian A. Maher Captain		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Air Force Institute of Technology (AFIT-EN) Wright-Patterson AFB, Ohio 45433		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS		12. REPORT DATE December, 1979 13. NUMBER OF PAGES 73
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Approved for public release; IAW AFR 190-17

JOSEPH P. HIPPS, Major, USAF
Director of Information

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Preston Tube
Wall Shear Stress
Similarity Law
Liquid Flow Systems

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The justification of Preston tube usage is based on a universal similarity law that relates the velocity profile in fully developed pipe flow to that of a boundary layer associated with external flow. The Preston tube measures these velocities at the wall and when calibrated for flow in a pipe, provides a means of determining the local wall shear stress. This study is intended to extend the validity of this method to other working fluids such as liquids. Four separate size Preston tubes are used in three

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) different experiments. The oil pipe provided a unique fluid in a narrow bore pipe and encompassed Reynolds numbers from just turbulent flow to 11600. Results indicated a calibration for oil that closely matched established air data. In the water tunnel some difficulty was encountered for low speed flow but results above Re = 12800 precisely matched that of air. A two dimensional experiment was designed to initially calibrate the tubes and to demonstrate practical usage in a venturi model. The calibration failed largely from insufficient precision of the measuring equipment. The model analysis provided an indication of flow separation but failed to specify trend information.