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**DESIGN, CONSTRUCTION AND COMMISSIONING OF A
TWO-PHASE (AIR-WATER) FLOW REGIME TRANSITION TEST RIG**

**by
Mohamed Limayem Lamari
B.A.Sc. (Mechanical Engineering)**

**A thesis submitted to the faculty of Graduate
Studies and Research in partial fulfillment
of the requirements for the degree of**

Master of Engineering

**THE OTTAWA-CARLETON INSTITUTE FOR
MECHANICAL AND AERONAUTICAL ENGINEERING**

**DEPARTMENT OF MECHANICAL AND AEROSPACE ENGINEERING
CARLETON UNIVERSITY
OTTAWA, ONTARIO
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January, 1991

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**"DESIGN, CONSTRUCTION AND COMMISSIONING OF A TWO-PHASE (AIR-WATER)
FLOW REGIME TRANSITION TEST RIG"**

**submitted by Mohamed L. Lamari, B.A.Sc.
in partial fulfilment of the requirements for
the degree of Master of Engineering**

Thesis Supervisor

Chair, Department of Mechanical and Aerospace Engineering

**Carleton University
15 January 1991**

Abstract

Theoretical prediction of the two-phase flow regime transitions is not generally possible. Taitel & Dukler (1976) developed semi-theoretical models for predicting gas-liquid flow regime transitions in horizontal and near horizontal pipes. Although these models are widely recognized, recent studies have uncovered deficiencies in some of the criteria used in the models' development.

A two-phase flow test rig has been designed and constructed to identify and understand the mechanism of flow regime transitions for air-water systems at near atmospheric conditions. The 13.65 metre long test section is also designed to explore effects of tube diameters on the pattern boundaries. Visual observation of flow patterns is supplemented by local void measurements. A twin-needle fibre-optic probe is used for this purpose. Using such a technique, the following additional two-phase flow information can be determined: bubble sizes, phase velocity (velocity of air-water interfaces), wave heights, plug and slug lengths and frequencies.

Results from initial testing show that the test rig operation is satisfactory. The technique used to measure void fraction and air-water interfacial surface velocities appears to be adequate. Based on the collected data for horizontal air-water flow in a 2.54 cm pipe, a generalized flow regimes map is presented and verified by comparison with published regime transition maps.

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Chapter 1

Introduction

Over the past three decades, great strides have been made in the knowledge of two-phase flow. There still exists an impasse, however, in reaching a general agreement on the flow pattern transition mechanisms. The present work was undertaken to design, develop, construct, and commission a two-phase flow air-water test rig. This apparatus will be used to investigate the air-water flow regime transition phenomena. The current research program is confined to horizontal flow in a 2.54 cm I. D. test section.

Two-phase flow is defined as the simultaneous flow of any two of the liquid, gas and solid phases. Furthermore, the term two-phase flow includes the flow of two immiscible liquids such as oil and water. However, in this report the term is more narrowly defined as the simultaneous flow of air and water in horizontal or vertical tubes at near atmospheric conditions.

This flow of a mixture of air and water, like other gas- liquid or vapour-liquid flows is quite complex. Much of the complexity can be attributed to the unstable and deformable interfaces of the liquid and gas phases.

Knowledge of the two-phase flow regime transitions is of particular interest to mechanical, nuclear and chemical engineers due to the wide-spread use of the process equipment working with two-phase flow systems. Examples of such equipment are: nuclear reactors, steam generators, condensers, heat exchangers and oil and gas transportation pipe lines. Moreover, computer codes developed to assess the safety of water cooled nuclear reactors demand a more thorough understanding of the two-phase flow pattern transitions.

The configuration assumed by the two phases is known as flow regime or flow pattern. Based on different techniques such as visual observations and photographic studies, numerous distinct flow regimes have been identified. Figure 1.1 shows the widely recognized flow regimes of gas-liquid mixtures in horizontal tubes. The existence of a particular flow pattern depends on the fluid properties, flow rates of the two phases, and pipe geometry.

As a simplified approach to the treatment of the two phase flow mixtures, earlier workers considered the phases to be thoroughly mixed and flowing at the same velocity. Suitable averaged properties are determined and the air-water mixture is treated as a single phase flow. This model, known as the homogeneous model, is totally inappropriate to apply in some cases where there is complete segregation of the two phases, for instance stratified and annular flow regimes (See figure 1.1.b and 1.1.f). Counter-current flow in vertical two-phase flow test sections is another case that cannot realistically be thought of as thoroughly homogeneous; here the two phases are flowing in two different directions.

Numerous investigators have tried to classify the two-phase flow regimes. Some success has been achieved but uncertainties still exist. As Chisholm (1983) indicated, there is no general agreement as to the most relevant groups of flow regimes

a: Bubbly flow regime

b: Stratified flow regime

c: Plug flow regime

d: Wavy flow regime

e: Slug flow regime

f: Annular flow regime

Figure 1.1: Gas-liquid flow regimes in horizontal pipes

for use in presenting horizontal two-phase flow maps. Previous classifications have been based on visual interpretations of these patterns. Consequently, the various classifications were subjective to the particular investigator.

Baker (1954), Hoogendoorn (1959), and Govier et al. (1972) were among the first investigators to make a systematic attempt to separate the flow regimes. Based on visual observations, they produced two phase flow regime maps which have the superficial velocities¹ of the liquid and the gas as coordinates. Figure 1.2 shows a comparison of the horizontal flow maps presented by the previously named investigators, for air-water at near atmospheric pressure. To supplement their visual observations, Govier et al. made an attempt to relate the flow regimes transition to the variation of the pressure drop curve. Unfortunately, the results were not totally satisfactory.

1.1 Horizontal flow regime identification

Due to the density differences of air and water in horizontal two-phase flow, gravity causes the air which is the less dense phase, to migrate to the top of the tube. As a result, unlike vertical two-phase flow, horizontal two-phase flow has non axisymmetric flow patterns.

Mandhane et al. (1974) provided the most commonly used classification of air-water systems. They indicated that the terms they used to label different flow regimes are consistent with the definitions proposed by Govier and Aziz (1972), except that Govier and Aziz refer to the plug flow regime as elongated bubbly flow regime. Weisman et al. (1979) indicated that Mandhane's classification gives a good

¹Superficial velocity is the velocity that the single phase would have if it was occupying the total area of the test section.

AM = annular mist, EB = elongated bubble,

S = slug, ST = stratified, W = wave. Replotted

Figure 1.2: Comparison of flow pattern map; Baker (1954), Hoogendoorn (1959) and Govier and Omer (Reproduced from Govier and Aziz - 1972)

characterization of gas-liquid flow patterns in horizontal pipes. However, literature reveals other classifications and subdivisions of the spectrum of the two phase flow patterns. Taitel and Dukler (1976) divided the horizontal two-phase flow patterns spectrum into what they consider the five basic flow patterns. They are as follows: Intermittent (I), Stratified Smooth (SS), Stratified Wavy (SW), Dispersed Bubble (DB) and Annular (A). In their study, Taitel and Dukler amalgamated the slug and the plug flow regimes; they considered these two patterns to be different conditions of the intermittent flow regime. Hewitt (1978) considers the semi-slug flow regime as a visually distinguishable flow pattern. Among a number of other subdivisions that have been defined are: laminar-stratified, stratified-roll wave, annular mist, annular wavy.

Other studies have shown that these classified flow regimes are somewhat idealized; such definite distinct regimes do not usually exist, but the various patterns gradually merge into one another. This transition behaviour is similar in the vertical flow case. In studying the steam-water flow regime transitions in vertical upward flows, Rogers (1985) stated that the transition phenomena between the flow regimes is gradual. Rogers also recommended that, in presenting flow regime maps, the pattern transition boundaries should be designated by bands rather than lines. These transition bands can be explained by the observer's doubt about the nature of the flow. Pearce (1982) recognized this difficulty and suggested that the regime boundaries be situated in the middle of the uncertainty bands.

For the purpose of this work the classification used by Taitel and Dukler is adopted. This classification is generally preferred for horizontal flow. Before studying the transitions between these flow regimes, it is necessary to give a general description of the visual criteria used in recognizing each one of them.

Dispersed bubble flow regime This regime is characterized by bubbles of gas,

randomly dispersed in a continuous liquid phase. These bubbles are relatively small in comparison to the diameter of the tube. Because of the gravity effect, the gas bubbles tend to move along the top of the tube as illustrated in figure (1.1.a).

Plug flow regime Increasing the air flow rate increases the bubble concentration. As these bubbles coalesce together they form larger bullet-shaped bubbles in an aerated continuous liquid flow. This regime is known as plug flow. See figure (1.1.c).

Stratified flow regime In this regime, the air flows along the top of the tube while the water flows along the bottom with no significant interfacial waves. As indicated in figure (1.1.b), this flow pattern is the simplest configuration of all the horizontal flow patterns. Here, the gravity separation is complete. The stratified flow regime is observed at low mass flow rates of gas and liquid.

Wavy flow regime As the gas velocity increases, the faster moving gas causes waves at the gas-liquid interface resulting in a wavy flow regime. As indicated in figure (1.1.d), there may be liquid entrained in the gas, and at the same time the liquid waves could be aerated. This regime is also referred to as stratified wavy flow regime.

Slug flow regime With increased air velocity, the magnitude of the waves increases. Ultimately, the waves build up, reaching the upper surface of the tube, then the liquid packets are transported at the higher velocity of the gas (See figure 1.1.e).

Annular flow regime In this regime, the liquid is swept up around the perimeter of the pipe in an annular form, while the fast air flows in the core of the tube entraining small droplets of liquid dispersed in the form of a mist (See figure 1.1.f). This regime normally occurs at high mass flow rates.

Reaching a full understanding and succinct classification of the two-phase flow regimes is possible only if the nature of the transition mechanisms between these regimes is well defined.

1.2 Flow regime transitions

The need for determining flow pattern transitions has been widely recognized. Numerous investigators have experimentally studied horizontal two phase patterns and their transitions.

Mandhane, Gregory and Aziz (1974) collected about 6,000 flow pattern observations of gas - liquid flow in horizontal pipes. Data was collected from published research results prior to that date. After a careful examination of the data bank, about 1,178 flow pattern observations for air - water systems were chosen to produce one of the earliest and perhaps the most durable horizontal flow pattern maps.

Taitel and Dukler (1976) developed physical models for predicting the flow regime transitions in horizontal and near horizontal gas - liquid flow. This was considered a clear attempt to break away from reliance on visual observations to predict the flow pattern transitions.

Based on some simple physical concepts, and assumptions which will be discussed later, Taitel and Dukler derived a mathematical expression for each of the transition boundaries. Their models, which were supported with some experimental data, incorporated the effects of fluid properties and conduit size and conduit inclination from the horizontal.

Taitel and Dukler expressed the transitions between earlier mentioned regimes

in terms of five dimensionless groups defined as follows:

$$X = \left[\frac{\left| \left(\frac{dP}{dx} \right)_L^S \right|}{\left| \left(\frac{dP}{dx} \right)_G^S \right|} \right]^{\frac{1}{2}} \quad (1.1)$$

$$T = \left[\frac{\left| \left(\frac{dP}{dx} \right)_L^S \right|}{(\rho_L - \rho_G) g \cos \theta} \right]^{\frac{1}{2}} \quad (1.2)$$

$$Y = \frac{(\rho_L - \rho_G) g \sin \theta}{\left| \left(\frac{dP}{dx} \right)_G^S \right|} \quad (1.3)$$

$$F = \sqrt{\frac{\rho_G}{\rho_L - \rho_G}} \frac{V_G^S}{\sqrt{D g \cos \theta}} \quad (1.4)$$

$$K = F \left[\frac{D V_L^S}{\nu_L} \right]^{\frac{1}{2}} = F [Re_L^S]^{\frac{1}{2}} \quad (1.5)$$

where

$\left(\frac{dP}{dx} \right)_L^S, \left(\frac{dP}{dx} \right)_G^S$: frictional pressure gradients for the liquid phase and the gas phase flowing alone.

D : pipe diameter

g : gravitational acceleration

θ : Angle of inclination from horizontal

ρ_G, ρ_L : gas and liquid densities, respectively.

V_L^S, V_G^S : respectively, the liquid and gas superficial velocities

Re_L^S : Reynolds number based on V_L^S and D

ν_L : kinematic viscosity of the liquid

X : Lockhart-Martinelli (1949) parameter, defined in eq. (1.1)

T : defined in eq. (1.2)

Y : defined in eq. (1.3), $Y = 0$ for horizontal pipes.

F : modified Froude number, defined in eq. (1.4)

K : defined in eq. (1.5)

Taitel and Dukler presented their results as per figure 1.3. The flow regimes are separated by transition curves controlled by the dimensionless parameters as follows:

- Transition from (SS) or (SW) to (AD) or (I) : X, F
- Transition from (DB) or (I) to (AD) : $X = 1.6$
- Transition from (SS) to (SW) : X, K
- Transition from (I) to (DB) : X, T

Transition from stratified flow to either intermittent or annular flow is represented in figure 1.3 by curve A. Taitel and Dukler indicated that this transition takes place when a finite amplitude wave becomes unstable and grows to reach the top of the tube to form either the slug or annular flow regime. They used the Kelvin-Helmholtz wave stability criterion in establishing this transition phenomenon.

In defining the transition between annular flow and intermittent flow, represented by curve B, Taitel and Dukler simply assumed that when the equilibrium liquid level occupies more than half of the pipe intermittent flow will result, otherwise flow annular will develop. This criterion has received a great deal of criticism by other researchers. For instance, Lin and Hanratty (1986) believe that annular flow is caused by entrainment and deposition phenomena.

The transition between stratified smooth and stratified wavy (curve C) is represented by the phenomenon of wave initiation. For horizontal flow, this transition curve can be plotted in terms of parameters K and X .

To separate the dispersed bubble and the intermittent sub-regions, Taitel and Dukler suggested that the dispersed bubble flow regime will develop when there is enough turbulent fluctuation within the liquid phase to overcome the buoyant forces

Figure 1.3: Taitel and Dukler horizontal two-phase flow map, $Y = 0$; (Reproduced from Taitel and Dukler 1976)

tending to keep the gas at the top of the tube.

In figure 1.4, Taitel and Dukler compare the results of their model to the empirical map derived by Mandhane et al., for air-water flow at atmospheric conditions in 2.5 cm horizontal pipes. Although these semi-theoretical predictions fairly agree with the experimental results presented by Mandhane, recent studies have uncovered some deficiencies in the Taitel and Dukler models.

Experimental studies conducted by Weisman et al. (1979) showed shifts in the location of the transition curves due to surface tension variations; the parameters suggested by Taitel and Dukler do not account for surface tension effects. On the other hand, Weisman et al. confirmed that there is little or no effect of viscosity on transition lines, whereas the stratified to intermittent transition model presented by Taitel and Dukler predicts shifts due to viscosity effects.

—— Taitel and Dukler

//// Mandhane et al.

Figure 1.4: Comparison of horizontal two-phase maps, air-water at atmospheric conditions in 2.54 cm I.D. pipes (Reproduced from Taitel and Dukler 1976)

From this literature review, it appears that despite the considerable amount of effort over the past few decades to classify the two-phase flow regimes and understand the mechanisms of their transition, these are still not well understood. Clearly, a comprehensive study of the flow regime transitions is justified.

This work is concerned with the development of a two-phase flow regime test rig. This test facility will eventually be used to identify the mechanisms governing the regime transitions and hopefully improve on the Taitel and Dukler flow regime transition models.

Chapter 2

Experimental apparatus

2.1 Introduction

The primary objective of this chapter is to provide a detailed description of the two-phase flow test rig. The experimental techniques and procedures employed are the subject of the following chapters.

In designing a flow pattern transitions test rig, particular attention has to be given to all physical parameters that might affect the regime transitions or their development. For this reason, a Fortran computer program, based on Homogeneous and Lockhart-Martinelli models, was developed to optimize the size of various parts of the apparatus, to predict the pressure drop through the test rig and to calculate the air and water flow rates needed to cover all possible flow patterns.

2.2 General description

The apparatus is located in room 227 and 126 of the C.J. Mackenzie Building at Carleton University. The general layout of the two-phase flow test rig is schematically shown in figure 2.1. The test rig has the following main components; each will

be described consecutively in the next sections.

1. Air supply system
2. Water supply system
3. Air-water mixer
4. Test section
5. Air-Water separator

The working fluids are air and water at near atmospheric conditions. The metered single phases are fed to a mixing chamber. The resulting two-phase mixture flows through the test section into the separator where the air is vented to the atmosphere and the water returns by gravity to the storage tank.

The test rig is equipped with instruments to monitor air and water inlet flow conditions, such as flow rates, static gage pressures and temperatures. Static pressure is also measured at three different locations along the test section. The locations of the instruments and static pressure taps are indicated in the line diagram shown in figure 2.1. All instruments are wired to a designated AT computer via a data acquisition system (DAS8-PGA). Information about the data acquisition system and the other instruments is given in the following chapters.

2.3 Air supply system

All possible alternatives of the air supply were studied. An available Centrifugal blower, manufactured by Canadian Blower and Forge Company Limited, (Model 4 RE) was first considered to supply the test section with the air required to establish the two-phase flow patterns. After reviewing the blower characteristics, it

Figure 2.1: Line diagram of the two-phase flow test rig

was found that this unit delivers a high flow rate, but unfortunately, does not provide the air pressure required for some of the flow patterns, such as the annular flow.

The second alternative was a 10 hp two stage compressor located in room 130 of the engineering building. After testing its capacities, it appeared that the unit delivers a sufficient pressure but it does not provide the air flow rates required.

A satisfactory air supply system was established using the University central compressed air system. A 2.54 cm air line was connected to the 10 cm main line. The University central system consists of two identical 50 hp compressors manufactured by Ingersoll.

A third compressor located in the engineering building tunnel is connected in parallel with the other two. This particular unit is rated with higher pressure relative to the other two. The pressure delivered by this compressor (90 psig) will be required for annular flow regime, when testing the 7.62 cm I.D. test section.

The air preparation system consists of a settling chamber, filter and regulator. Refer to figure 2.2, which indicates that the air is fed to settling chamber through 2.54 cm pipeline. The settling chamber is 0.406 m in diameter and 0.965 m long. Such length allows for the dispersion of the air jet at the inlet of the tank, while the diameter keeps the air velocity inside the tank under 1 % of the air inlet pipe velocity. For safety measures, the air tank is equipped with a relief valve and a gage pressure indicator. The working pressure of the tank is 690 KPa (100 Psig). As the air exits the tank, it goes through a conditioning unit that combines the functions of a filter and a regulator.

The filter eliminates contaminants from the atmosphere that could be drawn

Figure 2.2: Air supply preparation system

into the air system at the compressor intake. It removes bulk liquid (oil) and solid particles down to $5 \mu m$.

The regulator maintains the outlet pressure at a nearly constant level. The desirable air pressure can be achieved using the regulator's adjustment knob.

2.4 Water supply system

The Test Computer Program was used to calculate the water flow rate and total pressure required to establish the various flow regimes, in all test section tubes. In view of these requirements, different alternatives have been considered including the use of tap water.

Figure 2.3: Water supply system

Figure 2.3 schematically shows the water supply system adopted. It consists of close coupled single stage centrifugal pump (Model ES-2x3-9 1/2), and a 30 Hp 3500 RPM AC electric motor-driver. The complete system was manufactured by F.E. Myers and supplied by H.O Wright and Sons Ltd, a local supplier. The water is recirculated from and to the existing 2.5 m³ reservoir located in room 126. Filtered water from the tank is pumped to the test section or is recirculated through a by-pass 7.62 cm I.D. pipe. This by-pass system along with two manually controlled ball valves were used to adjust the water flow-rate (See figure 2.4); hence the water flow rate depends on the relative position of the two valves. Alignment of the water supply pipe with the air-water mixer was accomplished by using a flexible hose.

A paddlewheel sensor is used to measure the water flow rate; the inlet temperature and static pressure of the water are also monitored.

Figure 2.4: By-pass water control system

2.5 Air-water mixer

The air-water mixer is located upstream from the test section. It is a main part of the apparatus linking the two single phase inlet pipes to the test section. Figure 2.5 is a photograph of the mixer.

In the design of the mixing chamber the main considerations were the shape and the size. In light of this, the test Computer Program was used to optimize the size of the mixer that is, to minimize the pressure drop throughout the mixer, while ensuring that the air and the water are thoroughly mixed when used in the vertical test section.

The mixer was constructed from clear plexiglass. It is of a circular cross-section with overall dimensions of a 20.32 cm inner diameter and a length of 40.64 cm.

Figure 2.5: Photograph of the air-water mixer

2.6 Test section

The length of the test section is a key parameter in the design of a two phase flow regime transitions test rig. Even with a length to diameter ratio ($\frac{L}{D}$) of 128, Simpson et al. (1977) noticed some entrance effects on the flow regime development. This highlights the need for a very long test section in order to enable natural fully developed flow regimes to be achieved. Since this apparatus is intended to be used to examine regimes' transitions, forcing the mixture to take a particular distribution contradicts the objective of this work.

As it was intended to study the effect of pipe diameter on flow regime transitions, tubes of 2.54 cm, 5.01 cm and 7.62 cm inside diameter (I.D.) were carefully manufactured. Male and female grooved flanges were used to align the tube sections that forms the test section. In this work, only the 2.54 cm I.D. tube was used. The mixer was equipped with different size adapters to connect each of the test sections.

As indicated in figure 2.1, the test section has a total length of 13.65 m (45 feet). This allows for the following length to diameter (L/D) ratios:

For the 2.54 cm I.D. pipe L/D is 537,

For the 5.01 cm I.D. pipe L/D is 272,

For the 7.62 cm I.D. pipe L/D is 180.

The model developed by Taitel and Dukler predicts large shifts in the location of the regimes' transition curves due to small inclinations of the flow conduit from the horizontal. Therefore, the test section has to be and was accurately levelled. Conventional levelling instruments were used to obtain an approximate horizontal test section. Then, precise adjustment was obtained by using a theodolite while adjusting the fine threaded floating bases. Figure 2.6 is a photograph of the test section support system, which illustrates the manner in which the tube is firmly

Figure 2.6: Photograph of the test section support system

strapped to the support system. The floating base allows accurate adjustment of the test section level.

2.7 Air-water separator

A simple and effective air-water separator has been designed and constructed. It is located downstream from the test section. The separator body is made of 12.7 cm thick PVC tube which is 40.64 cm in inner diameter and 60 cm long.

The technique used to segregate the air from the two phase flow mixture is based on the air-water density difference. Injected at a 20° inclination, the two-phase mixture spins inside the separator with the water against the wall and the air at the centre. Segregation is then completed by gravity, where water flows down

the return pipe to the storage tank and the air is vented to the atmosphere. The 9 cm I.D. ABS pipe is used to return the segregated water to the storage reservoir. The pipe was given an inclination of about 10° to facilitate the water recirculation by gravity.

Chapter 3

Measurement techniques of two-phase flow parameters

3.1 Introduction

Two phase flow is an area in which theoretical prediction of flow parameters is not generally possible. Thus, the role of experiments and accurate parametric measurements is particularly important. The degree of precision of the results obtained depends on, among other factors, the apparatus, the instruments used and the experimental procedure.

Parameters which are known to govern the air-water flow regime transitions are: air and water inlet flow conditions (eg. flow rate, static pressure and temperature), air and water properties (density, viscosity and surface tension), void distribution and test section geometry. A literature review clearly indicated that these parameters have a direct impact on the air-water flow regime transitions.

Over the years, a vast range of techniques have been proposed for measuring the two-phase flow parameters. The following sections will describe only those methods employed in this research.

3.2 Air flow measurement

Because the air flow rate reveals valuable information about the air-water mixture distribution in pipes, its measurements are salient and form the basis of void fraction and air superficial velocity calculations. A vast number of flowmeters have been developed for closed-pipe systems. Among the most important of these devices are: orifice plate flowmeters, pitot tube, venturi tube, turbine and mass flowmeters, ultrasonic as well as electromagnetic devices.

The following is a list of the important criteria used in selecting the appropriate device to measure the air flow rate.

1. instrument flow range
2. device accuracy
3. instrument availability
4. pressure drop caused by the flowmeter
5. relative cost of the flowmeter

In light of these criteria a thermal type mass flowmeter was selected to monitor the air flow rate; this device is known as air velocity transducer.

3.2.1 Air velocity transducer

The air velocity transducer (AVT) is a relatively simple device compared to other equipment such as the ultrasonic and electromagnetic flowmeters.

Principle of operation

The AVT's basic principle of operation is simple. A heated sensing element is placed inside the air tube. The moving air, which has a temperature less than that of the heated member, transfers heat from the sensing element. The heat transferred to the air is a function of the velocity of the air. Measuring the energy required to keep the heated sensor at a constant temperature gives an indication of the air velocity. The AVT has a built-in temperature sensor that automatically corrects for any variations in the air ambient temperature.

Characteristics and capabilities

Figure 3.1 shows a diagram of the air velocity transducer. It is a model (FMA-607-V), manufactured by OMEGA Engineering Inc. The AVT is securely mounted to the tube wall, using a compression fitting with a teflon ferrule. As indicated in figure 2.1, sufficient upstream and downstream straight-run piping was provided in order to ensure that the air flow is fully developed at the position where it is being measured.

Both velocity and temperature sensors of the AVT are glass-coated platinum resistance temperature detectors (RTD). The transducer has an operating range of 0 to 60.96 sm/s¹ (0 to 200 sf/s) corresponding to (0 to 5 Volts) linear output voltage.

3.2.2 Air velocity transducer calibration

Although the AVT is a factory calibrated instrument, checking the calibration of each device has always been considered good practice.

¹sm/s, sf/s: Velocity units indicating that the air is under standard atmospheric conditions, ie. 25 °C and 101.33 KPa.

Figure 3.1: Air velocity transducer diagram

Figure 3.2: Air velocity transducer calibration curve

A pitot-static tube was used to check the AVT calibration curve. Both the pitot-static tube and the AVT were placed in a variable speed wind tunnel. For different wind tunnel speeds, the air velocity was measured using both instruments. The data obtained are analyzed and presented in figure 3.2. Results from this test experiment explicitly indicate that the air velocity measurements obtained by the pitot-static tube support the calibration curve provided by the manufacturer. A sub-routine called PRESSURE has been developed to convert the AVT output voltages into air standard velocities using the manufacturer's calibration curve. Note that the AVT calibration has been checked for an air velocity range which covers those encountered in use. The AVT performs measurements of the air velocity with an accuracy better than $\pm 2\%$.

3.3 Water Flow Measurement

Some of the devices previously used to measure the flow rate of the water include turbine meters, magnetic flowmeters, positive displacement meters and drag devices. Following the same criteria used in the selection of the air flow meter, a paddlewheel sensor was selected and used to perform measurements of water flow rates.

Paddlewheel sensors are similar to basic turbine meters with the exception of the rotor and blades which are perpendicular, and not parallel to the flow, see figure 3.3. The flowmeter device comprises two basic components: a flow sensor, (model FP-5300) which becomes part of the water pipeline, and a signal conditioner (model FLSC- 700); both components are manufactured by OMEGA Engineering Inc.

3.3.1 Flow sensor

The sensor is designed in a tee-fitting body. Aside from the propeller, all the sensor's components are housed out of the liquid stream, thus, minimizing the pressure drop through the water supply system. The six bladed propeller constitutes a primary element of the meter. In operation, the water's impact on the blade surfaces causes the propeller to rotate at an angular velocity proportional to the water flow rate. This angular velocity is sensed by a magnetic pick-up coil. Each blade that passes the magnetic coil causes a magnetic flux density change, thus producing a single voltage pulse. The frequency of these pulses is proportional to the liquid flow rate. The generated AC signal is approximately sinusoidal.

3.3.2 Signal conditioner

The low voltage AC signal from the flow sensor is transmitted by means of a shielded conductor to the signal conditioner. The former is a major component of the meter, converting the low voltage, low frequency signal to a linear DC output voltage.

Figure 3.3: Paddlewheel sensor, used for water flow measurement. (Reproduced from OMEGA Flow & Level Handbook & Encyclopedia, 1909)

The paddlewheel sensor is factory calibrated and has an operating range of 0 to $5.05 \times 10^{-3} \text{ m}^3/\text{s}$ (0 - 80 US-GPM) corresponding to an output level of 0-5 volts. The calibration of these meters depends on the operating flow range and the pipe diameter. As illustrated in figure 2.1, a sufficient upstream/downstream straight-run piping is provided to ensure that the water flow is fully developed. Using the paddlewheel sensor, the water flow rate is monitored with an accuracy better than $\pm 1\%$.

3.4 Void fraction measurements

3.4.1 Introduction

Void fraction or gas phase content is defined by Hewitt (1976) as either the fraction of the channel volume or cross-sectional area that is occupied by the gas phase. Measurements of void fraction are conducted to obtain information about the two-phase flow structure and distribution. Void fraction can be determined by one of the following measurement types:

1. Channel average: The average void fraction over the full test section is measured. Quick-closing valves are commonly used for this type of measurement.
2. Cross-sectional average: The void fraction is averaged over the channel's cross section. This method employs either neutron-scattering techniques or electrical impedance void gauges.
3. Chordal average: Measurements are made across the diameter of the channel and are normally achieved by radiation absorption methods, eg. X-ray and gamma-ray systems
4. Local measurements: To obtain local and instantaneous void fraction measurements, some of the most convenient instruments used are electrical probes,

optical probes, thermal anemometers and radio frequency probes.

Since the local measurement type gives more detailed information about the two-phase distribution than any of the other types, its selection is most appropriate for this research.

3.4.2 Fibre-optic probe

Principle of operation

Optical probes are the most promising devices for local and instantaneous void fraction measurements. These probes are sensitive to the change in the refractive index of the surrounding medium. Figure 3.4 shows the overall configuration of the probe. It consists of bifurcated (Y-junction) glass fibres, 50 μm in diameter.

Light is transmitted from one end of the glass fibre towards the probe's active end which is the base of the fibre. When the light beam strikes the surface of the fibre's bare tip, it is either deflected away from the fibre or almost totally reflected back along the fibre depending on the refractive index of the surrounding medium. If the tip of the fibre is immersed in the water, (with a refractive index of 1.33) the light beam is deflected away from the probe, see figure 3.4 b). However, if the fibre tip is immersed in the air, (with a refractive index of 1.0) the light beam is reflected back as indicated in figure 3.4 a). The intensity of the reflected light is collected at the other end of the fibre. Using a photometer, the light pulses returning from the fibre's active end are converted into electrical signals. The void fraction is determined by processing the signal output of the photometer.

Characteristics

Figure 3.5 illustrates the twin-needle fibre-optic probe constructed in the course of this work. It is used to measure the void fraction and the phase velocity, which is

Figure 3.4: Y-junction optic-fibre probe: a) Fibre tip immersed in air, b) Fibre tip immersed in water

Figure 3.5: The twin-needle fibre-optic probe

the velocity of the air-water interfacial surfaces. The probe consists of two identical bifurcated optical fibres manufactured by AMP Inc. The core of the fibre is $50\text{ }\mu\text{m}$ in diameter. This diameter size was chosen in order to minimize the deflection of air bubbles from the tip of the fibre. Both fibres are inserted into a protective stainless steel tube (1.6 mm I.D. and 2.4 mm O.D.). The tube is bent at an angle of 90° , giving a sensing point about 35 mm upstream from where the tube is inserted in the test section (refer to figure 3.5). The active end of the tube is aligned parallel to and opposing the flow streams.

To measure the void fraction, only one of the fibres is needed. However, both fibres are necessary for phase velocity measurement, which will be discussed in a subsequent section. In this case the void fraction is measured with the front probe

and then the measurement is repeated with the back probe. A comparison of results obtained through repetition of this measurement can be used to confirm the accuracy of results.

Miller and Mitchie (1969) used high speed cine technique (5000 frames/sec) to study the accuracy of single fibre-optic probe. They have concluded that using such a probe, the local void fraction can be measured to within $\pm 10\%$. However, in this research program, the local void fraction is expected to be measured with a better accuracy as a result of the improved characteristics of the instruments used in this experiment, ie. the high sampling rate of the data acquisition system and the very short response time of the light detection equipment. Uncertainties in void fraction measurements can be reduced by using longer sampling time period and higher sampling rate. Osamusali, Groeneveld and Cheng (1990) used this configuration to study distribution and void migration in horizontal rod-bundles.

3.5 Phase velocity measurement

As defined earlier, phase velocity is the velocity of the air-water interfacial surface. The probe previously described is used to measure the phase velocity. The two fibre needles are displaced from one another by a distance (L) in the direction of the flow. By measuring the time delay (T) between the front probe and the back probe, the phase interface velocity can be computed by using the following equation:

$$V = \frac{L}{T}$$

Velocities and frequencies of bubbles, plugs and slugs can be measured by using the same probe and the same technique. Figure 3.6 shows a typical output signal from the front and the back probes. It also illustrates the way the phase velocity is measured.

Figure 3.6: Phase velocity measurement, data processing

The signals from the front and back probes are fed into an exclusive-or gate. The output of the gate is low when both input signals are either high or low. The output of the gate is high whenever one of the outputs is high while the other is low. The width of the gate output pulses represents the time delay, ie. the time that takes an air-water interfacial surface to travel between the tips of the front and the back probes.

3.5.1 Photometers

The basic function of the photometer is to detect the light reflected from the fibre tip and to produce a DC voltage output proportional to the intensity of the returning light.

Two similar photometers are used to measure the intensity of the returning light from the front and the back fibre-optic probes. Both photometers, models E2X, manufactured by HAGNER Inc., are equipped with a standard external detector (model SD2). The detectors are light-sensitive devices and produce a photocurrent proportional to the intensity of the light falling within the detector's active area. The SD2 detector has a circular active area that is 10 mm in diameter. This area encompasses the cross-sectional area of the fiber which is 50 μm in diameter.

The photometer features a digital display as well as an analog output (0-2.4 volts). A stroboscope was used to test the transient behaviour of the photometer. With the stroboscope set to fire at 150 KHz, the photometer's output was observed on the oscilloscope. This test showed that the photometers and the detectors have a very short response time (in the order of 10^{-6} seconds).

3.6 Pressure measurements

The static pressure is measured at six different points in the test rig. Refer to figure 2.1, for measurement locations. The static pressure measuring system consists of six- tube pneumatic averagers, six air-water separators, a 48-port scanivalve and a differential pressure transducer. The static pressures are measured with reference to atmospheric pressure, in other words, the measured values represent the gage static pressure.

To obtain a true average value of the static pressure, a pneumatic averaging technique is used. This technique provides space averaging by having six pressure taps equally spaced around the pipe circumference. Pressure taps, made of stainless steel tubing (0.8 mm I.D. and 15 mm long), are exposed to the pipe wall. The holes in the pipe wall are carefully machined to ensure that they are blister free and square edged.

Using clear Tygon tubing (1.6 mm I.D. and 0.8 mm thick) each set of static averagers taps is connected to a six-tube pneumatic averager. The various components of the static pressure system are interconnected as schematically shown in figure 3.7.

The air-water separators are placed between the pneumatic averagers and the scanivalve. Their only role entails preventing water from reaching the scanivalve system, since the scanivalve is designed for air systems only. The air and water are separated by gravity, the water levels in the separators are observed visually and the accumulated water can be drained using the drain valve located at the bottom of each separator.

Figure 3.7: Static pressure measurement system

3.6.1 Pressure transducer

The differential pressure transducer employed in this experiment is a reluctance type (model DP30-0100-111) manufactured by Celesco transducer products Inc. The transducer employs interchangeable diaphragms for different pressure ranges. For this work the transducer is equipped with a diaphragm that has an operating range of 0 to 690 kPa (0 to 100 Psi). This pressure range allows for measurement of the air supply total pressure (550 kPa).

The pressure measurement system includes a Carrier- Demodulator (model LDCC-115) which serves as a signal conditioner. The carrier-demodulator amplifies and converts the low AC signal (3.62×10^{-2} mV/kPa) from the pressure transducer to a DC analog signal. In addition, the demodulator provides the excitation voltage drive required by the transducer. The demodulator is powered with 110 VAC-60 Hz line voltage and provides 0 to 5 VDC output corresponding to 0 to 690 kPa.

3.6.2 Pressure transducer calibration

A dead-weight gage tester was used to calibrate the pressure transducer over its full range; i.e. 0 to 690 kPa. Readings of the transducer output were taken while loading and unloading the tester. The whole calibration procedure was repeated twice; a comparison of repeated measurements shows a good agreement. As illustrated by the calibration curve presented in figure 3.8, the transducer has a linear output voltage. The slope of the line fit to the data is 8.77 mV/kPa (60.5 mV/Psi). The pressure transducer has an accuracy of $\pm 1\%$.

3.6.3 Scanivalve system

A 48-port Scanivalve model DSS-48C, manufactured by Scanivalve Corp., is used in measuring the static pressure throughout the test rig. Only six of the 48 ports

Figure 3.8: Pressure transducer calibration curve

are used, the assignment of these ports is given in appendix E. Complete control of the Scanivalve is achieved by using a Scanivalve controller. The controller (model ITF-488) is connected to the computer via an IEEE488 I/O board. Communication between the computer and the Scanivalve controller is attained by entering standard ASCII characters into the computer. Upon receiving these commands, the controller sets the scanivalve at the specified port, and subsequently reads the scanivalve's multiplexer port to confirm that the Scanivalve is addressed to the appropriate port number. A designated computer sub-routine called SCANIVALVE was developed to establish this communication process, a flowchart of this sub-routine is given in Appendix B.

3.7 Temperature Measurement

Type "T" thermocouples are used to measure air inlet temperature, water inlet temperature and the two-phase mixture temperature at the end of the test section. Refer to figure 2.1 for measurement locations. The two dissimilar metals that form the T-type thermocouples are copper and constantan, with copper being the positive metal and constantan the negative metal.

The thermocouples are connected via an electronic board (EXP-16) which provides stable amplifications of the low output voltage ($21 \text{ mV}/^{\circ}\text{C}$). The board also allows for cold junction compensation (CJC).

Linearization of the thermocouple output and allowance for the CJC are performed by using a computer subroutine called TEMPERATURE. The thermocouple output voltages are converted to temperature using a look-up data table provided by the manufacturer. A flowchart of the subroutine TEMPERATURE is given in Appendix B.

The thermocouples were manufactured by OMEGA Eng. Inc. (model TQSS-116) and they are sheathed with a 1.6 mm O.D. stainless tubes. The accuracy of the thermocouple readings were checked by comparison with a mercury thermometer, the temperatures were found to be within $\pm 0.5^{\circ}\text{C}$.

3.8 Data Acquisition and Control System

A data acquisition system is used to measure the voltage outputs of all the instruments and to control the scanivalve. The system consists of an IBM Compatible personal computer (AT), a DAS-8PGA Board and an IEEE488 Input/Output Board.

Figure 3.9 schematically shows the arrangement of the data acquisition system. In order to increase the noise rejection, all instruments are connected to the data acquisition system with shielded cables.

The DAS-8PGA System, manufactured by Metrabyte corporation, is the main component of the data acquisition system and it is contained in the (AT) personal computer. The system has 8 Analog input channels. The analog-to-digital (A/D) converter has a 12 bit resolution with a conversion time of 25 μsec . The system has selectable analog input ranges. Throughout this research program the system is configured for an analog input range of 0 to 10 volts. For such an input range the system is capable of measuring a voltage as small as 2.4 millivolts. The accuracy of the (A/D) converter was tested by comparison with readings taken by a digital voltmeter. The results of this test are plotted in figure 3.10.

The system features a very high sampling rate of up to 20,000 samples per second. The maximum conversion rate used in this experiment is 4,000 readings per second, utilized when measuring the void fraction and the phase velocity.

The EXP-16 is an expansion/multiplexer board. It is connected to the DAS-8PGA analog input channel no. 7. The board, mainly used to measure the thermocouple output voltages, features a low drift selectable amplifier and allows for cold junction compensation (CJC). In this experiment a gain of 200 is used to amplify the thermocouple output voltages.

The STA-8PGA screw terminal board is connected to the EXP-16 Board with a 37-pin connector. It permits direct connections of the instrumentations output voltages. Refer to figure 3.9, for channel assignments of the data acquisition system.

Figure 3.9: Data acquisition system arrangement

Figure 3.10: Calibration of the data acquisition system (A/D) converter

The IEEE488 I/O board, manufactured by IOtech Inc. (model GP488B), is contained in the (AT) computer. It is used to control the Scanivalve. Communication with the Scanivalve controller is established by using standard ASCII characters. A summary of the commands and their functions is given in Appendix E.

3.9 Miscellaneous apparatus

The following is a list of the equipment used during the course of the experimental setup and calibration. These instruments are not necessarily integral parts of the test rig. With the exception of the power supplies and the laser system, all the other electrical equipment was disconnected when performing measurements. This is to reduce the noise in the system.

1. A Fluke multimeter model 8050A: This was mainly used in setting and calibrating the data acquisition system. When used as a voltmeter with a range of 1 volt, it has an accuracy of 1 mV.
2. A Tektronix oscilloscope, model 2213 and serial number 9914370, was used to determine the response of the photometers and to study the transient behaviour of the fiber optic probe.
3. A stroboscope, manufactured by Strobotac model 1538-A, was used to study the response time of the light detector.
4. Two Omega regulated DC power supplies (model PSS-15 and model PST-A15) are used to supply the air velocity transducer and paddlewheel sensor with 15 volts DC.
5. A function generator model 180 manufactured by WAVETEK was used to determine the accuracy of the void fraction and the phase velocity measurements.
6. The layout of the light source system is schematically shown in figure 3.11. The system consists of a 300 mW argon laser and a beam splitter. The water cooled laser system, manufactured by Lexel Inc.(model 75), is operated at a wave length of 514 nm (green). At this wave length, the laser produces about 43 % of its 300 mW total power. The 50/50 beam splitter is used to divide and couple the laser beam into two optical fibres.
7. A 3M-Photodyne fibre optic tool kit model 1300B, used in preparing the bare tip of the fibre. The kit contains an optical fibre cleaver, cable cutter, jacket stripper, buffer stripper and an inspection microscope with connectors.

Figure 3.11: Layout of the light source system

Chapter 4

Test section commissioning

This chapter is concerned with the test section commissioning, signal processing and data analysis. The data acquisition system software is described. The accuracy of the data analysis method used in the void fraction and phase velocity measurements is presented. The chapter also includes the test rig operating instructions.

4.1 Air flow rate

The AVT measures the mass flow per unit area (ρV) referenced to the conditions at which it was calibrated. Information provided by the manufacturer states that the AVT was calibrated under standard atmospheric conditions, ie. 25 °C and 101.33 KPa. In this experiment, air velocity measurements are performed under conditions other than the standard atmospheric conditions. Therefore, the measured air standard velocity must be converted into actual air velocity. Since the transducer measures the mass flow rate per unit area, the following holds:

$$\rho_s V_s = \rho V$$

using the ideal gas equation ($P = \rho R T$) and substituting for ρ_s and ρ , we have

$$V = V_s \left(\frac{P_s}{P} \right) \left(\frac{T}{T_s} \right)$$

Where

V, V_s : actual and standard air velocity, respectively

ρ, ρ_s : actual and standard air density, respectively

T, T_s : actual and standard air temperature, respectively

P, P_s : actual and standard air pressure, respectively

The above equation was used to convert the air standard velocity into actual velocity.

The air velocity transducer measures the velocity at the centre of the air supply pipe; where the sensor of the transducer is placed. To find the air flow rate, a mean value of the air velocity across the pipe diameter must be computed.

If V_c is the centre velocity (measuring point), V_m the mean velocity and Re the Reynolds number based on V_c and the air supply pipe diameter, the ratio $\frac{V_m}{V_c}$ depends on Re . If $Re > 4800$, the flow is turbulent and the velocity profile is flat. Using the one seventh power-law formula for the velocity distribution $\frac{V}{V_c} = \left(\frac{R-r}{R}\right)^{\frac{1}{7}}$, the ratio $\frac{V_m}{V_c} = 0.82$. However, if the flow is laminar $Re < 4800$, the velocity profile is parabolic and the ratio $\frac{V_m}{V_c} = 0.5$. The laminar-turbulent transition region is considered to be small and therefore it is neglected.

4.2 Water Supply system

While testing the capabilities of the apparatus, it was noticed that the water temperature was continuously increasing with time. This was a result of the heat generated by the water pump. To examine the temperature variations over time, the water temperature was recorded for a 3 hour time period. Results from this test experiment are plotted in figure 4.1. The water temperature increases at a rate of $12^\circ\text{C}/\text{hour}$. It should be noted here that this water temperature gradient $\left(\frac{dT}{dt}\right)$ depends on the

Figure 4.1: Water supply temperature variations

water volume being circulated. For this particular test the water volume was $1.2m^3$.

This undesirable temperature increase will be reflected in the water properties, such as the viscosity. To remedy any problems caused by variations of viscosity, a feed and bleed technique was adopted during a test run. That is, cold water was added to the water system while at the same time heated water was extracted. This approach gave satisfactory results as it helped to stabilize the water temperature.

4.3 Data acquisition software

The DAS-8PGA Data acquisition system features a special input/output routine driver called DAS8.BIN. This driver is designed to simplify the programming development. With a single call statement from BASIC the driver performs a series of

instructions depending on the value of the passed variable (*MODE%*)¹ in the call statement.

A BASIC program called REGTRANS (for regime transitions) was developed to control the data acquisition system. The program contains a number of sub-routines used to analyze the raw data, and to produce output files containing results of the measured parameters.

The source code of REGTRANS is composed of a main calling routine and 26 sub-routines. Flowcharts of the main calling routine and the most important sub-routines are given in Appendix B, and the source code of REGTRANS is given in Appendix C. When executed, the REGTRANS program prompts the operator for the run number, the probe position and the two-phase flow regime type (eg. plug flow, slug flow, etc.). When the flow type is unclear or unknown, the operator can enter notes describing the nature of the flow. These parameters, if entered, will be stored with the measured values.

Some sub-routines are developed to convert the measured voltages to the appropriate engineering units, e.g. sub-routine PRESSURE is used to convert the output voltage of the pressure transducer to Pascals using the transducer calibration curve. SCANIVALVE sub-routine is used to communicate with the Scanivalve controller through a standard IEEE488 I/O board. At the end of each run the reduced data are displayed on the screen and then stored in the output files.

VOIDFRACTION sub-routine was developed to perform time-average measurements of the local void fraction. The output of the Photometer is sampled at rate of 4000 Hz, which means that the voltage output of the photometer is read every

¹*MODE%* is a parameter used by the data acquisition routine driver.

2.5×10^{-4} sec. The void fraction is averaged over a period of time that varies between 6 to 12 sec, depending on the repeatability of the two phase structure. At low mass flow rates the longer period of time is required, (12 sec) and vice versa.

To determine the time-average local void fraction, the sub-routine counts the number of readings that indicate high voltage. Dividing this number by the total number of readings, gives the time fraction over which the tip of the probe was immersed in the air phase. This time fraction represents the time-average local void fraction. The void distribution is determined by performing local measurements at 7 different positions equally spaced along the test section diameter. An average of these measurements represents the time and space averaged void fraction.

The sub-routine PHASEVELOCITY was conceived to determine the velocity of the air-water interfacial surfaces. The signal output of the exclusive-or gate is sampled at 4000 Hz. With this sampling rate and with a distance of 4 mm between the tips of the front and the back fibre probes, velocities up to 18 m/sec can be measured.

The PHASEVELOCITY sub-routine counts the number of readings that constitute each pulse. Knowing this number, the sampling rate and the distance separating the front and the back probes, velocities of the air-water interfacial surfaces can be computed. A flowchart of this sub-routine is shown in Appendix B.

The accuracy of the data analysis method used in the void fraction and the phase velocity measurements was tested. The VOIDFRACTION and PHASEVELOCITY were used to analyze data from a square wave of known pulse width. The results of this test are presented in figure 4.2 and 4.3. Figure 4.2 shows that error introduced in the void fraction measurement by using this analysis method is less than

Figure 4.2: Accuracy of void fraction data analysis

Figure 4.3: Accuracy of phase velocity data analysis

Figure 4.4: Typical output signal of the Photometer

1%. However, as shown in figure 4.3, in the phase velocity measurement the error introduced is less than 10%.

4.4 Signal processing

A typical output signal of the photometer is presented in figure 4.4. As it was expected the photometer does not produce an idealized signal, so that, waveshaping of the signal is required. The only information needed from the photometer's output signal is its state level (high or low voltage) and not an exact measurement of its amplitude. As mentioned before, the output voltage of the photometer is high (1.9 to 2.4 volts) when the fibre tip is immersed in air, or low (0.2 - 0.9 volts) when the fibre tip is immersed in water. The range of the signal state levels depends very much on the preparation of the tip of the fibre. With a clean and straight cut of

Figure 4.5: Photometer output signal conditioning; Schmitt trigger

the fibre tip, the intensity of the light reflected back to the photometer is high thus producing a higher output voltage.

A Schmitt trigger is used to distinguish between the two state levels of the photometer's output signal. Figure 4.5 illustrates the function of the Schmitt trigger. As the input signal rises from a low state, the output changes from a low state to a high state when the input crosses the "on" threshold, see figure 4.5. The output remains high until the input crosses the "off" threshold. The level of threshold can be changed by simply adjusting a pot resistor. During the course of this work, it was found that threshold adjustment was required for different mass flow rates. The threshold is set to discriminate between the air and water phases. It should be noted that two triggers were used, one for each of the fibre probes.

Outputs of both triggers are fed into an exclusive-or gate. The signal output of the exclusive-or gate is a series of pulses. The width of each pulse represents the time shift between the two pulses.

Chapter 5

Results and conclusions

5.1 Results and discussion

Results

The results were obtained from measurements made in the 2.54 cm I.D. horizontal test section. A total of 72 test runs were performed covering all flow regimes identified by previous workers, such as those recognized by Taitel and Dukler. The number of data points obtained for each of the flow patterns is as follows:

- Bubbly flow regime: 9
- Stratified flow regime: 5
- Plug flow regime: 28
- Wavy flow regime: 5
- Slug flow regime: 9
- Annular flow regime: 16

For this series of tests the air flow rate was varied over a range of 0 to $8.226 \times 10^{-3} \text{ m}^3/\text{sec}$, while the water flow rate ranged between 0 and $2.219 \times 10^{-3} \text{ m}^3/\text{sec}$. The maximum air and water superficial velocities recorded were 16.3 m/sec and 2.3 m/sec, respectively. As defined earlier, the superficial velocity is the velocity that the single phase would have if it was occupying the total area of the test section. Measurements of all the parameters represent the average values of 300 readings.

The processed data presented in Table 1, Appendix A, are the air and water superficial velocities required to establish the various flow regimes. Table 2, in Appendix A gives measurements of the local void fraction along the test section diameter, using the front and the back fibre-optic probes. The void distribution was performed for a plug flow regime. The local velocities of the air-water interfacial surfaces appear in the right most columns of Table 2.

The results of table 1 are also conveniently presented as shown in figure 5.1. Figure 5.1 represents a flow regime map of an air-water mixture observed in a horizontal 2.54 cm pipe, at near atmospheric pressure. The two-phase flow regime map is plotted in a log-log scale with the air superficial velocities as the abscissa and the water superficial velocity as the ordinate.

The preliminary results are compared with the theoretical prediction of Taitel and Dukler (1976) and with the experimental flow regime map presented by Mandhane et al. (1974).

Discussion

Results from the initial testing show that the test rig operation is satisfactory. As indicated in Figure 5.1, the flow regimes are situated in locations similar to those presented in earlier published flow regime maps. Unfortunately, due to the small

Present Data:

♦ Bubble flow. x Plug flow. Δ Stratified flow.
 z Navy flow. ★ Slug flow. # Annular flow.

— Mandhane et al. — Taitel and Dukler

Figure 5.1: Observations of air-water flow regimes in a 2.54 cm horizontal pipe

body of the collected data, the exact locations of transition boundaries between the flow regimes cannot be determined at this time. More data points are required before any firm conclusions about the transition boundaries can be attained.

Bubbly flow regime was observed at water superficial velocities higher than 1 m/s, see figure 5.1. The experimental results presented in figure 5.1 indicate that the bubbly flow regime exists at a water superficial velocity lower than that predicted by Taitel and Dukler, and Mandhane et al.,

Stratified flow regime was observed at low air and water superficial velocities. Most of the stratified flow test points had water height to test section diameter ratios ($\frac{H}{D}$) that were close to 0.5. This regime was hard to establish, as it was very sensitive to the air and water flow rates.

Annular flow regime was observed at high air superficial velocities (above 5 m/sec). It was hard to distinguish between the annular flow regime and slug flow regime at water superficial velocities higher than 0.3 m/sec. This difficulty has been recognized by many researchers. In fact, Lin and Hanratty (1987) suggested a separate regime that they called pseudo-slug. Wavy flow regime was also hard to establish, as the waves quickly build-up and the nature of the flow would be difficult to distinguish from the slug regime.

Due to the short time response of the photometer and the detector and to the sampling rate provided by the data acquisition system, the fibre-optic probe constructed during this work is quite efficient. The probe instantaneously discriminates between the air and water phases. Figure 5.2 shows a typical signal output from the photometer representing the plug flow regime.

Figure 5.2: Time trace from Photometer representing a plug flow regime

During the course of this work it was noticed that the signal output from the photometer is very sensitive to the preparation of the tip of the fibre. The probe has a very short response time if the cut of the fibre tip is clean and straight, see figure 5.3. Otherwise, as indicated in figure 5.4, if the fibre is not well prepared, the transient time of the probe is long and the efficiency of the probe thus decreases.

5.2 Summary and conclusions

A two-phase flow test facility has been developed to study the flow regime transitions in both horizontal and vertical air- water systems at near atmospheric conditions. The test rig will be used to study the effects of the various parameters on the two-phase flow regime transition boundaries.

Figure 5.3: Transient behaviour of the tip of the fiber probe; fiber tip well prepared

Figure 5.4: Transient behaviour of the tip of the fiber probe; fiber tip not well prepared

There are two key factors in the apparatus. First is the large length to diameter ratio of the test section tube; $\left(\frac{L}{D}\right) = 575$ for the 2.54 cm I.D. pipe. The second, is the use of a twin-needle fibre-optic probe to determine the average local void fraction along the pipe diameter and to measure the velocity of the air-water interfacial surface velocities.

The test rig is fully automated. A computer based data acquisition system is used to monitor all parametric measurements, and special subroutines were developed to reduce and analyze the raw data.

Testing of the apparatus shows the rig to be capable of producing stable air and water flow rates, and enough of both phases to cover all flow regimes of interest in this study (i.e, for the 2.54, 5.08 and 7.62 cm I.D. test sections). The fibre optic probe gives a virtually instantaneous response in discriminating between the two phases (air and water).

Preliminary measurements (72 test points) made with the 2.54 cm I.D. horizontal test section are conveniently summarized by a two phase flow regimes map.

Recommendations

During the course of this work, it was somewhat surprising to notice that data on regime transitions of air-water flow in inclined pipes are very scarce in the literature. The models developed by Taitel and Dukler (1976) indicate that small degrees of inclination, both upward and downward, have a very pronounced effect on the regime transitions. Inclination angles as small as -0.1° or $+2^\circ$, cause large shifts in the location of the flow regime transition curves. Therefore, it would be very interesting to study the two-phase flow transitions in inclined tubes. The present test rig can be easily modified to study the air-water regime transitions in inclined pipes.

The structure of the air-water mixture is identified by direct visual observation. The regime is then classified by using the pattern definitions given in chapter one. Direct visual observation is possible at low air and water mass flow rates. However at high mass flow rates of air and water, it is difficult to clearly observe the structure of the flow. Therefore, it would be very advantageous to use high speed photography to capture the changes in the structure of the two phases. This information could be viewed at a low speed for analysis.

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Appendix A

Tables of experimental results

Table #1: Flow regime observation; Air-Water in 2.54 cm tube

Bubbly flow regime

Run no.	Air sup. vel. m/sec	Water sup. vel. m/sec
1	0.0841	1.1904
2	0.0869	1.0083
3	0.0928	1.0341
4	0.0911	1.4815
5	0.0929	1.5198
6	0.1012	1.5081
7	0.1108	1.7168
8	0.1510	2.0919
9	0.2524	2.2996

Stratified flow regime

10	0.4742	0.0056
11	0.5312	0.0079
12	0.5904	0.0086
13	0.5807	0.0109
14	0.7009	0.0114

Plug flow regime

15	0.0976	1.3768
16	0.1611	1.2261
17	0.0943	1.3437
18	0.1778	1.2119
19	0.1135	1.3227
20	0.1618	0.9739
21	0.1622	0.7572
22	0.2695	0.3120
23	0.1464	1.1047
24	0.3452	1.2377
25	0.5320	1.1078
26	0.5136	1.1258
27	0.4974	1.0389

Run no.	Air sup. vel. m/sec	Water sup. vel. m/sec
28	0.5169	1.0702
29	0.4871	1.0392
30	0.4899	0.7508
31	0.4876	1.1686
32	0.4784	0.8905
33	0.4537	0.7116
34	0.4477	0.6375
35	0.4511	0.5915
36	0.4630	0.4948
37	0.4508	0.5063
38	0.1264	0.5708
39	0.1322	0.5571
40	0.1370	0.6292
41	0.3268	0.8053
42	0.7126	0.7140

Wavy flow regime

43	5.3663	0.0144
44	5.3326	0.0798
45	6.5365	0.1019
46	6.3577	0.0445
47	8.5865	0.0582

Slug flow regime

48	0.3388	1.7228
49	0.3218	0.1290
50	0.2591	0.2750
51	0.3964	0.1093
52	0.4827	0.1318
53	1.0483	0.6666
54	1.6159	1.1329
55	2.5300	0.5266
56	2.1497	0.6305

Annular flow regime

Run no.	Air sup. vel. m/sec	Water sup. vel. m/sec
58	6.1875	0.3237
59	5.9980	0.7140
60	5.0928	0.7063
61	5.4689	0.2897
62	12.2751	0.0444
63	11.6805	0.0535
64	14.7148	0.0565
65	16.5534	0.0767
66	14.3656	0.2861
67	15.7342	0.3556
68	5.1451	0.1483
69	10.8812	0.0908
70	5.5764	0.0371
71	7.2701	0.3622
72	11.4763	0.1766

Table #2: Plug flow regime

Probe position	Void fraction fraction #1	Void fraction Back probe	Phase Vel m/sec
1	0	0	=
2	0	0	=
3	0	0	=
4	0	0.02	0.001
5	0.33	0.41	0.027
6	0.32	0.39	0.024
7	0.4	0.37	0.028

Appendix B

Data acquisition system program flow charts

DACQS: Data acquisition program. (continued next page)

Subroutine VOIDFRACTION: Calculates the local voidfraction.

Subroutine LOCKCHN: Locks DAS8-PGA multiplexer to a certain channel.

Subroutine PHASEVELOCITY: Calculates the phase velocity.

Subroutine SCANIVALV: Controls the scanivalve.

Subroutine COUNTER: Performs multiple conversions at a defined rate.

Subroutine TEMPERATURE: Measures air, water and mixture temperatures.

Appendix C

Data acquisition system program listing


```

/  *-----*
/  *
/  *                      REGTRANS
/  *-----*
/  * This program is developed to control the data acquisition
/  * system of the two-phase flow test rig. The apparatus is
/  * conceived to study the two-phase flow regime transitions
/  * in vertical and horizontal test sections. The program
/  * consists of a main calling routine and 26 sub-routines.
/  * To run this program, with micro-soft Quick-basic, enter
/  * the following command while loading the program, the DAS8
/  * driver must be loaded:  QB /L DAS8 REGTRANS
/  * Note that the scanivalve and its controller have to be
/  * powered in order for the program to run, communication
/  * with the scanivalve controller is completed via an IEEE488
/  * I/O board contained in the computer. The thermocouples
/  * look-up data file is called T_TEMP.DAT, (for type " T "
/  * thermocouples), this file also must be available.
/  *
/  * References:
/  * [1] DAS8 and DAS8-PGA user's manual, Metrabyte corp.
/  * [2] Quick-basic user's manual. version 4.5
/  *-----*
/
/  SUBR INITIALIZE : Initialize DAS8-PGA board.
/  SUBR SCANIVALV  : Control the scanivalve.
/  SUBR LOCKCHN    : Lock DAS8-PGA to a certain channel.
/  SUBR SAMPDAT    : Lock DAS8-PGA to a channel and perform A/D
/                   conversion.
/  SUBR ADCONV     : Perform A/D conversion.
/  SUBR COUNTER    : Configure/Load counter 2 and perform multiple
/                   conversion.
/  SUBR VOIDFRACTION : Caculates the void fraction.
/  SUBR TEMPERATURE : Measure Air, Water and Mixture temperatures.
/  SUBR ERRCODES    : Display error message and end program.
/  SUBR PHASEVELOCITY: Calculate the phase velocity.
/  SUBR SCRNOUT     : Display output on screen.
/  SUBR CJCGET      : Get Cold junction compensation temperature.
/  SUBR TEMPINTRP   : Interpolate to find temperature.
/  SUBR TEMPLOOKUP  : Load type T thermocouple lookup temperature.
/  SUBR VOIDISTRBOUT: Store Void frac. at different probe positions.
/  SUBR REGIMESMAP  : Store Air / wat. sup. vel. in separate files.
/  SUBR SUPVELOUT   : Store Air / water superficial velocities.
/  SUBR INLTCONDOUT : Store Air / water inlet conditions. Pres. & Tem
/  SUBR MIXPRSOUT   : Store pressure of two-phase mixture dat.
/  SUBR VOIDFRACOUT : Store void fraction data.
/
/  SUBR AVERAGEREAD : Average the values of an array.
/  SUBR PRESSURE     : Convert voltage output to pressure.
/  SUBR WATFLOWRATE  : Convert voltage output to water flow rate.
/  SUBR AIRFLOWRATE  : Convert voltage output to air flow rate.

```

```

' SUBR BORDERLINES :
' SUBR INTRODUCTION:

' LT% :
' D% :
' DAT%() : Data acquired by mode 5.
' VOID1() : Void fraction measured by fiber # 1. Upstream.
' VOID2() : Void fraction measured by fiber # 2. Downstream.
' PHSVEL() : Phase velocity ( m/sec )
'
' CH% = 0 : Air Velocity Transducer.
' CH% = 1 : Paddlewheel Sensor.
' CH% = 2 : Pressure Transducer.
' CH% = 3 : Photometer unit 1, conditioned output.
' CH% = 4 : Photometer unit 2, conditioned output.
' CH% = 5 : Phase velocity.
' CH% = 6 : EXP-16 for air, water & mixture thermocouples.
' CH% = 7 : EXP-16 cold junction compensation temp.
'
'
' SCH% = 0 : Air inlet thermocouple.
' SCH% = 1 : Water inlet thermocouple.
' SCH% = 2 : 2 Phase mixture exit thermocouple.
'
'
' PORT% = 0 : Atmospheric pressure.
' PORT% = 1 : Air static pressure at velocity transducer.
' PORT% = 2 : Air inlet static pressure.
' PORT% = 3 : Water inlet static pressure.
' PORT% = 4 : Mixture static pressure at test section inlet.
' PORT% = 5 : Mixture static pressure at fiber probe position.
' PORT% = 6 : Mixture static pressure at test section exit.
'
' Dimension the arrays.

DIM LT%(2), D%(100)
DIM DAT%(16000)
DIM VOID1(20), VOID2(20), PHSVEL(20)

DIM TT(140)

' Declare the common shared variables.
' LT%(), d%() and DAT%() must be declared as inter-module variable
' since they are passed and returned by an external driver DAS8.

COMMON SHARED LT%(), D%(), CH%, DAT%()

COMMON SHARED AVTPRS, AINPRS, WINPRS, AIRTEMP, WATTEMP
COMMON SHARED MIXINPRS, MIXMDPRS, MIXEXPR, MIXTEMP
COMMON SHARED VOIDFRC1, VOIDFRC2, PHASEVEL

COMMON SHARED VOLT, NT, TT(), SVT, SIT, CJC

```

2

of/de

2

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS
STANDARD REFERENCE MATERIAL 1010a
(ANSI and ISO TEST CHART No. 2)

COMMON SHARED RUNUMB%, POSITION%, PATTERN\$, PHOTO%

' Declare subroutines.

DECLARE SUB INITIALIZE ()
DECLARE SUB SCANIVALV (PORT%)
DECLARE SUB LOCKCHN (CH%)
DECLARE SUB SAMPDAT (CH%, NC, VALUE)
DECLARE SUB ADCONV (CH%, NC, VALUE)
DECLARE SUB COUNTER (F, DTS)
DECLARE SUB VOIDFRACTION (CH%, VOID)
DECLARE SUB TEMPERATURE (CJC, ATEMPR, WTEMPR, MXTEMPR)
DECLARE SUB ERRCODES (FLAG%)
DECLARE SUB PHASEVELOCITY (CH%, PHAVGVEL)
DECLARE SUB SCRNOOUT (ASUPVEL, WSUPVEL)
DECLARE SUB CJCGET (NC, CJC)
DECLARE SUB TEMPINTRP (VOLT, CJC, TC, TF)
DECLARE SUB TEMPLOOKUP ()

DECLARE SUB VOIDISTRBOUT (I!, VOID1!(), VOID2!(), PHSVEL!())
DECLARE SUB REGIMESMAP (ASUPVEL, WSUPVEL)
DECLARE SUB SUPVELOUT (RUNUMB%, ASUPVEL!, WSUPVEL!, PATTERN\$)
DECLARE SUB INLTCONDOUT (RUNUMB%, AVTPRS!, AINPRS!, WINPRS!, AIRTEMP!,
WATTEMP!)
DECLARE SUB MIXPRSOUT (RUNUMB%, MIXINPRS!, MIXMDPRS!, MIXEXPR!,
MXTEMP!)
DECLARE SUB VOIDFRACOUT (RUNUMB%, VOIDFR1!, VOIDFR2!, PHASEVEL!,
PATTERN\$)

DECLARE SUB AVERAGEREAD (I!, READNGS!(), AVERAGE!)
DECLARE SUB PRESSURE (PRSVOLT!, PRSPAS!)
DECLARE SUB OUTPUTFILES (RUNUMB%, ASUPVEL!, WSUPVEL!, PATTERN\$)
DECLARE SUB WATFLOWRATE (WFLOWV!, WATFLOW!, WSUPVEL!)
DECLARE SUB AIRFLOWRATE (ASVEL!, AVTPRS, AIRTEMP, AIRFLOW!, ASUPVEL!)
DECLARE SUB BORDERLINES ()
DECLARE SUB INTRODUCTION ()

' Declare the DAS8 Driver, this is essential to the execution
' of the DAS8 call. Declaring the following subroutine makes
' the driver known to this module.

DECLARE SUB das8 (MODE%, BYVAL dummy%, FLAG%)

' Initialize DAS8-PGA.

CALL INITIALIZE
CALL INTRODUCTION
CALL TEMPLOOKUP

NC = 300

LOCATE 20, 4

```

PRINT "Program is running, please WAIT. ! "
LOCATE 21, 4
PRINT " Now measuring....."
,
LOCATE 22, 4
PRINT " Air superficial velocity .           "
,
' Measure the air velocity.
,
CH% = 0
,
CALL SAMPDAT(CH%, NC, VALUE)
AIRSVELV = VALUE
,
' Measure static pressure at air velocity transducer.

LOCATE 22, 4
PRINT " Air pressure at vel. trans.         "
,
PORT% = 1
CALL SCANIVALV(PORT%)
,
CH% = 2
CALL SAMPDAT(CH%, NC, VALUE)
AIRVPRSV = VALUE

' Measure air inlet pressure.

LOCATE 22, 4
PRINT " Air inlet pressure.                 "

PORT% = 2
CALL SCANIVALV(PORT%)

CH% = 2
CALL SAMPDAT(CH%, NC, VALUE)
AIRINPRV = VALUE
,
' Measure water flow-rate.
LOCATE 22, 4
PRINT " Water superficial velocity .       "

CH% = 1
CALL SAMPDAT(CH%, NC, VALUE)
WATFLOWV = VALUE

' Measure water inlet pressure.
LOCATE 22, 4
PRINT " Water inlet pressure.             "

PORT% = 3
CALL SCANIVALV(PORT%)

```

```

CH% = 2
CALL SAMPDAT(CH%, NC, VALUE)
WATINPRV = VALUE

'Measure two-phase flow inlet pressure.
LOCATE 22, 4
PRINT " Two-phase inlet pressure.      "

PORT% = 4
CALL SCANIVALV(PORT%)
,
CH% = 2
CALL SAMPDAT(CH%, NC, VALUE)
MIXPRSV1 = VALUE
,
'Measure two-phase static pressure at fiber probe.
LOCATE 22, 4
PRINT " Two-phase pressure at fiber probe.  "
,
PORT% = 5
CALL SCANIVALV(PORT%)

CH% = 2
CALL SAMPDAT(CH%, NC, VALUE)
MIXPRSV2 = VALUE
,
,
'Measure two-phase flow exit pressure.
LOCATE 22, 4
PRINT " Two-phase exit pressure.          "
,
PORT% = 6
CALL SCANIVALV(PORT%)
,
CH% = 2
CALL SAMPDAT(CH%, NC, VALUE)
MIXPRSV3 = VALUE

'Measure air , water and exit mixture tempearature.
LOCATE 22, 4
PRINT " Air, Water and Mixture temperature.  "
,
CALL TEMPERATURE(CJC, ATEMPR, WTEMPR, MXTEMPR)
AIRTEMP = ATEMPR
WATTEMP = WTEMPR
MIXTEMP = MXTEMPR
,

BEEP
BEEP

FOR I = 1 TO 7

```

```

'Move the probe to the new position then press anykey.
'Measure void fraction at fiber # 1
LOCATE 22, 4
PRINT " Void fraction at fiber # 1.      "

CH% = 3
CALL VOIDFRACTION(CH%, VOID)
VOID1(I) = VOID

'Measure void fraction at fiber # 2
LOCATE 22, 4
PRINT " Void fraction at fiber # 2.      "

CH% = 4
CALL VOIDFRACTION(CH%, VOID)
VOID2(I) = VOID

'Measure phase velocity.
LOCATE 22, 4
PRINT " Phase velocity.                  "
CH% = 5
CALL PHASEVELOCITY(CH%, PHAVGVEL)
PHSVEL(I) = PHAVGVEL
,
' Move the probe to the new position then press anykey.
LOCATE 20, 4
PRINT " Move the probe to the new position.  "
LOCATE 21, 4
PRINT "                                     "
LOCATE 22, 4
PRINT " Enter any key when ready.          ";

INPUT QWER
POSITION% = I + 1
LOCATE 4, 42
PRINT POSITION%

NEXT I
I = I - 1

BEEP
,
' Average the values for the different positions of the probe.
,
CALL AVERAGEREAD(I, VOID1(), VOIDFRC1)
CALL AVERAGEREAD(I, VOID2(), VOIDFRC2)
CALL AVERAGEREAD(I, PHSVEL(), PHASEVEL)
,
' Pressure conversion.
,
CALL PRESSURE(AIRVPRSV, AVTPRS)
CALL PRESSURE(AIRINPRV, AINPRS)

```

```

CALL PRESSURE(WATINPRV, WINPRS)
,
CALL PRESSURE(MIXPRSV1, MIXINPRS)
CALL PRESSURE(MIXPRSV2, MIXMDPRS)
CALL PRESSURE(MIXPRSV3, MIXEXPR)
,
CALL AIRFLOWRATE(AIRSVELV, AVTPRS, AIRTEMP, AIRFLOW, ASUPVEL)
CALL WATFLOWRATE(WATFLOWV, WATFLOW, WSUPVEL)
,
CALL SCRNOOUT(ASUPVEL, WSUPVEL)
,
LOCATE 3, 53
PRINT "Record this data? Y or N "
LOCATE 4, 53
INPUT A$

IF A$ = "N" OR A$ = "n" THEN END

CALL VOIDISTRBOUT(I, VOID1(), VOID2(), PHSVEL())

CALL REGIMESMAP(ASUPVEL, WSUPVEL)
CALL SUPVELOUT(RUNUMB%, ASUPVEL, WSUPVEL, PATTERN$)
CALL INLTCONDOUT(RUNUMB%, AVTPRS, AINPRS, WINPRS, AIRTEMP, WATTEM)
CALL MIXPRSOUT(RUNUMB%, MIXINPRS, MIXMDPRS, MIXEXPR, MIXTEMP)
CALL VOIDFRACOUT(RUNUMB%, VOIDFRC1, VOIDFRC2, PHASEVEL, PATTERN$)
,
END

```

```

'-----'
SUB ADCONV (CH%, NC, VALUE) STATIC
' This subroutine is to perform a total number of NC single
' A/D conversions and convert the binary numbers read from
' channel CH% to voltage.
,
' The passed variables:
' CH% : Number of channel to be sampled.
' NC : Numer of A/D conversion for time averaging.
' The returned variables:
' VALUE : Average voltage read from channel # CH%. (Volts)
,
' DATVAL() : Array to store measured values. (Binary form)
' Size must be greater or equal to NC.
,
DIM DATVAL(1000)

' Perform NC A/D conversions on channel CH% using mode 4.

FOR I = 1 TO NC

MODE% = 4 ' Single 12-bit A/D conversion.

CALL das8(MODE%, VARPTR(D%(CH%)), FLAG%)

```



```

        IF FLAG% <> 0 THEN CALL ERRCODES(FLAG%)

        DATVAL(I) = D%(CH%)

    NEXT I

    ' Average the NC values read from channel CH%.

    CALL AVERAGEREAD(NC, DATVAL(), VALUE)

    ' Convert the binary data to volts.
    ' Analog Input V. = Binary Output X Span resolution.
    ' Here User should note the Data Acquisition Board is configured
    ' for a UNIPOLAR input range of 0 - 10 Volts.

    VALUE = VALUE * 10 / 4095

    ' Return to calling module.
    END SUB

```

```

-----
SUB AIRFLOWRATE (ASVELV, AVTPRS, AIRTEMP, AIRFLOW, ASUPVEL) STATIC

```

```

    ' This subroutine calculates the air actual velocity, flow-rate
    ' and superficial velocity.
    ' The air velocity transducer has a linear output of 0 - 5 volts
    ' for a standard air velocity of 0 - 12000 sfpm. This gives calibration
    ' curve a slope of 2400 sfpm / volts. Converting to metric units the
    ' slope is equal to 12.192 smps / volt.
    '
    ' The passed variables:
    ' ASVELV : Air vel. transducer output voltage. (Volts)
    ' AVTPRS : Air pressure at vel. transducer ( Pa )
    ' AIRTEMP : Air inlet temperature ( C )
    '
    ' The returned variables:
    ' AIRFLOW : Air actual flow rate. (m*m*m/sec)
    ' ASUPVEL : Air superficial velocity. (m/sec)
    '
    ' The variables used in this subroutine:
    ' ASVEL : Air standard velocity. (sm/s)
    ' STDPRES : Standard Air pressure. ( Pa)
    ' AVTPRSA : Absolute Air pressure at vel. transducer ( Pa )
    ' STDTEMP : Standard Air temperature. ( C )
    ' AAVEl : Air actual velocity at position where it's
    '         measured. ( m / sec)
    ' ADIAM : Diameter of the air inlet pipe. ( m )
    ' AINAREA : Area of the air inlet pipe. ( m*m )
    ' DIAM : Test section diameter ( m )
    ' AREA : Test section cross-sectional area ( m*m )
    ' RE : Reynolds number based on pipe diameter and
    '      the air actual velocity at the center of pipe

```

```

'      (where it is measured).
'
ASVEL = ASVELV * 12.192
'
' The Air-velocity transducer has a linear output.
' 12.192 (sm/s)/volt.

'Read air flow condition: pressure and temperature.

AVTPRSA = AVTPRS + 101          'Pa absolute.

' The presure and temperature standard conditions under which
' the velocity transducer is calibrated.

STDPRES = 101.33                ' KPa
STDTEMP = 20!                  ' C

' Air actual velocity.

AAVEL = ASVEL * (STDPRES / AVTPRSA) * (AIRTEMP / STDTEMP)

' Find Reynolds number based on actual velocity (where it is
' measured) and pipe diameter. Air kinematic vescosity is
' assumed constant and at 20 C, = 1.51 * 10E-5
'
RE = AAVEL * (1.5 * .0254) / (.0000151#)

IF RE < 2400 THEN AAVEL = AAVEL / 2      ' Laminar flow
IF RE > 2400 THEN AAVEL = AAVEL * .82    ' Turbulent flow

PI = 3.14

'Area of the air inlet pipe. 1.5" ID.
ADIAM = 1.5 * .0254

AINAREA = PI * ADIAM ^ 2 / 4

' Air flow-rate. (m**3/sec)

AIRFLOW = AINAREA * AAVEL

' Cross-sectional area of the test section . (m**2)
DIAM = 1 * .0254                ' 1" ID Test section
AREA = PI * DIAM ^ 2 / 4
' Air superficial velocity . (m/sec)
ASUPVEL = AIRFLOW / AREA
' Return to calling program.
END SUB

'-----
SUB AVERAGEREAD (I, READNGS(), AVERAGE) STATIC

```

```

' This subroutine is to average values passed in an array form.
'
' The passed variables:
'   I : Number of values to be averaged.
'   READNGS : Array of of values to be averaged.
' The returned variables:
'   AVERAGE : Average value of Readings.
'
'   SUM : Sum of the array values.

SUM = 0!

FOR J = 1 TO I

    SUM = SUM + READNGS(J)

NEXT J

AVERAGE = SUM / I

END SUB

```

```

-----
SUB BORDERLINES STATIC
' This subroutine is used to draw a table that will display
' to the user when entering some of the parameters.
' This subroutine is called by INTRODUCTION subroutine.
'
' Draw a horizontal line.
CLS
FOR I = 1 TO 50: LOCATE 1, I: PRINT "-": NEXT I
FOR I = 1 TO 50: LOCATE 3, I: PRINT "-": NEXT I
FOR I = 1 TO 50: LOCATE 5, I: PRINT "-": NEXT I
FOR I = 1 TO 50: LOCATE 7, I: PRINT "-": NEXT I
FOR I = 1 TO 50: LOCATE 9, I: PRINT "-": NEXT I
FOR I = 1 TO 50: LOCATE 15, I: PRINT "-": NEXT I
FOR I = 1 TO 50: LOCATE 17, I: PRINT "-": NEXT I
' Draw vertical lines.
FOR I = 2 TO 16: LOCATE I, 1: PRINT "|". NEXT I
FOR I = 2 TO 16: LOCATE I, 50: PRINT "|": NEXT I
FOR I = 2 TO 14: LOCATE I, 40: PRINT "|": NEXT I
' Draw corners.
LOCATE 1, 1: PRINT "┌"
LOCATE 1, 50: PRINT "┐"
LOCATE 17, 1: PRINT "└"
LOCATE 17, 50: PRINT "┘"
' Draw lines intersection.
LOCATE 3, 1: PRINT "├"
LOCATE 5, 1: PRINT "├"
LOCATE 7, 1: PRINT "├"
LOCATE 15, 1: PRINT "├"

```

```

LOCATE 3, 40: PRINT "├"
LOCATE 5, 40: PRINT "├"
LOCATE 7, 40: PRINT "├"
LOCATE 9, 40: PRINT "├"

```

```

LOCATE 1, 40: PRINT "└"
LOCATE 15, 40: PRINT "└"

```

```

LOCATE 3, 50: PRINT "├"
LOCATE 5, 50: PRINT "├"
LOCATE 7, 50: PRINT "├"
LOCATE 15, 50: PRINT "├"

```

END SUB

```

SUB CJCGET (NC, CJC)

```

```

'CJCGET is designed to read cold junction compensation temperature
'provided by a sensor built in the EXP-16 board.
'Output of CJC channel is scaled at 24.4mV/deg.C. This corresponds to
'0.1 deg.C./bit( 10/4095). Dividing output in bits by 10 yields degrees
C.

```

```

' Note that the CJC channel is connected to DAS-8 channel # 7,
'this could be changed by changing the EXP-16 jumper.

```

```

' The passed variables:
'   NC : Number of readings
' The returned variables:
'   CJC : Cold junction compensation temperature. ( C)

```

```

'Lock DAS-8 to channel #7 (CJC channel selected) using mode 1

```

```

  CH% = 7
'Next get CJC data from this channel using Mode 4

```

```

  CALL SAMPDAT(CH%, NC, VALUE)

```

```

'Change output from volts back to bits

```

```

  CJ% = VALUE * 4095 / 10

```

```

'Change output in bits to real temperature

```

```

  CJC = CJ% / 10

```

```

' Return to calling module.
END SUB

```

```

SUB COUNTER (F, DTS) STATIC

```

```

' This subroutine is designed to perform the following tasks:
'   1 - From sampling rate and duration of scan, calculates total
'       number of conversion.
'   2 - Configure counter number 2 to generate a periodic
'       interrupts to trigger A/D conversions.
'   3 - Load counter number 2.
'   4 - Do multiple conversions and transfer data to DAT%().
'
' In order for this subroutine to run properly, make sure of the
'   following.
'   1 - Counter 2 output (pin 6) must be jumped to the interrupt
'       input (pin 24).
'   2 - IP1 (pin 24) is left open or connected to a logic high
'       level ( 2.4 - 5.0 volts).

'F : Sampling Rate ( samples/sec )./ Output frequency of counter # 2.
'N : Number loaded in the counter.
'   Counter # 2 is driven by 1 MHz clock.
' Counter output frequency = Counter clock rate / N
' F = 1 Mhz / N      or N = 1 / F      (MHz/samples/sec)
'
N = 10 ^ 6 / F

'
' DTS : Duration of scan ( seconds ), Period of time for data
'       scanning.
'
' NC : Total number of conversion .
'       Translate duration in a number of conversions for mode 5
'       Number of conversions = duration x sample rate

NC = F * DTS

' Check if N is within the range of counter # 2, if not
' display a msg and end the program excution.

IF N < 2 OR N > 65535! THEN
  PRINT "Warning! A sample rate of "; F; "is outside the range of
    Counter 2"
  END
END IF

' TSTEP : Time increment (sec ) is the time taken to do one
'         measurement.
'
TSTEP = 1 / F

' Note only counter # 2 has an internal clock input.
'
'--- Step : Configure Couter #
2-----
MODE% = 10                                'Mode 10 for setting counter configuration

```

```

D%(0) = 2           'Operate on counter #2
D%(1) = 3           'Configuration #2 = rate generator
CALL das8(MODE%, VARPTR(D%(0)), FLAG%)
IF FLAG% <> 0 THEN CALL ERRCODES(FLAG%)

```

```

'--- Step : Load Counter # 2
-----

```

```

MODE% = 11          'Mode 11 to load counter
D%(0) = 2           'Operate on counter #2
,
' Correct for integer.
,
IF N < 32767 THEN D%(1) = N ELSE D%(1) = N - 65536!
,
CALL das8(MODE%, VARPTR(D%(0)), FLAG%)
IF FLAG% <> 0 THEN CALL ERRCODES(FLAG%)
,
' At this point counter # 2 is active and producing the selected
' frequency F
' through Pin 6 ( Counter 2 out ). In order to have DAS-8PGA sampling
' at this frequency, Pin 6 should be jumpered to Pin 24, interrupt
' input.
'--- Step : Set mode 5 going and acquire data -----
MODE% = 5           'Mode 5, do conversions direct to array
D%(0) = VARPTR(DAT%(1)) Starting location of array, conversion
                        1 'is in DAT%(1)
D%(1) = NC          'Number of conversions
,
CALL das8(MODE%, VARPTR(D%(0)), FLAG%)
IF FLAG% <> 0 THEN CALL ERRCODES(FLAG%)
,
' Note that the data stored in DAT%( ) array is in the binary form so
' it
' has to converted to voltage.

END SUB

```

```

'-----
SUB ERRCODES (FLAG%) STATIC
,

```

```

' This subroutine gives a summary of the error codes:
' Depending on the problem a message will be displayed to the
' user and the program execution ends here . This subroutine
' will be called only if the passed variable FLAG% is different
' from zero.
' For more information consult the appropriate section in
' the DAS-8PGA User's Manual.

```

```

PRINT " The returned FLAG% = "; FLAG%

```

SELECT CASE FLAG%

```
CASE IS > 19
  PRINT " FLAG% > 19 - Error type not specified..!": END
CASE 1
  PRINT "1: Base address unknown.(I/O location not
    initialized)":
    END
CASE 2
  PRINT "2: Mode number <0 or > 22.": END
CASE 3
  PRINT "3: Invalid base address, < 256 or > 1016.": END
CASE 4
  PRINT "4: Mux scan limits out of range or reversed order,<0 or
    >7.": END
CASE 5
  PRINT "5: Channel number out of range, <0 or >7.": END
CASE 6
  PRINT "6: A/D timeout. Incorrect busy signal from A/D.": END
CASE 7
  PRINT "7: Interrupt level out of range, <2 or >7.": END
CASE 8
  PRINT "8: Mode 8 data transfer parameters out of range.": END
CASE 9
  PRINT "9: Mode 9 data transfer parameters out of range.": END
CASE 10
  PRINT "10: Counter number out of range, <0 or >2.": END
CASE 11
  PRINT "11: Counter configuration number out of range, <0 or
    >5.":
    END
CASE 12
  PRINT "12: Digital output data out of range, <0 or >15.": END
CASE 13
  PRINT "13: Mode 18 trigger channel number out of range <0 or
    >7.": END
CASE 14
  PRINT "14: Mode 18 trigger level out of range, <2048 or
    >2047.":
    END
CASE 15
  PRINT "15: Mode 18 trigger slope not 0 or 1.": END
CASE 16
  PRINT "16: PGA gain codes illegal, <0 or >3.": END
CASE 17
  PRINT "17: PGA function not available (no DAS-8PGA).": END
CASE 18
  PRINT "18: Mode number unavailable for this language.": END
CASE 19
  PRINT "19: Mode 21 not initialized.": END
```

END SELECT

END SUB

SUB INITIALIZE STATIC

'
' This is to initialize DAS-8PGA. Address is
' stored in DAS.ADR file.
,

OPEN "DAS8.ADR" FOR INPUT AS #1
INPUT #1, BASADR%

CLOSE #1
,

FLAG% = 0
MODE% = 0 ' Initialize DAS8-PGA.
CALL das8(MODE%, VARPTR(BASADR%), FLAG%)
' IF FLAG% <> 0 THEN CALL ERRCODES(FLAG%)
,

END SUB

SUB INLTCONDOUT (RUNUMB%, AVTPRS, AINPRS, WINPRS, AIRTEMP, WATTEMP)
STATIC

'
' Subroutine to store both single phases inlet conditions
' ie. pressures and temperatures.
' The variables are defined the same way as in the main program.

OPEN "A:INLTCOND.OUT" FOR APPEND AS #1

FORMAT\$ = " ##### ###.### ###.### ###.### ##.# ##.#

PRINT #1, USING FORMAT\$; RUNUMB%; AVTPRS; AINPRS; WINPRS; AIRTEMP;
WATTEMP

CLOSE #1
CLOSE #2

END SUB

SUB INTRODUCTION STATIC

' This subroutine allows the user to enter all the parameters
' needed to perform a run.

CLS
,

CALL BORDERLINES
,

LOCATE 2, 3

PRINT "Enter run number :"

LOCATE 4, 3

PRINT "Enter fiber probe position :"

LOCATE 6, 3


```

PRINT "Enter photograph number :"
LOCATE 8, 3
PRINT "Enter flow type :"
,
LOCATE 9, 3: PRINT " Enter : B for Dispersed Bubble Flow."
LOCATE 10, 3: PRINT "          P for Plug Flow. "
LOCATE 11, 3: PRINT "          ST for Stratified Flow."
LOCATE 12, 3: PRINT "          W for Wavy Flow. "
LOCATE 13, 3: PRINT "          S for Slug Flow. "
LOCATE 14, 3: PRINT "          A for Annular Flow. "
,
LOCATE 2, 42
INPUT RUNUMB%
LOCATE 2, 42: PRINT " "
LOCATE 4, 42
INPUT POSITION%
LOCATE 4, 42: PRINT " "
LOCATE 6, 42
INPUT PHOTO%
LOCATE 6, 42: PRINT " "
LOCATE 12, 42
INPUT PATTERN$
LOCATE 12, 42
PRINT " "

LOCATE 16, 3: PRINT "Do you wish to continue";
INPUT ANSW$
LOCATE 16, 3: PRINT "
END SUB

```

```

'-----'
SUB LOCKCHN (CH%) STATIC
' This subroutine when called, it locks DAS8-PGA
' to CH% and make sure that the multiplexer is actually
' at that channel.
,
'CH% : is the channel number.
'Lock channel using MODE 1.

    LT%(0) = CH%
    LT%(1) = CH%
,
    MODE% = 1
    CALL das8(MODE%, VARPTR(LT%(0)), FLAG%)
    IF FLAG% <> 0 THEN CALL ERRCODES(FLAG%)
,
'Read the multiplexer channel using mode # 3

    MODE% = 3
    D%(0) = 1
    'read mux channel
    'mux addrflag% = 0

```

```

CALL das8(MODE%, VARPTR(D%(0)), FLAG%)
IF FLAG% <> 0 THEN CALL ERRCODES(FLAG%)

IF D%(0) <> CH% THEN PRINT " Mux chn is different from CH%": END

END SUB

```

```

'-----'
SUB MIXPRSOUT (RUNUMB%, MIXINPRS, MIXMDPRS, MIXEXPRS, MXTEMP) STATIC
,
OPEN "A:MIXPRESS.OUT" FOR APPEND AS #1

FORMAT$ = "      ###      ###.###      ###.###      ###.###      ##.##  '

PRINT #1, USING FORMAT$; RUNUMB%; MIXINPRS; MIXMDPRS; MIXEXPRS;
      MXTEMP

CLOSE #1
CLOSE #2

END SUB

```

```

'-----'
SUB PHASEVELOCITY (CH%, PHAVEL) STATIC

'DYNAMIC
REDIM VALUE(16000), PHVEL(10000)
'STATIC

DISTANCE = .00437
VREF = 1!

' Set the sampling rate at 4000 Samples/sec.
,
F = 4000      'samples/sec

,
' DTS : Duration of scan ( seconds ), Period of time for data
      scanning.
,
DTS = 4
NC = F * DTS

,
,
' TSTEP : Time increment (sec ) is the time taken to do one
      measurement.
,
TSTEP = 1 / F

```

```

' The phase velocity signal is fed to DAS-8PGA through channel # 5.
' Lock DAS-8PGA to channel # 5

    CH% = 5
    CALL LOCKCHN(CH%)

' Note that the data stored in DAT% array is in the binary form so it
' has to be converted to voltage.
,
,
    CALL COUNTER(F, DTS)

' Note in the following loop I starts at 1 since the array pointer was
' set at 1 before using mode 5.
,

' Set counter COUNT to zero.
COUNT = 0
' Set X to zero ; X is to check if a pulse has been detected.
X = 0

J = 1      ' Set starting array of velocity.

FOR I = 1 TO NC

    ' Convert Binary values to voltage.

    VALUE(I) = DAT%(I) * 10 / 4095
    ' PRINT DAT%(I), VALUE(I)
    IF VALUE(I) > VREF THEN
        COUNT = COUNT + 1
        X = 1
    ELSE
        IF X = 1 THEN
            PHVEL(J) = DISTANCE / (COUNT * TSTEP)
            ' PRINT PHVEL(J)
            ' INPUT XE
            J = J + 1
            COUNT = 0
            X = 0
        END IF
    END IF
NEXT I

,
' J-1 is the number of pulses received, the first and the last
values
' of the phase velocities are to be disregarded in case the pulse
' analysis had started or finished half way thru a pulse. This
leaves us with J-3 phase-velocity measurements.
,

```

' Average the (J-3) values of phase velocity during DTS time period.
SUMVEL = 0!

FOR K = 2 TO J - 2
SUMVEL = SUMVEL + PHVEL(K)
NEXT K

PHAVEL = SUMVEL / (J - 3)

END SUB

-----'
SUB PRESSURE (PRSVOLT, PRSPSI) STATIC
' From calibration certificate, the transducer's voltage is 0.2975
' mV/V.psi.
' With 15 VDC power supply, the transducer's slope becomes equal to
' 4.476 mV/psi . ///// !!!! CHANGE
' SLOPE = 60.5 mV / Psi
'
PRSPSI = ((PRSVOLT * 1000) / 8.77) ' KPa

END SUB

-----'
SUB REGIMESMAP (ASUPVEL, WSUPVEL) STATIC
'
IF PATTERN\$ = "B" OR PATTERN\$ = "b" THEN
FILENAIR\$ = "A:BUBFLOW.AIR"
FILENWAT\$ = "A:BUEFLOW.WAT"
END IF

IF PATTERN\$ = "P" OR PATTERN\$ = "p" THEN
FILENAIR\$ = "A:PLUGFLOW.AIR"
FILENWAT\$ = "A:PLUGFLOW.WAT"
END IF

IF PATTERN\$ = "ST" OR PATTERN\$ = "st" THEN
FILENAIR\$ = "A:STRTFLOW.AIR"
FILENWAT\$ = "A:STRTFLOW.WAT"
END IF

IF PATTERN\$ = "W" OR PATTERN\$ = "w" THEN
FILENAIR\$ = "A:WAVYFLOW.AIR"
FILENWAT\$ = "A:WAVYFLOW.WAT"
END IF

IF PATTERN\$ = "S" OR PATTERN\$ = "s" THEN
FILENAIR\$ = "A:SLUGFLOW.AIR"
FILENWAT\$ = "A:SLUGFLOW.WAT"
END IF

```

IF PATTERN$ = "A" OR PATTERN$ = "a" THEN
  FILENAIR$ = "A:ANLRFLOW.AIR"
  FILENWAT$ = "A:ANLRFLOW.WAT"
END IF

```

```

OPEN FILENAIR$ FOR APPEND AS #1
OPEN FILENWAT$ FOR APPEND AS #2

```

```

FORMAT$ = "      ####.####      "

```

```

PRINT #1, USING FORMAT$; ASUPVEL
PRINT #2, USING FORMAT$; WSUPVEL

```

```

CLOSE #1
CLOSE #2

```

```

END SUB

```

```

-----
SUB SAMPDAT (CH%, NC, VALUE) STATIC
' This subroutine is designed to take a sample measurement
' of the specified channel.
  CALL LOCKCHN(CH%)
  CALL ADCONV(CH%, NC, VALUE)

```

```

END SUB

```

```

-----
SUB SCANIVALV (PORT%) STATIC

```

```

' This subroutine sets the scanivalve at the specified port
' and checks if the scanivalve is actually at that port.

```

```

OPEN "\DEV\IEEEOUT" FOR OUTPUT AS #1
OPEN "\DEV\IEEEIN" FOR INPUT AS #2

```

```

PRINT #1, "OUTPUT 15;??"
PRINT #1, "ENTER 15"
INPUT #2, MUXP%

```

```

IF PORT% < MUXP% THEN PRINT #1, "OUTPUT 15;HM"

```

```

SELECT CASE PORT%

```

```

  CASE IS > 6
    PRINT " Error scanivalve port out of range: PORT% = ", PORT%
  CASE 0
    PRINT #1, "OUTPUT 15;00"
  CASE 1
    PRINT #1, "OUTPUT 15;01"

```

```

CASE 2
  PRINT #1, "OUTPUT 15;02"
CASE 3
  PRINT #1, "OUTPUT 15;03"
CASE 4
  PRINT #1, "OUTPUT 15;04"
CASE 5
  PRINT #1, "OUTPUT 15;05"
CASE 6
  PRINT #1, "OUTPUT 15;06"

END SELECT

PRINT #1, "OUTPUT 15;??"
PRINT #1, "ENTER 15"

INPUT #2, MUXP%

IF MUXP% <> PORT% THEN PRINT "Error : scanivalve is not on specified
  port": END

' After setting the scanivalve to the specified port, wait for 3.0
' seconds.

' PRINT #1, "OUTPUT 15;DL99"

CLOSE #1
CLOSE #2
,
TIME$ = "00:00:00"
DELT% = 10
TEND% = TIMER + DELT%
TLOOP:
  IF TIMER < TEND% THEN GOTO TLOOP
END SUB

'-----
SUB SCRNOOUT (ASUPVEL, WSUPVEL) STATIC
,
' This is used to display the data on the computer screen.
,
CLS
LOCATE 1, 1
PRINT "-----"
PRINT USING "Run Number.... : #### ; Photograph No...: ####";
  RUNUMB%; PHOTO%
PRINT "-----"
PRINT "Flow type.....:", PATTERN$
PRINT "-----"
PRINT USING "Ch. No. 0 : Air sup. vel.....   ###.### m/sec.";
  ASUPVEL
PRINT USING "Ch. No. 1 : Water sup. vel.....   ###.### m/sec.";

```

```

      WSUPVEL
PRINT "-----"
PRINT USING "Ch. No. 2-1 : Air Press. @ Trans.... ####.### KPa.";
  AVTPRS
PRINT USING "Ch. No. 2-2 : Air inlet Press..... ####.### KPa.";
  AINPRS
PRINT USING "Ch. No. 2-3 : Water inlet Press..... ####.### KPa.";
  WINPRS
PRINT "-----"
PRINT USING "Ch. No. 2-4 : Mix. Inlet Press..... ####.### KPa.";
  MIXINPRS
PRINT USING "Ch. No. 2-5 : Mix. Press. @ Probe... ####.### KPa.";
  MIXPMDRS
PRINT USING "Ch. No. 2-6 : Mix. Exit Press..... ####.### KPa.";
  MIXPEXRS
PRINT "-----"
PRINT USING "Ch. 6 EXP.No 2: Air temperature..... ###.## Deg.C.";
  AIRTEMP
PRINT USING "Ch. 6 EXP.No 3: Water temperature... ###.## Deg.C.";
  WATTEMP
PRINT USING "Ch. 6 EXP.No 4: Mixture exit temp... ###.## Deg.C.";
  MIXTEMP
PRINT "-----"
PRINT USING "Ch. No 3: Void fraction, Fiber No. 1  ##.#### ";
  VOIDFRC1
PRINT USING "Ch. No 4: Void fraction, Fiber No. 2  ##.#### ";
  VOIDFRC2
PRINT USING "Ch. No 5: Phase velocity..... ###.####
(m/sec)";
  PHASEVEL
PRINT "-----"
END SUB

```

```

'-----'
SUB SUPVELOUT (RUNUMB%, ASUPVEL, WSUPVEL, PATTERN$) STATIC

```

```

  OPEN "A:SUPVELS.OUT" FOR APPEND AS #1

```

```

  FORMAT$ = "      ##      ###.###      ###.###

```

```

  PRINT #1, USING FORMAT$, RUNUMB%, ASUPVEL, WSUPVEL;
  PRINT #1, PATTERN$

```

```

  CLOSE #1
  CLOSE #2

```

```

END SUB

```

```

'-----'
SUB TEMPERATURE (CJC, ATEMPR, WTEMPR, MXTEMPR) STATIC

```

```

  'This subroutine measures air, water and two-phase mixture

```

```

' temperatures. This is performed as follow:
'   1 - Lock DAS8-PGA to EXP-16 channel. ( # 6 in this case )
'   2 - Measure output voltage of thermocouple on EXP-16
'       sub-multiplexer.
'   3 - Measure temperature of connector block from CJC channel.
'   4 - Convert, correct and linearize thermocouple output
'       to degrees
'
' The returned variables:
'ATEMP : Air inlet temperature, thermocouple 1. ( deg. C ).
'WTEMP : Water inlet temperature, thermocouple 2. ( deg. C ).
'MXTEMP : Mixture exit temperature, thermocouple 3. ( deg. C ).
'
' The local variables:
'AV : EXP-16 gain setting. ( see dip switch on EXP-16 board )
'NC : Number of A/D conversions, whenever sub. ADCONV is called.
'ATEMPR : Air thermocouple voltage output. ( Volts )
'WTEMPR : Water thermocouple voltage output. ( Volts )
'MXTEMPR : Mixture thermocouple voltage output. ( Volts )
'
'TC : Interpolated temperature in degrees Centigrade ( C ).
'TF : Interpolated temperature in degrees Fahrenheit ( F ).

AV = 200
NC = 300

' Lock DAS8-PGA to channel that EXP-16 is connected to, here
' it channel number 6. Change to suit.

CH% = 6
CALL LOCKCHN(CH%)

FOR SBCH% = 0 TO 2

' Use mode 14 to set the EXP-16 sub-multiplexer channel.

MODE% = 14
CALL das8(MODE%, VARPTR(SBCH%), FLAG%)
IF FLAG% <> 0 THEN CALL ERRCODES(FLAG%)

' Perform A/D conversion of sub-multiplexer channel.

CALL ADCONV(SBCH%, NC, VALUE)

SELECT CASE SBCH%

CASE 0
ATEMPR = VALUE / AV
CASE 1
WTEMPR = VALUE / AV
CASE 2
MXTEMPR = VALUE / AV

```



```

END SELECT

NEXT SBCH%

' Get cold compensation temperature. CJC ( deg. C )

CALL CJCGET(NC, CJC)

'Call the interpolation subroutine to find T-type thermocouple
' temperature for air, water and the phase mixture.

CALL TEMPINTRP(ATEMPR, CJC, TC, TF)
ATEMPR = TC

CALL TEMPINTRP(WTEMPR, CJC, TC, TF)
WTEMPR = TC

CALL TEMPINTRP(MXTEMPR, CJC, TC, TF)
MXTEMPR = TC

```

```

END SUB

```

```

'-----
SUB TEMPINTRP (VOLT, CJC, TC, TF) STATIC
'
'----- Interpolation routine to find T thermocouple temperature
'Entry variables:-
'   CJC = cold junction compensator temperature in deg. C.
'   VOLT= thermocouple voltage in volts
'Exit variables:-
'   TC = temperature in degrees Centigrade
'   TF = temperature in degrees Fahrenheit
'Execution time on std. IBM P.C. = 46 milliseconds
'Perform CJC compensation for T type

  VT = 1000 * VOLT + .992 + (CJC - 25) * .040667'VT in mV
'
'Find look up element
  ET = INT((VT - SVT) / SIT)
  IF ET < 0 THEN TC = TT(0): GOTO BOUND'Out of bounds, round to
    lower limit
  IF ET > NT - 2 THEN TC = TT(NT - 1): GOTO BOUND'Out of bounds,round
    ' to upper limit
'Do interpolation

  TC = TT(ET) + (TT(ET + 1) - TT(ET)) * (VT - ET * SIT - SVT) /
    SIT 'Centigrade

BOUND: TF = TC * 9 / 5 + 32 'Fahrenheit
END SUB
'-----

```

```

SUB TEMPLOOKUP STATIC
' This subroutine loads the T Type thermocouple lookup
' tables. This data is stored in A:T_TEMP1.DAT. The
' information read from this file are in common shared variables.
'
' NT: Number of data points.
' SIT: Voltage step interval ( mV ).
' SVT: Starting voltage (mV ).
' TT() : T type thermocouple temperature.
'
'
' Open the file where the T type thermocouple data is stored.
'
' OPEN "A:T_TEMP1.DAT" FOR INPUT AS #1
'
' Read values in that file.
'
' INPUT #1, NT, SIT, SVT
' FOR L = 0 TO NT - 1
' INPUT #1, TT(L)
' NEXT L
'
' Close data file and return to calling routine.
'
' CLOSE #1
'
END SUB

```

```

'-----'
SUB VOIDFRACOUT (RUNUMB%, VOIDFR1, VOIDFR2, PHASEVEL, PATTERN$)
    STATIC
    '
    '
    OPEN "A:VOIDFRAC.OUT" FOR APPEND AS #1
    OPEN "LPT1:" FOR OUTPUT AS #2
    '
    FORMAT$ = "      ####      ###.##      ###.##      ###.####"
    '
    PRINT #1, USING FORMAT$; RUNUMB%; VOIDFR1; VOIDFR2; PHASEVEL;
    PRINT #1, PATTERN$
    '
    CLOSE #1
    CLOSE #2
    '
END SUB

```

```

'-----'
SUB VOIDFRACTION (CH%, VOID)
    DIM VOLTG(16000)

```

```

VREF = 1
COUNTH = 0

F = 4000
DTS = 4
NC = F * DTS

'CH% : is the channel number.
'Lock channel using MODE 1.

CALL LOCKCHN(CH%)

/
/
CALL COUNTER(F, DTS)
/
' The number of data collected is equal to NC
/
FOR K = 1 TO NC
    'Convert binary numbers to voltage.
    VOLTG(K) = DAT%(K) * 10 / 4095

    ' Count the high pulses.
    IF VOLTG(K) > VREF THEN COUNTH = COUNTH + 1
NEXT K
/
' Note the total number of pulses is equal to NC.
' COUNTH : Total number of high pulses.

VOID = COUNTH / NC

END SUB

'-----
SUB VOIDISTRBOUT (I, VOID1(), VOID2(), PHSVEL())
/
' Store data for void fraction distribution.
' I: Total number of probe positions.
' K: Position number. (Starting from lower position)
/
OPEN "A:VOIDISTB.OUT" FOR APPEND AS #1

FORMAT$ = "      ###      ###.###      ###.###
          #####      "

PRINT #1, RUNUMB%, PATTERN$
FOR K = 1 TO I
/
PRINT #1, USING FORMAT$; K; VOID1(K); VOID2(K); PHSVEL(K)
/

```

NEXT K

CLOSE #1

END SUB

```
-----  
SUB WATFLOWRATE (WFLOWV, WATFLOW, WSUPVEL) STATIC  
,  
' This subroutine calculates the water flow rate and superficial  
' velocity. The factory calibrated Paddlewheel sensor has a  
' output voltage linear to the water flow rate.  
' The slope of this linear relationship is:  $1.0094 \times 10^{-3}$   
'  $(\text{m}^3/\text{s})/(\text{volt})$   
' Entry variable:  
' WATFLOWV: Paddlewheel sensor voltage output. ( Volts)  
' Returned variables:  
' WATFLOW: Water flow rate.  $(\text{m}^3/\text{s})$   
' WSUPVEL: Water superficial velocity. (m/s)  
,  
' DIAM: Test section inside diameter. (m)  
' AREA: Test section tube cross-sectional area.  $(\text{m}^2)$   
,  
    PI = 3.14  
    DIAM = 1 * .0254  
    AREA = PI * DIAM ^ 2 / 4  
,  
    WATFLOW =  $1.0094 \times 10^{-3} \times \text{WFLOWV}$   
    WSUPVEL = WATFLOW / AREA  
,  
END SUB
```

Appendix D

Experimental procedure

The quality of the data obtained depends to a considerable degree on the experimental procedure. In this experiment the procedure can be divided into two steps: the test rig initial setup and the parameter measurements. The following is the step- by-step sequence required to operate the test rig and to perform the parameter measurement.

Test rig operating instructions

1. Ensure that the air flow rate control valve is in the closed position; valve located before the air-water mixer.
2. Open the air valve located upstream from the air settling chamber.
3. Make sure that there is a sufficient volume of water in the water reservoir; Tap water is filtered into the reservoir; normally a water level of 0.5 m is enough when using the 2.54 cm test section.
4. Set the water by-pass recirculation valve to the open position and the other valve to the closed position.
5. Set both switches of the water pump controller to the ON position. The controller is located in room # 227.
6. Activate the water pump; push button located by the water reservoir in room # 126.
At this point the water should be circulating through the by-pass pipe and back to the reservoir.
7. Slowly open the water flow rate control valve. This allows the water to flow through the test section pipe.
8. Gradually open the air flow rate control valve.

9. To establish different flow regimes, gradually adjust the air and water flow rates.

Instrumentation Setup

1. Turn on laser cooling system and then activate the laser.
2. Power the following equipments: the pressure transducer, the air velocity transducer, the paddlewheel sensor, both photometers and the computer. With the exception of the photometers, which are battery powered, all other equipment can be powered by switching on the two power-bars. Note that the data acquisition system is powered by the computer.
3. Check the water level in the air-water separators. If there is any accumulated water, it should be drained.
4. Check the position of the fibre optic probe.
5. Run the data acquisition program (REGTRANS). The program will collect, reduce, and store the data. Refer to the routine flow-charts and listings for more information about the parameter measurements. The computer will prompt the user for the two-phase flow regime type and the position of the fibre optic probe. The entered information will be stored with the rest of the data.
6. Change the air and/or the water flow rate, relocate the fibre optic probe and run the data acquisition program. It is advisable to set the water flow at a certain rate and vary the air flow rate.

Appendix E

Static pressure measurement system

A.1 Assignments of Scanivalve ports

Port #	Static pressure
0	Atmospheric pressure
1	Static pressure of the air at the AVT location
2	Air inlet static pressure
3	Water inlet static pressure
4	Static pressure at the inlet of the test section
5	Test section static pressure at void measurement location
6	Static pressure at the test section exit

A.2 Scanivalve controlling commands

The following is a summary of the standard ASCII characters used to communicate with the Scanivalve controller via an IEEE488 I/O Board. Refer to the SCANIVALV subroutine in Appendix C, to see how these commands are entered when using Quick-basic software.

ST: Causes the Scanivalve to step to the next port.

HT: Home the Scanivalve, ie. port "00".

PP: Step the Scanivalve to port # "PP", PP is from "00" to "47".

??: This Command is to request the position of the Scanivalve multiplexer.

ER: This command is to request the error status.

- 1- Port no used
- 2- Scanivalve changed position without command
- 4- Command buffer full
- 8- Port number not found in one revolution
- 16- This command is not defined
- 32- Home position error
- 64- Scanivalve time out error

128- Step position error

ES: Enable SRQ, allows device to request service upon completion of any motion request.

DS: Disable SRQ, powered up state for the SRQ line.

DLnn: This command is used to delay the SRQ for n.n seconds after it reaches the specified port.

This list of commands was provided by RECORDING DEVICES company, San Diego.

END

03/03/92

FIN