SGP-TR-181

AN INVESTIGATION OF VOID FRACTION AND DISPERSED-PHASE VELOCITY MEASUREMENT TECHNIQUES

Egill Juliusson

June 2006

Financial support was provided through the Stanford Geothermal Program under Department of Energy Grant No. DE-FG36-02ID14418, and by the Department of Petroleum Engineering, Stanford University

Stanford Geothermal Program
Interdisciplinary Research in Engineering and Earth Sciences
STANFORD UNIVERSITY
Stanford, California
Abstract

Research efforts have been oriented toward investigation of ways to measure enthalpy down hole. These efforts have thus far led to methods applicable for determining the void fraction and dispersed-phase velocity, which are two essential factors required for calculations of flowing enthalpy.

Experiments with temperature, resistivity and optical sensors have been carried out. The resistivity and optical experiments have yielded successful estimates for dispersed-phase velocity. Measurements based on temperature have not as of yet proven to be successful. Bulk estimates of void fraction based on impedance of two-phase flow surrounding parallel plates have also been investigated and revealed somewhat promising results.
Acknowledgments

This research was conducted with financial support to the Stanford Geothermal Program from the US Department of Energy under grant DE-FG07-02ID14418, the contribution of which is gratefully acknowledged.

Additional acknowledgements go to The William J. Fulbright Fund and The Icelandic National Power Company (Landsvirkjun) which have contributed to this research by student financial aid.

Finally, I would like thank for all of the wise and insightful advice from my research advisors Professor Roland Horne and Senior Research Engineer Kewen Li.
Contents

Abstract ............................................................................................................................... v
Acknowledgments ........................................................................................................... vii
Contents ............................................................................................................................. ix
List of Tables ..................................................................................................................... xi
List of Figures .................................................................................................................. xiii
1. Introduction .................................................................................................................. 1
2. Background and Motivation ...................................................................................... 3
3. Theory ........................................................................................................................... 7
   3.1. Enthalpy of Static and Flowing Fluids ............................................................... 7
   3.2. Measurements in Two-Phase Flow ...................................................................... 9
      3.2.1. Void Fraction ............................................................................................. 9
      3.2.2. Dispersed-Phase Velocity ...................................................................... 11
      3.2.3. Continuous Phase Velocity ..................................................................... 12
   3.3. Enthalpy from Wellbore Simulators ................................................................. 13
4. Experiments .................................................................................................................. 15
   4.1. Phase Discrimination Sensors .......................................................................... 15
      4.1.1. Test Loop .................................................................................................. 15
      4.1.2. Optical Sensor ........................................................................................ 16
      4.1.3. Resistivity Sensor .................................................................................... 18
      4.1.4. Temperature Sensor ................................................................................ 19
      4.1.5. Measurement and Power Circuit for Sensors ......................................... 21
   4.2. Bulk Impedance Sensor ..................................................................................... 22
      4.2.1. Test Flow Loop ........................................................................................ 22
      4.2.2. Impedance Probe ..................................................................................... 24
5. Data Analysis and Results ......................................................................................... 26
   5.1. Phase Discrimination Sensors .......................................................................... 26
      5.1.1. Bubble Velocity ....................................................................................... 26
      5.1.2. Void Fraction and Bubble Geometry ....................................................... 29
         5.1.2.1. Bimodal Histogram Threshold ......................................................... 30
         5.1.2.2. Moving Average Threshold ............................................................. 32
      5.1.3. Crosstalk .................................................................................................. 34
   5.2. Void Fraction from Bulk Impedance Measurements ......................................... 36
6. Conclusions .................................................................................................................. 43
Nomenclature .................................................................................................................... 45
References................................................................................................................................. 47
Appendices...................................................................................................................................... 49
  A.  LabView Program for Phase Discrimination Sensor Experiment................................. 49
  B.  LabView Program for Bulk Impedance Sensor Experiment............................................ 53
  C.  MATLAB Codes for Phase Discrimination Data Analysis ............................................. 55
  D.  MATLAB Codes for Bulk Impedance Data Analysis....................................................... 63
List of Tables

Table 5-1: Summarized results for calculated bubble flow properties from Pilot test 1. . 33
Table 5-2: Summarized results for calculated bubble flow properties from Pilot test 2. . 33
Table 5-3: Summarized results for calculated bubble flow properties from Pilot test 3. . 33
Table 5-4: Reference results given by the flow meter. ..................................................... 34
List of Figures

Figure 2-1: $P$-v-$T$ relations for a substance ................................................................. 4
Figure 3-1: Segmented air water flow ................................................................. 10
Figure 3-2: Average void fraction profile integrated over the whole cross section to obtain the flow rate ................................................................. 11
Figure 4-1: A schematic of the experiment setup .................................................... 15
Figure 4-2: An explanation of the setup of the phototransistor and light source in the 1/8 in diameter test loop ................................................................. 17
Figure 4-3: The photograph shows the 1 inch inner diameter tube with a phototransistor and laser pointer directly opposite one another ........................................ 18
Figure 4-5: A simple representation of the electrode sensors in the 1/8 inch diameter flow loop ................................................................................................. 19
Figure 4-6: The fine gage thermocouples protruded into the segmented air-water flow stream ................................................................................................. 20
Figure 4-7: A photograph of the LED, electrodes and thermocouple all glued into a brass fitting ................................................................................................. 21
Figure 4-8: A circuit diagram for the phototransistor and resistivity sensors .............. 22
Figure 4-9: A schematic diagram of the flow loop used for the bulk impedance experiment ................................................................................................. 23
Figure 4-10: Cross section of a wellbore with an in-situ probe that consists of an electrode made of two brass plates ................................................................. 24
Figure 4-11: A photograph of the bulk impedance probe inside the artificial well pipe .. 25
Figure 5-1: Signals obtained from the resistivity and optical sensors ......................... 27
Figure 5-2: Signals from the resistivity and optical sensors ......................................... 27
Figure 5-3: Signals from the resistivity and optical sensors ......................................... 28
Figure 5-4: This graph of $R_{s1,s2}(t)$ for each sensor type ........................................ 28
Figure 5-5: This graph of $R_{s1,s2}(t)$ for each sensor type ........................................ 29
Figure 5-6: A histogram of measurements made with phototransistor 1 ................. 31
Figure 5-7: A histogram of measurements made with resistivity sensor 1 ....................... 31
Figure 5-8: A moving average threshold used to determine whether the signal from a phototransistor corresponds to air or water................................................................. 32
Figure 5-9: A moving average threshold used to determine whether the signal from a resistivity sensor corresponds to air or water................................................................. 32
Figure 5-10: Schematic diagram of the resistivity sensor circuit, including the cross electrode resistors $R_{e12}$ and $R_{e21}$ ................................................................. 35
Figure 5-11: The cross-correlation between the lagging signal ($S_2$) and the difference between the leading and the lagging signal ($\Delta S = S_1 - S_2$) .............................................. 36
Figure 5-12: Impedance probe modeled as a variable resistor and capacitor in parallel .. 36
Figure 5-13: Correlation between the void fractions as inferred from a differential pressure measurement versus the impedance measurement ............................................ 38
Figure 5-14: An example of the differential pressure measurements taken to obtain a single bulk average value of the void fraction. ................................................................. 39
Figure 5-15: An example of the impedance measurements taken to obtain a single bulk average value of the void fraction ................................................................................... 39
Figure 5-16: A plot of the flow rate ratio versus the void fraction as estimated from the impedance measurement................................................................. 40
Figure 5-17: A plot of the flow rate ratio versus the void fraction as estimated from the differential pressure measurement................................................................. 40
Figure 5-18: A plot of the flow rate ratio versus the void fraction as estimated from the measured resistance ................................................................................... 41
Figure 5-19: A plot of the flow rate ratio versus the void fraction as estimated from the reactance ................................................................................... 41
Figure A-1: A screen capture of the front panel of the program developed in LabView for data acquisition from the phase discrimination sensors................................. 49
Figure A-1: The back panel of the program developed in LabView for data acquisition from the phase discrimination sensors ................................................................. 51
Figure A-3: A screen capture of the front panel of the program developed in LabView for data acquisition from the bulk impedance sensors ................................................................. 53
Figure A-1: The back panel of the program developed in LabView for data acquisition from the bulk impedance sensors.......................................................................................................................... 54
Chapter 1

1. Introduction

Downhole measurement of enthalpy in geothermal wells is a topic of interest to the industry for several reasons. For example, measuring enthalpy down hole would lead to more accurate estimates of the flowing enthalpy in the reservoir, especially at early times after well completion. Moreover, abrupt changes in the enthalpy profile would help to reveal fractures and to quantify the energy output from each fracture directly.

Measuring enthalpy down hole is very challenging and is related to the problem of measuring flow rates over a range of flow regimes in two-phase flow. The problem is further complicated by the fact that the measurement must be done in-situ and the sensor must be able to function at temperatures up to 350°C. At this temperature, most electronics will fail. Hence, either a nonelectronic solution must be found or the electronics must be specially designed to survive the downhole environment. Successful gauges have been designed for temperature, pressure and spinner measurements, where the electronics are either contained in a vacuum flask and thereby isolated from the heat, or built from a limited array of expensive nonstandard high-temperature resistant components. Recent developments of optical fiber technology have brought new ways to measure pressure and temperature down hole but optical sensors to quantify flow rate or void fraction are not yet available commercially.

A direct measurement of the enthalpy rate of a two-phase flow would require knowledge of the temperature and flow rate of both phases. In practice it has proven difficult to develop sensors that can predict the flow rates of each phase accurately in a two-phase flow over all flow regimes. Hence, the focus of this research project has been reduced to looking at ways to measure the void fraction and flow rate of one of the phases, over a limited range of flow regimes. This means that we are only working on one piece of the
problem, but hopefully this piece will help to reveal plausible ways of solving the whole task.
Chapter 2

2. Background and Motivation

Through the centuries, warm geothermal water has been used for bathing and washing. Around the beginning of the 19th century further awareness of potential utilization of this energy resource awoke. One of the earliest geothermal district heating systems was built in Idaho around the year 1900 and the first geothermal power plant for electricity was erected in Larderello, Italy, in 1904 (Pálmason, 2005). Since then, a vast amount of geothermal energy has been harnessed and much research has been focused on better understanding of the underlying energy source.

In geothermal power production, 1-3 km deep wells are drilled into the earth at places with unusually hot groundwater flow (geothermal reservoirs). The hot fluid (water and steam) is brought up to the surface, separated and used to drive a steam turbine which generates electrical power. In this process, energy is mined from the hot reservoir rock and carried by the geothermal fluid to the turbine. The energy carried by the fluid is conveniently quantified in a property called enthalpy. The enthalpy of a system is a property that defines the combination of energy stored as heat and energy stored by compression. In mathematical terms, the usual definition is (per unit mass):

\[ h = u(T) + Pv \quad 2.1 \]

Where \( u(T) \) is the internal energy of the system per unit mass and is dependent on temperature, \( T \). The pressure is denoted by \( P \) and \( v \) is the specific volume. Enthalpy is a thermodynamic property and can therefore be found from \( P-v-T \) relations given two of the parameters \( P, v \) and \( T \). At static, single-phase conditions it is in most cases easiest to evaluate \( P \) and \( T \), however at saturation conditions (two-phase) the temperature and pressure become fixed with respect to one another. Hence, the specific volume, \( v \), or
some parameter that can be related to the specific volume must be determined to obtain the enthalpy.

Figure 2-1: \( P-v-T \) relations for a substance. At saturation (vapor-liquid) conditions \( P \) and \( T \) become fixed with respect to one another. (http://hyperphysics.phy-astr.gsu.edu)

When a new geothermal well is drilled, it is usually tested in a discharge test to determine how the flow from the well varies with well head pressure. During this test the discharge enthalpy is also measured, most commonly by a method called the tracer dilution method. The tracer dilution method is quite cumbersome and is typically performed only once a year. A resistivity correlation technique, recently developed by Spielman (2003, 2006), has shown that relatively good estimates of the enthalpy can be obtained in the annular and dispersed flow regimes. This method has a simple implementation and provides continuous enthalpy estimates, which makes it especially convenient for steam quality monitoring and optimization of well production rates. However, both of these methods are designed for surface applications.

Direct measurement of the enthalpy down hole would be advantageous for several reasons. Firstly, during the evaluation stage of a project, it would be feasible to determine the reservoir enthalpy without having to conduct a long term flow test in order to heat up
the entire wellbore, a process that can take several weeks. A second use would be the ability to measure the enthalpy at any given depth of the well. This could be used to verify results from wellbore flow simulations, thereby helping to improve reservoir modeling techniques. In relation to this it might be interesting to see if and where fractures carrying hot or cold water cross the well and how the enthalpy is affected by those entries. Thirdly, comparing the downhole enthalpy to the surface enthalpy could be useful in estimating the effects of wellbore heat losses if one wanted to make a more comprehensive model of the reservoir status.

To estimate the enthalpy of a flowing two-phase fluid, the contribution delivered by each flowing phase must be considered. To be able to determine this, the flow rate of each phase must be known (in addition to the temperature or pressure). In vertical flow the presence of buoyancy and frictional forces greatly complicates the relation between the velocities of the two phases. Some empirical relations have been suggested, e.g. by Hughmark and Pressburg (1961) for a certain range of pipe diameters (0.4 to 2.34 inches). Obviously this type of relation would be very useful because only the velocity of either phase and the void fraction would have to be measured. However, since the relation is empirical and has not been validated for all practical cases, it should be used with caution.
Chapter 3

3. Theory

3.1. Enthalpy of Static and Flowing Fluids

In geothermal applications the enthalpy is carried by water. Hence, enthalpy can be established by use of the steam tables. For example, given either pressure or temperature at static saturation conditions and the vapor phase mass fraction, the enthalpy can be calculated from

\[ h_{\text{static}} = x h_g + (1 - x) h_l \]  \hspace{1cm} 3.1

Where \( h_g \) is the enthalpy of the saturated vapor, \( h_l \) is the enthalpy of saturated liquid at the given saturation temperature or pressure and \( x \) is the vapor phase mass fraction.

\[ x = \frac{m_g}{m_g + m_l} \]  \hspace{1cm} 3.2

Where \( m_g \) and \( m_l \) are the mass of the vapor and liquid phase, respectively.

Now consider estimating the enthalpy in steam-water two-phase flow. In this case one must account for the fact that the two phases might be traveling with different velocities and at different flow rates. The enthalpy of the flowing fluid is then described by

\[ h_{\text{flowing}} = \frac{W_g h_g + W_l h_l}{W_g + W_l} \]  \hspace{1cm} 3.3

Where \( W_l \) and \( W_g \) are the liquid and vapor mass flow rates, respectively. In the reservoir some of the fluid will be immobile and the two phases will impede each other in flowing through the porous media. This behavior is described by a parameter called relative permeability, which is usually described by a function specific to the type of reservoir.
rock and the fluid/phase in question. By use of Darcy’s law for flow through porous media, Equation 3.3 can be rewritten as

\[ h_{\text{flowing}} = \frac{k_{rg}}{v_g \mu_g} h_g + \frac{k_{rl}}{v_l \mu_l} h_l \]

Where \( k_r \) denotes relative permeability and \( \mu \) denotes dynamic viscosity.

When measuring down hole, this is the enthalpy that we want to estimate. In the flowing wellbore we can assume that all of the fluid is in fact flowing but we should still consider the fact that the two phases are impeding each other as they flow up the wellbore. This effect is quantified by a parameter called the void fraction (or liquid hold-up in liquid-liquid flows) and is much like the relative permeability, difficult to estimate. By knowing the void fraction and the velocity of each flowing phase one can estimate the mass flow rate of each phase. Rewriting Equation 3.3 as

\[ h_{\text{flowing}} = \frac{\alpha \rho_g u_g h_g + (1 - \alpha) \rho_l u_l h_l}{\alpha \rho_g u_g + (1 - \alpha) \rho_l u_l} \]

it is clear that as an alternative to measuring each flow rate, one can measure the velocity of each phase \((u_g, u_l)\) and the void fraction

\[ \alpha = \frac{A_g}{A_g + A_l} \]

Where \( A_g \) and \( A_l \) denote the average cross sectional area of the wellbore occupied by gas and liquid, respectively. The void fraction should actually be a volume ratio but, looking at a relatively thin slice of the wellbore where the change in flow pattern is negligible, this definition should hold.
3.2. Measurements in Two-Phase Flow

In this research project, a few different techniques were tested to obtain parameters describing two-phase flow. The following subsections will discuss the most important of these parameters for enthalpy evaluation, i.e. void fraction, dispersed phase velocity and continuous phase velocity. The discussion on continuous phase velocity is more qualitative because no attempt was made to measure that parameter directly in this research.

3.2.1. Void Fraction

To describe the flow of two distinct phases it is useful to define the local dispersed-phase density function

$$\gamma(r, t) = \begin{cases} 
1 & \text{if } r \text{ is in the disperse phase at time } t \\
0 & \text{otherwise}
\end{cases}$$

3.7

For a stationary measurement, the localized void fraction can be defined by

$$\alpha(r) = \lim_{t \to \infty} \left( \int_0^t \gamma(r, \tau) d\tau / t \right)$$

3.8

For a sufficiently long measurement time ($t_{tot}$) Equation 3.8 can be approximated by

$$\alpha(r) = \sum \frac{t_g}{t_{tot}}$$

3.9

Where $\sum t_g$ is the total time the dispersed phase was present at measurement point $r$. This is the form normally used for experimental purposes and was the basis for the void fraction estimates made in this investigation.
Figure 3-1: In segmented air water flow (i.e. that the water and air velocities are the same), the local void fraction measurements can be used to calculate overall flow rate ratio. Moreover, the dispersed-phase velocity can be estimated from the travel time estimated by the shift in signal measured by sensor 1 and sensor 2. See further discussion in Section 3.2.2.

Some of the experiments made dealt with segmented flow (Figure 3-1) where the bubble geometry could be modeled as a cylinder of diameter equal to the tubing diameter and length $L_{b,i}$ which could be calculated from

$$L_{b,i} = u_b t_{b,i} \quad 3.10$$

where $u_b$ is the bubble velocity (as obtained from Equation 3.12) and the $t_{b,i}$ is the time it took bubble number $i$ to pass the sensor.

Several papers have been published on local void fraction estimates utilizing sensors of varying basic functionality. Studies using resistivity based techniques were for example carried out by Liu and Bankoff (1993b) and Van der Welle (1985). Investigations using
hot-wire anemometry were also investigated by Liu and Bankoff (1993a) and more recently by Hamad and Bruun (2000). Finally, optical probe methods have been researched e.g. by Morris (1987), Cartellier (1992) and Hamad et al. (1997).

3.2.2. Dispersed-Phase Velocity

The velocity of the dispersed phase is another quantity that is closely related to estimation of enthalpy. The dispersed phase can either be the gas bubble or a liquid drop traveling through the respective continuous phase. By measuring this velocity, an estimate of either $u_g$ or $u_l$ in Equation 3.5 can be obtained. If, in addition, the void fraction profile and total cross sectional area are known, the mass flow rate of gas can be found from (assuming a radially symmetric, circular cross sectional area)

$$W_g = 2\pi \rho_g \int_0^R \alpha(r) u_g(r) r dr$$

Where $R$ is the total well radius, $\rho_g$ is the density of the gas phase and $u_g(r)$ is the measured velocity profile. A similar relationship applies if liquid is the dispersed phase.

A common and effective method of measuring dispersed-phase velocity using vapor-liquid discrimination sensors is to measure signals at two separate locations along the same stream line. The distance between the sensors ($L$ in Figure 3-1) is kept small and, by observing a characteristic signal as a bubble/drop passes, the travel time can be estimated. This way the dispersed-phase velocity can be found from
\[ u_g = \frac{L}{t_{t,g}} \]  \hspace{1cm} 3.12

Where \( t_{t,g} \) is the bubble travel time, estimated by the time shift in the characteristic signal. In many practical cases, the travel time cannot be easily estimated by eye since multiple particles will be passing the sensor during the measurement interval \( t \) and a pattern can not be readily identified. To solve this, it is useful to plot the cross-correlation function between the two measurements. The cross-correlation function describes the correlation between the signal measured by one sensor and the time shifted signal obtained by the other sensor. It is defined as

\[ R_{S_1,S_2}(\tau) = \frac{1}{t_{tot}} \int_0^{t_{tot}} (S_1(t-\tau) - \overline{S_1})(S_2(t) - \overline{S_2}) dt \]  \hspace{1cm} 3.13

Where \( S_1 \) and \( S_2 \) are the measured signals as a function of time and \( \tau \) is the time shift in \( S_1 \). The overbar denotes an average of the signal over the entire measurement interval. A global maximum of this function will occur at the time shift that gives the maximum correlation between the signals. This time shift is the dispersed-phase travel time, \( t_t = \tau_{\text{max}} \).

The cross-correlation method is described in the textbook “Multiphase Flows with Droplets and Particles” by Crow, Sommerfeld and Tsujinaka. The method is claimed to work well for flow metering with concentration signals that are stochastic in nature. This is most often the case in turbulent two-phase flows. The cross-correlation method has for example been applied successfully in two-phase flow applications by Hamad et al. (2000) for optical probe sensors and by Zenit et al. (2003) using impedance based sensors.

### 3.2.3. Continuous Phase Velocity

Continuous phase velocity measurements in two-phase flow can be made in several ways. Most of these methods have initially been used for wind measurement, i.e. anemometry. A commonly used tool in geothermal applications is the spinner, which consists of an impeller wheel that is mounted on a wireline gauge. A useful property of this device derives from the fact that by measuring the spinner velocity both on the way up and down
the well, one can eliminate the relevance of the well diameter. This would otherwise cause problems because most geothermal wells have a slotted liner, which prevents accurate estimates of the actual well diameter to be obtained. Attempts have been made to infer both the continuous and dispersed-phase flow rates by this method in two-phase flow. However, those efforts have in most cases brought poor results, especially in turbulent flow.

Another viable method is hot-film anemometry. Hot-film anemometry is based on the cooling effect of a fluid flowing passed a high temperature metal film. The film is usually very small in diameter (~0.05mm) and will have resistance proportional to its temperature. Since the relationship between resistance and temperature in the film is known for static conditions, the heat flux to the surrounding fluid can be inferred and thereby the fluid velocity. These types of sensors have proven very efficient for measurement in turbulent flows. A method based on the same principle of heat transmission (but by heating of a cool fluid) gave relatively promising results in a study for direct enthalpy measurement at surface conditions made by James et al. (1985).

Finally, laser anemometry through optical fiber is an option worth investigating. The principle of this method is to focus two laser beams on a spot slightly upstream of the anemometer. Any entrained particles in the flow passing through in the focal region of the laser beams scatter a small amount of the transmitted laser light backwards to the laser anemometer. These particles are assumed to have the same velocity as the phase that carries them. The velocity of the entrained particles introduces a Doppler shift in the frequency of the backscattered laser light which in turn allows the phase velocity to be determined (http://www.dantecdynamics.com/LDA/Princip/Index.html).

3.3. Enthalpy from Wellbore Simulators

At present, downhole enthalpy is usually estimated using wellbore simulators. In that process a prior estimate of the number and position of fractures is needed. This is normally obtained from gradient changes in temperature profiles measured in the well just after drilling is completed (i.e. when the wellbore is still relatively cold). When the
fractures have been identified, an estimate of the flow and enthalpy of the fluid coming out of each fracture needs to be given. Temperature and pressure profiles for the well can then be calculated using the wellbore simulator. The flow and enthalpy from each fracture are finally determined by the values that give the best match between the measured and calculated temperature and pressure profiles. In many cases the solution to this problem is nonunique. Therefore, an estimate of a single additional parameter (say void fraction or gas flow rate) could help to solve the problem uniquely and improve the estimate of the downhole enthalpy.

In summary, to be able to determine the rate of enthalpy of a flowing fluid directly at saturation conditions one needs to measure either temperature or pressure, void fraction and both the velocity profile of the vapor phase and the liquid phase. Alternatively, indirect estimates of downhole enthalpy from wellbore simulations might be further constrained given measurements of only a few of these parameters.
Chapter 4

4. Experiments

4.1. Phase Discrimination Sensors

Experiments testing the applicability of using temperature, resistivity and optical sensors to detect the difference between liquid and vapor were carried out. Following is a description of each of the sensors and the test loop.

4.1.1. Test Loop

The phase discrimination tests were performed in a simple setup of air-water flow through pipes of two different kinds, a 1/8 inch inner diameter brass pipe and a 1 inch inner diameter plexiglas pipe. A schematic diagram of the flow loop is shown in Figure 4-1.

Figure 4-1: A schematic of the experiment setup. A vertical air-water flow is investigated by three types of sensors. A simple flow meter then measures the flow rate of each phase separately.
The figure shows how a mixed air-water flow (flowing vertically upwards) passes three types of sensors, at three different locations. At locations 1 and 2 an optical, temperature and resistivity measurement was made. At location 3 a temperature measurement was made in the experiments involving the 1/8 inch diameter tube, but no measurement was made at this location for the 1 inch tube. After the fluid mixture passed the sensors it was separated and the quantity of each phase was measured over a specific time interval to find the individual flow rates. In retrospect, the air accumulator should have been placed in front of the water accumulator in order to improve the measurement estimates made by this simple flow meter.

This basic apparatus was used with the two different pipes. First the 1/8 inch diameter brass pipe was used, in which segmented air-water flow could be assumed. Later, the 1 inch plexiglas tube was used such that a single, fully-formed, bubble could flow through the cross section. In this case the length of the tube compared to the sensor spacing was quite short, which lead to the bubble pattern changing significantly on the way from one sensor to the other. Therefore the results for the 1 inch tube were used more qualitatively to assess the applicability of using one sensor type versus the other for phase discrimination.

### 4.1.2. Optical Sensor

The optical sensor was based on a technique similar to the FFRD (fractional flow ratio detector) developed by Chen et al. (2004). It consisted of a phototransistor on one side of the tube and a light source on the opposite side. When a bubble passed the sensor, a different amount of light got through, there by changing the resistance measured across the phototransistor.
Two types of phototransistors were tested, types NTE3032 and NTE3037, both available from NTE Electronics. The NTE3032 showed a slightly sharper response signal and was therefore determined more applicable. The light source used in the 1/8 inch tube flow loop was a light emitting diode (LED) which was glued into the side of the pipe. For the 1 inch tube the light from the LED was not concentrated enough so a laser pointer was used instead. The laser pointer was not water proof but was made so by placing a layer of thin, transparent duct tape over the lens. This treatment did not affect the concentration of the laser beam in a significant manner. Both the LED and laser pointer were available from a local retail store (Fry’s Electronics). Figure 4-3 shows the setup of the laser pointers and phototransistors. A third phototransistor is seen directly below the laser pointer on the right. This third phototransistor was placed there in an attempt to catch a reflective signal as a bubble passed but that did not prove successful.
4.1.3. Resistivity Sensor

A resistivity sensor was made by fixing two electrodes a small distance apart. The electrodes consisted of two open ended wires. Approximately 5 mm of the insulator on each end was removed and the two segments glued together such that the spacing between the electrodes was about 2 mm. A photograph of the probe is seen in Figure 4-4.
When the sensor was placed in the flow path the voltage drop across the electrodes would depend on the resistivity of the surrounding medium. A simplified diagram of the sensor arrangement is shown in Figure 4-5.

Figure 4-5: A simple representation of the electrode sensors in the 1/8 inch diameter flow loop.

4.1.4. Temperature Sensor

Temperature was measured with a thermocouple. The foremost selection criterion was to choose a thermocouple with an adequately short response time. Hence, the finest gage thermocouple available from Omega Engineering (type: 5TC-TT-T-40-36) was used. The specified response time for the thermocouple was ~20 milliseconds. The arrangement is shown in Figure 4-6.
Figure 4-6: The fine gage thermocouples protruded into the segmented air-water flow stream.

All three types of sensors were placed in the flow loop at the same location. Figure 4-7 shows the how the thermocouple, electrode and LED were all fit into the brass pipe by gluing each component into a brass fitting. The phototransistor was placed in a similar fitting that came in on the opposite side of the pipe.
4.1.5. Measurement and Power Circuit for Sensors

A schematic diagram of the circuit powering the resistivity and optical sensors is shown in Figure 4-8. The resistance across the electrode and phototransistor depended on the medium flowing passed the sensors. To measure this resistance, a reference resistor was connected in series with the electrode/phototransistor. Hence, the characteristic signal could be found by measuring the voltage drop across this reference resistor. The reference resistor for the electrodes was 0.5 MΩ and for the phototransistors it was 0.5 kΩ. A single 12 V DC power supply was used for the whole circuit. Proper grounding of the anode of the power source (not shown in Figure 4-8) was essential to eliminating noise in the measurements. The terminal block and data acquisition (DAQ) card used were of type NI-SCB-68 and NI-6281, respectively. Both were available from National Instruments. The NI-DAQmx driver used for the DAQ card was available from the National Instruments website (www.ni.com).
Figure 4-8: A circuit diagram for the phototransistor and resistivity sensors. As the diagram shows, a single 12 V DC source drives the whole circuit.

The data acquisition program was developed in LabView. The program was capable of logging all seven sensors simultaneously at 1 kHz and wrote the results to a scaled binary output file. The output file was then decoded in MATLAB for further data processing. Each test run was logged for approximately 10 seconds.

Some problems were encountered because of 60 Hz electrical noise in the measurements. Grounding the power source made a particularly large difference in that respect but nevertheless the noise in the temperature signal was never reduced to less than ±0.5°C. Moreover, there were some issues regarding crosstalk between the two resistivity sensors i.e. a fluctuation in the signal from sensor 1 was sometimes seen at the same time in sensor 2. This phenomenon is discussed further in Section 5.1.3.

4.2. Bulk Impedance Sensor

An experiment based on a technology similar to that developed by Spielman (2003) for void fraction measurements at surface conditions was designed. A series of measurements of the bulk impedance of mixed air-water flow were made in a full size artificial well.

4.2.1. Test Flow Loop

The artificial well was 5.5 inches in inner diameter and 2 m tall, made of plexiglas and had adjustable air and water flow rates. The water was circulated by a pump capable of
pumping up to 150 lb/min (~2.40 cu.ft./min) and air was supplied from an in-house compressed air system and capable of supplying up to 5 SCFM (standard cubic feet per minute). A flow mixer was placed at the bottom of the artificial well such that the flow would be more homogeneous. The water flow rate was measured by a digital flow meter and the air flow rate was measured by a rotameter. As reference for the void fraction, the differential pressure between two heights in the water column was measured using a pressure transducer and logging to LabView every 70 milliseconds. Assuming that the frictional pressure drop is negligible (the pipe is relatively large in diameter and very smooth) the reference void fraction could be calculated from the relation

\[
\alpha = \frac{\Delta P}{g \Delta h (\rho_l - \rho_g)}
\]

Where \( g \) is the gravity constant, \( \Delta P \) is the measured pressure difference and \( \Delta h \) is the height difference between the two pressure gauges. A schematic of the flow loop is shown in Figure 4-9.

![A schematic diagram of the flow loop used for the bulk impedance experiment.](image)
4.2.2. Impedance Probe

The impedance probe was designed to be in a form similar to many of the wireline gauges developed for the petroleum industry. Two electrodes consisting of thin copper plates, (approximately 1 mm thick and 2 cm by 4 cm in area) were mounted on the outside of a 1.5 inch outer diameter plexiglas pipe. Electrical wires were connected to the plates using conductive epoxy and brought up through the inside of the plexiglas probe. The conductive epoxy used to attach the wire to the plate was not completely resistant to water and therefore a thin line of sealant was applied to the edges of the plates. This effectively isolated the inside of the probe from the water. The probe electrodes were placed approximately 1.2 m above the flow mixer. The electrode design is roughly sketched in Figure 4-10.

![Figure 4-10: Shown is a cross section of a wellbore with an in-situ probe that consists of an electrode made of two brass plates (brown). The resistance across the electrode depends on the void fraction in the wellbore.](image)

The wires leading from the probe electrodes were connected to an LCR (Inductance (L), Capacitance (C), Resistance (R)) meter (type: Quadtech Digibridge LCR1715) from which data was logged using LabView. The LCR meter used a 1 kHz alternating...
excitation current and was set to measure the impedance and the phase angle at 70 millisecond intervals.

A photograph of the probe inside the artificial well pipe is shown in Figure 4-11. The two brass plates are shown and their connection to the blue and red wire which lead to the impedance meter. A protruding aluminum pipe which leads to one end of the differential pressure transducer is seen on the right.

Figure 4-11: A photograph of the bulk impedance probe inside the artificial well pipe.

Experiments were run with water flow rate ranging from 0 to 150 lb/min and air going from 0 to 5 SCFM. A large number of measurements (usually 100-1000) were taken at each given flow condition, since the goal was to estimate the bulk average void fraction in the flow path. Then the average of these measurements was computed and used as the bulk estimate.
5. Data Analysis and Results

5.1. Phase Discrimination Sensors

The phase discrimination sensors could be used to acquire local estimates of the void fraction and the bubble velocity. In addition to that, estimates of the number of bubbles passing and the bubble length were obtained.

5.1.1. Bubble Velocity

An estimate of the bubble velocity was obtained using the phase discrimination sensors and the methods described in Section 3.2.2. The travel time, $t_r$, was estimated using the cross-correlation technique (Equation 3.12) and from that estimate the mean bubble velocity was calculated by Equation 3.11. For slow and dispersed bubble flow (Figure 5-1) the travel time was easily estimated visually by looking at the signals but when the bubble flow became more rapid (Figure 5-3) the pattern in the signal became harder to discern and the usefulness of the cross-correlation technique became more apparent.
Figure 5-1: Signals obtained from the resistivity and optical sensors at two different locations. The bubble flow was relatively slow and dispersed. Hence a bubble pattern is clearly detectable and the time shift can be estimated visually. This will be referred to as Pilot test 2.

Figure 5-2: Signals from the resistivity and optical sensors. As seen by comparison to the signals in Figure 5-1, the bubble flow is getting more rapid and the pattern is now harder to discern. This will be referred to as Pilot test 1.
Figure 5-3: Here the response from the same sensors as used previously is seen, but now the bubble flow is much more rapid. The bubble pattern is very hard to discern. This will be referred to as Pilot test 3.

The cross-correlation function was computed for each of the signals and the results for Pilot test 2 and 3 are shown in Figure 5-4 and Figure 5-5.

Figure 5-4: This graph of $R_{S1,S2}(\tau)$ for each sensor type (test corresponding to Figure 5-1) shows a clear maximum at $\tau \approx 0.28$ s. Phototransistor data are in green (grey) and resistance data are in blue (black). This verifies that the cross-correlation method works.
It was shown that the time shift could be found surprisingly clearly and accurately by this method. The only case in which the method broke down was when measuring the rapid bubble flow using the resistivity sensors. In that case the maximum correlation was found for time shift $\tau \approx -0.001$. This erroneous result was introduced because of crosstalk between the two electrode sensors. Ways to resolve that problem are discussed in Section 5.1.3.

5.1.2. Void Fraction and Bubble Geometry

One of the more important quantities that we wanted to measure was the void fraction. To that end, estimating the bubble size and being able to count the bubbles became important. This proved nontrivial using the electrical resistivity measurements, due to a low signal-to-noise ratio and crosstalk effects. This section introduces some of the problems involved and the methods that were used for the analysis.

The experiment dealt with segmented flow (Figure 3-1) so Equation 3.10 could be used to calculate the bubble length, given a previous estimate of the average bubble velocity. Another property arising from the fact that the flow was segmented was that the water
and air flow velocities were the same, and therefore the overall void fraction could be calculated as

\[
\alpha = \frac{\sum_i A L_{b,i}}{L_{tot}} = \frac{\sum_i L_{b,i}}{L_{tot}} / u
\]

where \( L_{tot} \) is the total length of fluid (air and water) that passed through the measured section over the entire measurement period and all other quantities are as defined earlier.

Given these assumptions, the total time that bubbles were present was all that was needed to calculate the void fraction. However, this quantity was not determined uniquely from the measurements because of the relatively slow response time of the sensors. Moreover, in the case of the resistivity measurements, the low signal-to-noise ratio and the crosstalk complicated the analysis even further. Two basic methods were investigated to infer consistent estimates of the void fraction between all four sensors.

**5.1.2.1. Bimodal Histogram Threshold**

In the first method, a histogram of the measurement points was made and some intermediate value that could correspond to a transition value between air and water measurements was to be determined. This intermediate value had to be somewhere between the two peaks corresponding to measurement values for air and water as shown in Figure 5-6 (data taken from Pilot test 1).
The threshold value for transition between air and water measurements was not clearly defined from the histogram for the phototransistor measurements and the situation did not improve by looking at the resistivity measurements (Figure 5-7). Thus, this method was abandoned for the time being, keeping in mind that it might become feasible if the response time and accuracy of the sensors could be improved.
5.1.2.2. Moving Average Threshold

The second method investigated was to draw a threshold line that varied in time, based on local variations in the signal. One advantage of using a method like this was that it might be useful in situations where the properties of the fluid are changing in time (e.g. if the measurement tool is being used downhole, the resistivity of the fluid would vary with temperature and salinity). The threshold line was drawn as a one second moving average (note that the actual signal had also been filtered to remove the 60 Hz electrical noise). Figure 5-8 illustrates data from the phototransistor and Figure 5-9 has data from the resistivity sensor (data taken from Pilot test 1).

Figure 5-8: A moving average threshold used to determine whether the signal from a phototransistor corresponds to air or water.

Figure 5-9: A moving average threshold used to determine whether the signal from a resistivity sensor corresponds to air or water.
As indicated by Figure 5-8 and Figure 5-9, a fairly accurate bulk estimate of the presence of bubbles was obtained. The bubble signals from the two sensors showed a relatively good correlation and the calculated void fraction was 29.3% as calculated from the phototransistor 1 measurement but 31.1% using the resistivity sensor 1. Note also that because of the electrical noise, the resistivity measurement tended to estimate more frequent and smaller bubbles than did the phototransistor.

The moving average threshold method works fairly well as long as the void fraction is in the intermediate ranges (say 25-75%), but as the limit of pure water or pure air is approached the method will cease to work because the moving average threshold will move too close to the signal from the dominant fluid. Hence, the noise in the signal will start to dictate the transition between water and air, leading to an underestimate of the dominant fluid.

Table 5-1 to Table 5-3 summarizes estimates of bubble velocity, average bubble length, void fraction and the number of bubbles counted over the measurement period for each of the three Pilot tests.

Table 5-1: Summarized results for calculated bubble flow properties from Pilot test 1.

<table>
<thead>
<tr>
<th>Pilot test 1</th>
<th>Sensor</th>
<th>Resistivity1</th>
<th>Resistivity2</th>
<th>Phototrans1</th>
<th>Phototrans2</th>
<th>STD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ebl Velocity [m/s]</td>
<td>0.287</td>
<td>0.287</td>
<td>0.281</td>
<td>0.281</td>
<td>0.0038</td>
<td></td>
</tr>
<tr>
<td>Avg Ebl Length [mm]</td>
<td>6.5</td>
<td>5.4</td>
<td>9</td>
<td>8.6</td>
<td>1.7</td>
<td></td>
</tr>
<tr>
<td>Void Fraction</td>
<td>31.1%</td>
<td>27.6%</td>
<td>29.3%</td>
<td>30.8%</td>
<td>2%</td>
<td></td>
</tr>
<tr>
<td>Number of Bbs.</td>
<td>270</td>
<td>296</td>
<td>184</td>
<td>203</td>
<td>55</td>
<td></td>
</tr>
</tbody>
</table>

Table 5-2: Summarized results for calculated bubble flow properties from Pilot test 2.

<table>
<thead>
<tr>
<th>Pilot test 2</th>
<th>Sensor</th>
<th>Resistivity1</th>
<th>Resistivity2</th>
<th>Phototrans1</th>
<th>Phototrans2</th>
<th>STD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ebl Velocity [m/s]</td>
<td>0.181</td>
<td>0.181</td>
<td>0.179</td>
<td>0.179</td>
<td>0.0008</td>
<td></td>
</tr>
<tr>
<td>Avg Ebl Length [mm]</td>
<td>6.4</td>
<td>4.8</td>
<td>9.3</td>
<td>8.2</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>Void Fraction</td>
<td>27.4%</td>
<td>24.8%</td>
<td>20.1%</td>
<td>20.1%</td>
<td>4%</td>
<td></td>
</tr>
<tr>
<td>Number of Bbs.</td>
<td>143</td>
<td>173</td>
<td>71</td>
<td>82</td>
<td>49</td>
<td></td>
</tr>
</tbody>
</table>

Table 5-3: Summarized results for calculated bubble flow properties from Pilot test 3.

<table>
<thead>
<tr>
<th>Pilot test 3</th>
<th>Sensor</th>
<th>Resistivity1</th>
<th>Resistivity2</th>
<th>Phototrans1</th>
<th>Phototrans2</th>
<th>STD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ebl Velocity [m/s]</td>
<td>0.467</td>
<td>0.467</td>
<td>0.467</td>
<td>0.467</td>
<td>0.0000</td>
<td></td>
</tr>
<tr>
<td>Avg Ebl Length [mm]</td>
<td>8.2</td>
<td>9.2</td>
<td>12.8</td>
<td>10.3</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>Void Fraction</td>
<td>35.9%</td>
<td>49.6%</td>
<td>58.2%</td>
<td>54.9%</td>
<td>10%</td>
<td></td>
</tr>
<tr>
<td>Number of Bbs.</td>
<td>378</td>
<td>464</td>
<td>382</td>
<td>459</td>
<td>45</td>
<td></td>
</tr>
</tbody>
</table>
The flow rates and flow rate ratios measured by the simple flow meter are shown in Table 5-4. Given the aforementioned assumptions for segmented flow, the ratio \( \frac{Q_{\text{air}}}{Q_{\text{tot}}} \) should equal the void fractions shown in Table 5-1 through Table 5-3 and hence the two values could be compared to get an estimate of the accuracy of these calculations. Some caution should be taken in the comparison since the uncertainty in the air flow measurements from the flow meter was rather large.

As expected the moving average threshold method seemed to work fairly well when the void fraction was at an intermediate value. This was seen in Pilot test 2. In Pilot test 1 the void fraction had become too low (\( \alpha \approx 0.13 \)) for a proper estimate to be made by this method and an underestimate of the water (the dominant fluid) was seen. In the case of Pilot test 3, an underestimate of air was seen, which was not predicted by this simple model of the segmented flow, but it could perhaps be explained by turbulence and vibrational effects that the flow had on the electrode. The crosstalk effect may also have played a role here.

### 5.1.3. Crosstalk

The resistivity measurements had a crosstalk effect between the two sensor readings. This means for example, that sometimes when a bubble passed the resistivity sensor at location 1, a characteristic signal change was also seen in the resistivity measurement at location 2. As an example, this can be seen very clearly in the “Resistivity1” signal around time 1.7 s in Figure 5-1.

An attempt to explain this behavior is propose that the anode of electrode 1 and the cathode of electrode 2 were connected through the water, thereby forming another electrode (Figure 5-10). Let the resistance across this electrode be denoted by \( R_{e12} \). Then the measured voltage drop in circuit 2 could be calculated as

<table>
<thead>
<tr>
<th></th>
<th>( Q_{\text{air}} )</th>
<th>( \Delta Q_{\text{air}} )</th>
<th>( Q_{\text{water}} )</th>
<th>( \Delta Q_{\text{water}} )</th>
<th>( \frac{Q_{\text{air}}}{Q_{\text{tot}}} )</th>
<th>( \Delta \left( \frac{Q_{\text{air}}}{Q_{\text{tot}}} \right) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pilot Test 1</td>
<td>1.15</td>
<td>0.61 (53%)</td>
<td>7.43</td>
<td>0.37 (5%)</td>
<td>0.13</td>
<td>0.08 (64%)</td>
</tr>
<tr>
<td>Pilot Test 2</td>
<td>1.41</td>
<td>0.32 (23%)</td>
<td>4.88</td>
<td>0.24 (5%)</td>
<td>0.22</td>
<td>0.07 (32%)</td>
</tr>
<tr>
<td>Pilot Test 3</td>
<td>12.58</td>
<td>037 (6%)</td>
<td>4.88</td>
<td>0.24 (5%)</td>
<td>0.72</td>
<td>0.08 (11%)</td>
</tr>
</tbody>
</table>
\[ V_{R2} = V - I \left( \frac{1}{R_{e2}} + \frac{1}{R_{e12}} \right)^{-1} \]

where \( R_{e2} \) is the voltage drop across electrode 2 and \( V = 12 \text{ V} \) is the total voltage supplied to the circuit. When a bubble passes electrode 1 the connection between electrodes 1 and 2 weakens and \( R_{e12} \) goes up. According to Equation 5.2 this leads to a lower value of \( V_{R2} \). The change in the signal because of this disturbance should be much smaller than the change in the signal if the bubble were passing at spot 2 because \( R_{e12} >> R_{e2} \)

![Image of resistivity sensor circuit]

Figure 5-10: Schematic diagram of the resistivity sensor circuit, including the cross electrode resistors \( R_{e12} \) and \( R_{e21} \).

A similar relation should exist the other way around, between the anode of electrode 2 and cathode of electrode 1, but it was not seen as strongly in the experiments. Perhaps the current could not travel as easily upstream, i.e. \( R_{e12} \) was not equal to \( R_{e21} \) because of a second bubble, traveling in-between the sensors, which impeded the electrical current.

This explanation is perhaps not completely satisfactory and using separate power supplies for each sensor has been suggested by specialists that have developed similar technology for oil and gas wells at the Schlumberger Experimental Facilities in Cambridge, England.

Alternative ways to deal with the crosstalk, i.e. signal processing methods, were also investigated. The way that gave the best results was to subtract the lagging signal \( S_2 \) from the leading signal \( S_1 \) and then cross-correlate \( \hat{S}_1 = S_1 - S_2 \) to \( S_2 \). This way the
erroneous part of the signal (resulting from crosstalk) could be subtracted out of the leading signal and the peak in $R_{S1,S2}(\tau)$ at $\tau \approx 0$ was eliminated (Figure 5-11).

![Sample cross-correlation](image)

**Figure 5-11:** The cross-correlation between the lagging signal ($S_2$) and the difference between the leading and the lagging signal ($\delta_i = S_i - S_2$) provides an appropriate estimate of the time shift.

### 5.2. Void Fraction from Bulk Impedance Measurements

The impedance probe (described in Section 4.2.2) was modeled as a resistor and a capacitor in parallel (Figure 5-12).

![Impedance probe model](image)

**Figure 5-12:** The impedance probe was modeled as a variable resistor and capacitor in parallel.

Hence, the impedance was calculated as

$$Z = \left( \frac{1}{R^2} + \frac{1}{X_C^2} \right)^{1/2} \quad 5.3$$
Where $R$ is the average resistance in the flow path through the fluid and $X_C$ is the capacitive reactance, which depends on the capacitance, $C$, and the excitation frequency, $f$:

$$X_C = \frac{1}{2\pi fC} \quad 5.4$$

The phase angle, $\varphi$, is related to $R$ and $X_C$ by:

$$\varphi = -\arctan \frac{R}{X_C} \quad 5.5$$

Alternatively, the resistance and reactance can be represented as:

$$R = \frac{Z}{\cos \varphi} \quad 5.6$$

$$X_C = -\frac{Z}{\sin \varphi} \quad 5.7$$

The mathematical model used for determining the void fraction is described by Equation 5.8. The model assumes that pure air flowing in the well leads to impedance measurements ($Z_g$) so much larger than if pure water were flowing in the wellbore ($Z_l$) that the ratio $Z_l/Z_g$ tends to zero. Hence, the void fraction can be modeled by the relation:

$$\alpha = 1 - \frac{Z_l}{Z_{\text{measured}}} \quad 5.8$$

Results from a series of measurements showed that within the range of 0 to 30% void fraction, there is a relatively good correlation between void fraction and impedance.
Figure 5-13: Correlation between the void fractions as inferred from a differential pressure measurement versus the impedance measurement.

The results shown in Figure 5-13 are from experiments that were run over a series of water flow rates and air flow rates. The trend shows that the impedance grows not only with air flow rate, but also as the water flow rate grows. This latter observation has not been taken into account in our mathematical model since more data would be necessary to verify this effect.

Although this experiment revealed a rather straightforward relationship between the impedance and the void fraction it should be noted that the errors involved in both the impedance and reference ($dP$) measurements were very large, especially for large void fractions. Examples of the $dP$ measurements and corresponding impedance measurements made at a water flow rate of 100 lb/min and 3 SCFM are shown in Figure 5-14 and Figure 5-15.
Figure 5-14: An example of the differential pressure measurements taken to obtain a single bulk average value of the void fraction.

![Differential Pressure Measurement](image1)

Figure 5-15: An example of the impedance measurements taken to obtain a single bulk average value of the void fraction.

![Impedance Measurement](image2)

It was speculated that the variability in the void fraction estimate from the $dP$ measurement (the reference) was actually larger than that of the impedance measurement. To confirm this, the void fraction was plotted versus the volumetric flow rate ratio. The flow rate measurements had less than 3% error and were considered relatively reliable. Figure 5-16 shows the trend for void fraction from impedance and Figure 5-17 shows the trend for void fraction from $dP$. Since it was visually (and intuitively) observed that the
void fraction increased proportionally and fairly smoothly as the flow rate ratio increased, one can infer that the data from the impedance sensor shows more realistic behavior than that from the differential pressure transducer. This leads to the conclusion that improved reference measurement methods must be implemented.

Figure 5-16: A plot of the flow rate ratio versus the void fraction as estimated from the impedance measurement.

Figure 5-17: A plot of the flow rate ratio versus the void fraction as estimated from the differential pressure measurement.
A final topic of interest was to investigate the alternative of using either the resistance, $R$, or the reactance, $X_C$, in place of the impedance in Equation 5.8 to calculate the void fraction. Since the reference data was not found very reliable, these values were plotted as a function of the volumetric flow rate ratio. The results for the resistance (Figure 5-18) showed a trend very similar to what was seen for the impedance. The data for the reactance (Figure 5-19) did however not line up quite as smoothly.

Figure 5-18: A plot of the flow rate ratio versus the void fraction as estimated from the measured resistance.

Figure 5-19: A plot of the flow rate ratio versus the void fraction as estimated from the reactance.
The reason for the impedance not being affected by the somewhat noisy behavior in the reactance was that the impedance was mostly governed by the resistivity in these experiments. The phase angle was always around -5 degrees and therefore the reactance was approximately an order of magnitude larger than the resistance. Hence, the reactance term in Equation 5.3 will be negligible. This does however not mean that measuring the resistance will always be sufficient. One can for example imagine a situation with annular flow of water and air flowing through the center of the well. In that case the resistance will become very high and the reactance might become the governing measurement parameter. Moreover, increasing excitation frequency ($f$) would reduce the reactance. An interesting continuation of the project would be to investigate topic.

The uncertainty in the reference data made it hard to judge whether the closeness of the fitted lines in Figure 5-13 to a unit slope was coincidental for this data set. Repeated measurements at the same conditions gave rise to that suspicion. In light of this, more measurements over a longer time interval and an experimental setup, with a more reliable way of measuring the reference void fraction would be advisable. An interesting design note on improving gradiomanometer data for void fraction estimates is given in the reference by Fordham et. al (1999). An alternative reference method would be to insert a quick closing valve at the bottom of the artificial well. This seems to be a simple and applicable modification since the bulk void fraction could be estimated from the height of the water level after the air and water have separated.
Chapter 6

6. Conclusions

Direct downhole measurements of enthalpy could provide important additional information for geothermal reservoir characterization and monitoring. Our research has identified ways of measuring two important factors leading to an estimate of the enthalpy of two-phase flow, i.e. the void fraction and the dispersed-phase velocity.

Small scale phase discrimination experiments using both resistivity and optical sensors have lead to accurate estimates of the bubble velocity. The data have also been used to infer void fraction in a limited range of flow regimes, but more accurate reference measurements are desirable to verify these results. Having sensors with higher signal-to-noise ratio and faster response times would also be extremely beneficial to determining the void fraction. Some more sophisticated phase discrimination sensor design could probably be borrowed from the oil and gas industry or the nuclear power industry.

Bulk estimates of void fraction have been inferred from measurements of the impedance between two outward-looking parallel plates. A mathematical model was suggested for the relationship between the impedance and void fraction. This model showed a relatively good correlation to the reference data in the range from 0 to 30% void fraction. However, large fluctuations in the reference data make it hard to judge the reliability of these correlations. Moreover, it was shown that the resistance was the dominant parameter in the void fraction estimates. If however, the void fraction or excitation frequency were to increase the capacitive reactance would play a more significant role.
Nomenclature

Variables:

\( \mathcal{A} \) = area \([m^2]\)
\( \alpha \) = void fraction \([-]\)
\( \mathcal{C} \) = capacitance \([F]\)
\( \Delta P, dP \) = measured pressure difference between two locations in a vertical water column \([Pa]\)
\( \Delta h \) = height difference between pressure gauges \([m]\)
\( \gamma \) = dispersed-phase density function \([-]\)
\( f \) = excitation frequency \([s^{-1}]\)
\( g \) = gravity constant \([m/s^2]\)
\( h \) = enthalpy per unit mass \([kJ/kg]\)
\( I \) = current \([A]\)
\( \phi \) = phase angle \([-]\)
\( k_r \) = relative permeability \([-]\)
\( L \) = length \([m]\)
\( m \) = mass \([kg]\)
\( \mu \) = dynamic viscosity \([Pa \cdot s]\)
\( P \) = pressure \([Pa]\)
\( Q \) = volumetric flow rate \([m^3/s]\)
\( R \) = radius of a well or pipe \([m]\)
\( R \) = resistance \([\Omega]\)
\( R(\tau) \) = cross correlation function
\( r \) = radial location in cross section of a well or pipe \([m]\)
\( \rho \) = density [kg/m³]
\( S_i \) = measurement signal from sensor \( i \) [V (usually)]
\( \bar{S}_i \) = average value of signal from sensor \( i \) over the entire measurement interval
\( \dot{S}_i \) = difference between the leading and the lagging signal, \( S_1 - S_2 \)
\( T \) = temperature [K]
\( t \) = time [s]
\( \tau \) = time shift or dummy variable for time [s]
\( u \) = velocity [m/s]
\( u(T) \) = internal energy per unit mass [kJ/kg]
\( V \) = voltage [V]
\( v \) = specific volume, volume per unit mass [m³/kg]
\( W \) = mass flow rate [kg/s]
\( X_C \) = reactance [Ω]
\( x \) = vapor phase mass fraction [-]
\( X_C \) = reactance [Ω]
\( Z \) = impedance [Ω]

**Subscripts:**

\( b \) = bubble, is interchangeable with \( g \) when used with velocity \( u \)
\( e \) = electrode
\( g \) = gas or vapor phase
\( i \) = 1, 2…counter, e.g. counting sensors, bubbles etc.
\( l \) = liquid phase
\( R2 \) = reference resistor 2
\( S1 \) = sensor 1
\( t \) = travel, as in travel time \( t_r \)
\( tot \) = total
References


Appendices

A. LabView Program for Phase Discrimination Sensor Experiment

A program was developed in LabView 7.1 for logging the signals from the phase discrimination sensors. Programs in LabView are generally referred to as the Virtual Instruments (VIs). The VI was used to log signals from seven sensors simultaneously at a 1 kHz. The results for every 500 measurements collected were graphed on the front panel (Figure A-1). Furthermore, the results were time stamped and written to a scaled binary file for storage and further data processing.

![Figure A-1: A screen capture of the front panel of the program developed in LabView for data acquisition from the phase discrimination sensors.](image)
The interconnection between the VI and the data acquisition board was made by creating a task specifically designed for the types of sensors connected to the board, or more precisely to the terminal block (SCB-64) which then connects to the data acquisition board. This task was created using the Measurement and Automation Explorer (MAX). The data acquisition board was a high precision PCI board of type NI-6281 from National Instruments (further description available at www.ni.com). The NI-DAQmx driver needed for communication with the board was included in the installation of LabView 7.1 (it also came on a CD with the board and is available on the NI website).

Since LabView is a very graphically oriented software package, the program is probably best understood by looking at the block diagram, i.e. the back panel shown in Figure A-2.
Figure A-1: The back panel of the program developed in LabView for data acquisition from the phase discrimination sensors.

Steps:
1. Create or replace a file to store the data.
2. Select predefined task from MAX.
3. Set the rate for the sample clock and define the sample mode to be continuous.
4. Create a header and write it to the binary file.
5. Call the Start VI to start acquiring samples.
6. Read the unscaled data in a loop until the user hits the stop button or an error occurs.
7. Transpose the unscaled array of data and append it to the file.
9. Call the Stop VI to stop acquiring samples.
10. Use the popup dialog box to display an error if any.
B. LabView Program for Bulk Impedance Sensor Experiment

A program was developed in LabView for logging the signals from the bulk impedance sensors. This program is referred to as a Virtual Instrument (VI). The VI was used to log signals with a 70 millisecond interval from the impedance sensor (LCR 1715) and the differential pressure transducer. The results were time stamped and written to a scaled binary file for storage and further data processing. Data acquisition from the pressure transducer was obtained through the same board as described in Appendix A. The data acquisition for the LCR 1715 was obtained by connection through an RS-232 serial port. Example VIs for communication with the LCR 1715 were available through the website www.quadtech.com. These example VIs were used to build the combined VI shown here. The front panel is shown in Figure A-3 and the back panel is shown in Figure A-4.

![Figure A-3: A screen capture of the front panel of the program developed in LabView for data acquisition from the bulk impedance sensors.](image-url)
Figure A-1: The back panel of the program developed in LabView for data acquisition from the bulk impedance sensors.
C. MATLAB Codes for Phase Discrimination Data Analysis

Much of the MATLAB code written for data analysis just applied the straightforward calculation given by the formulas presented in this report. Some of the more tricky parts were to convert the data from the scaled binary format written by LabView into something readable by MATLAB. Moreover, finding the proper smoothing algorithms for some of the phase discrimination data and making the cross correlation function work was slightly challenging. Some of the code developed will be presented in the following few pages.

C.1. Main: ProcessPhaseDiscriminationTest.m

```matlab
% Program to handle the analysis of data from LabView in the phase
discrimination sensor experiments.
The program begins by reading the data file from LabView and arranging the
data from each sensor into separate vectors.
Then various averaging and smoothing algorithms are run.
A script that plots the responses of the various sensors over suitable
a time interval is then available.
Thereafter some codes to estimate void fraction from the histogram method
% could be run.
Next comes a code that estimates the time shift from cross correlation
% which then enables the calculation of average bubble velocity.
Finally comes the function Bubble.m that calculates void fraction (from
% the moving average threshold method), the number of bubbles and the
% average bubble length.
By Egill Juliusson
% Last modified: May 29th 2006

clear all; clc; close all

global SensorName

% Basic parameters for test
FileName = '20051104_Test2 scl';
SensorName = ['Temperature1'; 'Temperature2'; 'Temperature3'; ...
'Resistivity1'; 'Resistivity2'; 'Phototrans1'; 'Phototrans2 '];
LPFilterFreq = 60; % Low pass filter frequency

% Imports LabView file, extracts data from header and arranges sampled data from
% vector to array format. Each channel is a column in the array, the first column is
time.
[Ch, Time, N, NumCh, SampRate] = ImportLabViewFile(FileName);
```
%Vrms = \[\frac{\text{norm}(\text{Ch}(:,4))}{\text{norm}(\text{Ch}(:,4))}\] / \sqrt{N}
%V = \[\frac{\text{mean}(\text{Ch}(:,4))}{\text{mean}(\text{Ch}(:,4))}\]

N = N; %Number of samples reduced to shorten computation time
% just to get a quick glance at the data

%Calculate moving averages, used as a filter for 60Hz noise
AveragingSampNum = round(SampRate/LPFilterFreq) + (1 - mod(SampRate/LPFilterFreq, 2));
for i = 1:NumCh
    Chavg(1:N,i) = smooth(Ch(1:N,i), AveragingSampNum, 'moving');
    Chrms(1:N,i) = smooth((Ch(1:N,i).^2).^0.5*sqrt(41), 20, 'moving');
end

%Apply low pass filter LPFilter(DataArray, SampRate, MaxFreq)
IFCh = LPFilter(Ch, SampRate, LPFilterFreq);

%Call a small program that plots the responses over suitable time intervals
PlotResponces3

%A function that calculates flow rates based on the analyzed data
% (see function for better descr.)
% [Qratio_air, Qratio_wat] = FindRatio1(Ch, SampRate);
% [Qratio_air_MA, Qratio_wat_MA] = FindRatio1(Chavg, SampRate);
% [Qratio_air_FT, Qratio_wat_FT] = FindRatio1(IFCh, SampRate);

%Another function that calculates flow rates based on the analyzed data
% (see function for better descr.)
% StdConst = [1/3, 1/3, 1/3, 2/3, 2/3, 1/4, 1/4];
% [Qratio_air, Qratio_wat] = FindRatio2(Ch, SampRate, StdConst);
% [Qratio_air_MA, Qratio_wat_MA] = FindRatio2(Chavg, SampRate, StdConst);
% [Qratio_air_FT, Qratio_wat_FT] = FindRatio2(IFCh, SampRate, StdConst);

%CrsTlkCo = mean(Ch(:,4))/mean(Ch(:,5));
CrsTlkCo = 0;

%Calculate the time shift (see function for details)
TShR = TimeShift(Ch(:,4) - CrsTlkCo*Ch(:,5), 0.5*SampRate, N, 1, 'b.');
TShP = TimeShift(Ch(:,6), Ch(:,7), 0.5*SampRate, N, 1, 'g.);
title(FileName)
%legend('Electrode couple', 'Location', 'Best')
legend('Resistivity', '', 'Phototransistor', '', 'Location', 'Best')
%TSh = TimeShift2(Ch(:,4), Ch(:,5), 0.5*SampRate, N, 1, 'b.');
SensorSpacing = 0.05;
BubbleVelocityR = SensorSpacing/TShR;
BubbleVelocityP = SensorSpacing/TShP;

%Calculate various properties for the bubbles (see function for details)
% Bubble(DV, Time, Span, SampRate, NumSamp, BubbleVelocity, PlotAirWat, PlotHist)
[VoidR1, NumBubblesR1, AvgBubbleLengthR1] = ...
    Bubble(Ch(:,4) - 0*Ch(:,5), Time, SampRate, SampRate, N, BubbleVelocityR, false, false);
[VoidR2, NumBubblesR2, AvgBubbleLengthR2] = ...
    Bubble(Ch(:,5) - 0*Ch(:,4), Time, SampRate, SampRate, N, BubbleVelocityR, false, false);
[VoidP1, NumBubblesP1, AvgBubbleLengthP1] = ...
    Bubble(Ch(:,6), Time, SampRate, SampRate, N, BubbleVelocityP, false, false);
[VoidP2, NumBubblesP2, AvgBubbleLengthP2] = ...
    Bubble(Ch(:,7), Time, SampRate, SampRate, N, BubbleVelocityP, false, false);

%Save results
save([FileName(1:(length(FileName))), '_results.mat'])
OutputN = [BubbleVelocityR BubbleVelocityR BubbleVelocityP BubbleVelocityP;
    NumBubblesR1 NumBubblesR2 NumBubblesP1 NumBubblesP2;
    AvgBubbleLengthR1 AvgBubbleLengthR2 AvgBubbleLengthP1 AvgBubbleLengthP2;
    VoidR1 VoidR2 VoidP1 VoidP2];
NormSTD = std(OutputN')./mean(OutputN');

Output = {'Sensor:' SensorName(4,:)
    SensorName(5,:)
    SensorName(6,:)
    SensorName(7,:)
    'Normalized STD':
    'Bbl Velocity [m/s]:'
    BubbleVelocityR BubbleVelocityR BubbleVelocityP
    BubbleVelocityP NormSTD(1);
    'Number of Bbls:'
    NumBubblesR1 NumBubblesR2 NumBubblesP1 NumBubblesP2
    NormSTD(2);
    'Avg Bbl Length [m]:'
    AvgBubbleLengthR1 AvgBubbleLengthR2 AvgBubbleLengthP1
    AvgBubbleLengthP2 NormSTD(3);
    'Void Fraction:'
    VoidR1 VoidR2 VoidP1 VoidP2 NormSTD(4)}

C.2. Sub: ImportLabViewFile(FileName)

%This function imports data from a LabView file in .scl format and converts
%it to a number format that matlab can understand. The first few values of
%the labview file should describe the structure of the file. Hence, this
%function can rearrange the data into an array, with data from each channel
%as a column in the array Ch and the time in the vector Time. The function
%assumes that the labview vi has been set up such that time is the first
%value recorded at every measurement.
%By Egill Juliusson
%Last modified: March 22nd 2006

function [Ch, Time, NumSamp, NumCh, SampRate] = ImportLabViewFile(FileName)

    %Open file for read in big endian form and give id number
    fid = fopen(FileName, 'r', 'ieee-be');

    %Read file to vector assuming double format of digits
    DataV = fread(fid, 'double');
    M = size(DataV,1);

    %Extract data from header
    NumScalingParam = DataV(1); %Number of scaling parameters used for each
        %measurement channel (here usually 5)
    NumCh = DataV(2);
    SampRate = DataV(3);
    HeaderSize = 2 + NumScalingParam*NumCh;
    NumCol = NumCh+1; %Number of columns is 1+NumCh b/c time
        %takes one column

    %Rearrange data from vector format into array with columns depending
    %on measured quantity.
    %First values come after header (here at elem 38)
    for i = 1:NumCol
        Ch(:,i) = DataV(HeaderSize+i:NumCol:M-(NumCol-i));
    end

    %Store time in separate vector
    Time = Ch(:,1)-Ch(1,1);
    %Remove the time vector (column) from the data array
    Ch(:,1) = [];

    %Find number of samples from each channel
    NumSamp = size(Ch,1);
C.3. Sub: LPFilter(DataArray, SampRate, MaxFreq)

% Low pass filter. Filters out high frequencies using Fourier transforms
% By Egill Juliusson
% May 12th 2005

function [IFCh] = LPFilter(DataArray, SampRate, MaxFreq)
% Perform Fast Fourier Transform on signal
FCh = fft(DataArray);
[N, M] = size(FCh);

% Calculate power factor, i.e. length of each Fourier coefficient. I take
% only half of the coefficients b/c the elements of the FCh vector are
% symmetric, i.e. first half is the same as the last half mirrored.
for k = 1:M,
Pw(:,k) = sqrt(FCh(1:N/2,k).*conj(FCh(1:N/2,k)));
end

% Set Nyquist frequency, which is half the sampling freq. and the maximum
% detectable freq.
Nyq = SampRate/2;
% Freq = linspace(0,Nyq,N/2)';
% plot(Freq, Pw)

% Set filter criteria
index = floor(N*MaxFreq/SampRate); % number of coefficient to cut off from
FCh(index:N-index+1,:) = 0;
IFCh = real(ifft(FCh))

C.4. Sub: FindRatio1(DataArray, SampRate)

%A program that tries to infer the fraction of air and water from the
%signal measured. This function calculates the area between the actual
%signal and the absolute min value of the signal and divides that with the
%area between the max and min value

function [Qratio_air, Qratio_wat] = FindRatio1(DataArray, SampRate)
% Find average flow ratio of air and water from the accumulated data
N = length(DataArray); % Number of samples
Maxs = max(DataArray(1:N,:)); % Max value for each sample
Mins = min(DataArray(1:N,:)); % Min value for each sample
Qtot = Maxs*N/SampRate-Mins*N/SampRate; % Tot area between max and min in
time interval
Qwat = sum(DataArray(1:N,:))./SampRate-Mins*N/SampRate; % Tot area betw.
signal and min in time interv
Qair = Qtot-Qwat; % Tot area betw. signal and max in time interv

% Calculate flow ratios
Qratio_air = Qair./Qtot;
Qratio_wat = Qwat./Qt

C.5. Sub: FindRatio2(DataArray, SampRate, Const)

%A program that tries to infer the fraction of air and water from the
%signal measured. This function calculates the fraction of the time that
%the signal is within a specific interval related to the std of the signal.

function [Qratio_air, Qratio_wat] = FindRatio2(DataArray, SampRate, Const)
% Find average flow ratio of air and water from the accumulated data
N = length(DataArray); %Total number of samples

for i=1:size(DataArray,2)
    [BinFreq,Bins] = hist(DataArray(:,i),100);
    [MaxFreq,MaxIndex] = max(BinFreq);
    MaxVal = Bins(MaxIndex);
    StDev = std(DataArray(:,i));

    Nair(i) = length(find(DataArray(:,i)<(MaxVal-Const(i)*StDev)))); %Number of samples corresp. to air
    Nwat(i) = N-Nair(i);
end

N = length(DataArray); %Total number of samples

%Calculate flow ratios
Qratio_air = Nair/N;
Qratio_wat = Nwat

C.6. Sub: TimeShift(D1,D2,MaxTimeSh,SampRate,NumSamp,Plot,Color)

%Program that finds the time shift between two measurements
%By Egill Juliusson
%July 12th 2005

function TimeSh = TimeShift(D1,D2,MaxTimeSh,SampRate,NumSamp,Plot,Color)

s = [-SampRate*MaxTimeSh:MaxTimeSh*SampRate];

[XCF,Lags] = xcorr(D2-mean(D2),D1-mean(D1),...
SampRate*MaxTimeSh,'coeff');

IndexOfMax = find(XCF==max(XCF));
TimeSh = Lags(IndexOfMax)/SampRate;

if Plot==1
    figure(5)
    plot(s/SampRate,XCF,Color)
    hold on
    plot(TimeSh,max(XCF),'r', 'MarkerSize',25);
    text(TimeSh+0.02,max(XCF),['Time shift = ',num2str(TimeSh),...
    ' [s]', 'FontSize',12], 'FontSize',12);
    grid on
    title('Travel time from cross-correlation', 'FontSize',14)
    xlabel('Time increments-\tau [s]', 'FontSize',12);
    ylabel('Sample cross-correlation', 'FontSize',12);
end

C.7. Sub: Bubble(DV, Time, Span, SampRate, NumSamp, BubbleVelocity, PlotAirWat, PlotHist)

%Program that that estimates the time it takes each bubble to pass the
%sensors and computes the estimated vertical bubble length, based on an
%estimate of the bubble velocity.
%By Egill Juliusson
%August 25th 2005

function [Void,NumBubbles,AvgBubbleLength] =... Bubble(DV,Time,Span,SampRate,NumSamp,BubbleVelocity,PlotAirWat,PlotHist)

%Determine if the signal is corresponding to a bubble or not
MACh = smooth(DV,Span,'moving');
IsBubble(1:NumSamp) = false;
for i = 1:NumSamp
  if DV(i)<=MACh(i)
    IsBubble(i) = true;
  end
end
Void = sum(IsBubble)/NumSamp;

%Plot air/water distribution
if PlotAirWat
  Time = Time/1000;
  figure(6)
  subplot(2,1,1)
  plot(Time,DV,'b',Time,MACh,'r')
  axis([3 4 min(DV)-0.05 max(DV)+0.05])
  xlabel('Time [s]')
  ylabel('Signal')
  legend('Actual signal',[num2str(Span/SampRate), ' second moving'...
    ' average'],'Location','Best')
  subplot(2,1,2)
  stairs(Time,IsBubble)
  axis([3 4 -0.1 1.1])
  xlabel('Time [s]')
  ylabel('Water(0) or Air(1)')
  title('Air-water distribution')
end

%Find the time it takes each bubble to pass the sensor
NumBubbles = 0;
counter = 0;
for i = 2:NumSamp
  if IsBubble(i)
    counter = counter + 1;
  elseif ~IsBubble(i) && IsBubble(i-1)
    NumBubbles = NumBubbles+1;
    BubbleTimes(NumBubbles) = counter/SampRate;
    counter = 0;
  end
end

%Calculate bubble lengths and average length of a bubble
BubbleLengths = BubbleTimes*BubbleVelocity;
AvgBubbleLength = mean(BubbleLengths); %Needs to be modified to account for bubble geometry

%Plot histograms of bubble times and bubble lengths
if PlotHist
  figure(7)
  subplot(1,2,1)
  hist(BubbleTimes,NumBubbles/3)
  hold on
  plot(mean(BubbleTimes),10,'g.','MarkerSize',25)
  ylabel('Frequency - Number of Bubbles')
  xlabel('Time it takes bubble to pass sensor [s]')
subplot(1,2,2)
hist(BubbleLengths,NumBubbles/3)
hold on
plot(mean(BubbleLengths),10,'g.','MarkerSize',25)
xlabel('Vertical bubble length [m]')
end
**D. MATLAB Codes for Bulk Impedance Data Analysis**

The bulk impedance experiment did not require much manipulation of data and therefore the MATLAB code was quite limited. The calculations of the appropriate ratios and plots were made in Excel. The MATLAB code is still be presented here for completeness.

**D.1. Main: ProcessBulkImpedanceTest.m**

```matlab
% A script that calculates the mean and std of pressure transducer and resistivity measurements made in an Experiment with a resistivity probe in a 5.5 inch diameter plexiglas tube.
% By Egill Juliusson
% Last modified: May 29th 2006

clear all; close all; clc

global SensorName

% Add path to subfunction(s)
addpath('M:\School\Research')

% Variable endings in test file names
Ntest = ['01','02','03','04','05','06','07','08','09','10','11','12',... '13','14','15','16','17','18','19','20','21','22','23','24'];

for nt = 1:24;
    testN = Ntest(2*nt-1:2*nt);
    FileName = ['20060420_Test',testN,'.scl'];

    % Imports LabView file, extracts data from header and arranges sampled data from vector to array format. Each DAQ channel is a column in the array.
    [Ch, Time, N, NumCh, SampRate] = ImportLabViewFile2(FileName);

    meanZ(nt) = mean(Ch(:,1)); % mean impedance [Ohm]
    stdZ(nt) = std(Ch(:,1)); % std of impedance [Ohm]

    meanPh(nt) = mean(Ch(:,2)); % mean phase angle meas. [deg]
    stdPh(nt) = std(Ch(:,2)); % std of phase angle meas. [deg]

    meanP(nt) = mean(Ch(:,3)); % mean dP meas. [V]
    stdP(nt) = std(Ch(:,3)); % std of dP meas. [V]
end

Pdata = [meanP' stdP']
Zdata = [meanZ' stdZ']
Phdata = [meanPh' stdPh']
```
D.2. Sub: ImportLabViewFile2(FileName)

This function is the same as ImportLabViewFile except in the way that NumCol is calculated. The function imports data from a file in .scl format and converts it to a number format that Matlab can understand. The first few values of the LabView file should describe the structure of the file. Hence, this function can rearrange the data into an array, with data from each channel as a column in the array Ch and the time in the vector Time. The function assumes that the LabView vi has been set up such that time is the first value recorded at every measurement.

By Egill Juliusson

%Last modified: May 28th 2006

function [Ch, Time, NumSamp, NumCh, SampRate] = ImportLabViewFile2(FileName)

%Open file for read in big endian form and give id number
fid = fopen(FileName, 'r', 'ieee-be');

%Read file to vector assuming double format of digits
DataV = fread(fid, 'double');
M = size(DataV, 1);

%Extract data from header
NumScalingParam = DataV(1); %Number of scaling parameters used for each measurement channel (here usually 5)
NumCh = DataV(2);
SampRate = DataV(3);
HeaderSize = 2 + NumScalingParam*NumCh;
NumCol = NumCh+3; %Number of columns is 1+NumCh b/c time takes one column

%Rearrange data from vector format into array with columns depending on measured quantity.
%First values come after header (here at elem 38)
for i = 1:NumCol
    Ch(:,i) = DataV(HeaderSize+i:NumCol:M-(NumCol-i));
end

%Store time in separate vector
Time = Ch(:,1)-Ch(1,1);
%Remove the time vector (column) from the data array
Ch(:,1) = [];

%Find number of samples from each channel
NumSamp = size(Ch, 1);