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Ultrasonic Rate Measurement of Multiphase Flow

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Abstract

One of the most important tools in production logging and well testing is the downhole flowmeter. Unfortunately, existing tools are inaccurate outside of an idealized single phase flow regime. Spinner tools are inaccurate at extremely high or low flow rates and when the flow rate is variable. Radioactive tracer tools have similar inaccuracies and are extremely sensitive to the flow regime. Both tools completely fail in the presence of multiphase flow, whether gas/oil, gas/water or fluid/solid. (Bennett et al., 1991, Hill and Oolman, 1982, Hill, 1990 and McKinley, 1982)

Downhole flowmetering is important for locating producing zones and thief zones and monitoring production and injection rates. The effects of stimulation can also be determined. (Leach et al., 1974)

This goal of this project is the investigation of accurate downhole flowmetering techniques for all single phase flow regimes and multiphase flows. The measurement method investigated in this report is the use of ultrasound. There are two ways to use ultrasound for fluid velocity measurement. The first method, examined in Chapter 2, is the contrapropagation, or transit-time, method which compares travel times with and against fluid flow. Chapter 3 details the second method which measures the Doppler frequency shift of a reflected sound wave in the moving fluid.

Ultrasonic fluid flow measurement was first proposed in Rütten's German Patent in 1928 (issued in 1931), using the transit-time method, for single phase liquid pipe flow. Commercial transit-time flowmeters have been available since the early 80's (Lynnworth, 1989) and one such was purchased and tested for this research. The results are found in Chapter 4. A natural

gas contrapropagation flowmeter was tested by the Gas Research Institute in 1987 (McBane et al., 1991).

The Doppler effect was first utilized, not for fluid flow, but as a "radar" gun to measure boat velocity in 1916 by Chilowski and Langevin. This is the same style gun used today by the Highway Patrol. The first Doppler fluid flowmeter research began around 1969 by EDO Corporation and resulted in the first commercially available Doppler flowmeter in 1970 (Lynnworth, 1989).

Both of these technologies need to be incorporated in order to build a true multiphase flowmeter. Chapter 4 describes the proposed downhole multiphase flowmeter. It will have many advantages besides the ones previously mentioned and will be discussed in full in that chapter.

Chapter 2

Contrapropagation Flowmeters

2.1 Theory

The theory behind the contrapropagation flowmeter is straightforward. Sound waves travelling with fluid flow travel faster than sound waves moving against fluid flow. A simple analogy is that a boat travels faster downstream than it does upstream. It is possible to take advantage of this by constructing a flowcell with a set of ultrasonic transducers (sonic transmitter/receivers) that are immersed in the fluid stream, one upstream and one downstream, which can measure the fluid velocity. Knowing the fluid velocity, it is then possible to calculate the volumetric flow rate. The mass flow rate can also be found if the fluid density is known.

The flowcell is a section of pipe or conduit where the transducers are mounted and measurements are taken. The transducers can be mounted in many different ways, but are usually diagonally offset (Figure 2.1) (Lynnworth, 1989). The flowcell configuration used for testing was a seven path zigzag cross-correlation flowcell similar to the four path model pictured in Figure 2.2. The zigzag flowcell was chosen since it is designed to obtain a better average flow velocity than a single pass flowcell. The flowcell is inserted into a pipeline to monitor flow. The experimental zigzag flowcell was inserted into an experimental flow loop and subjected to testing.

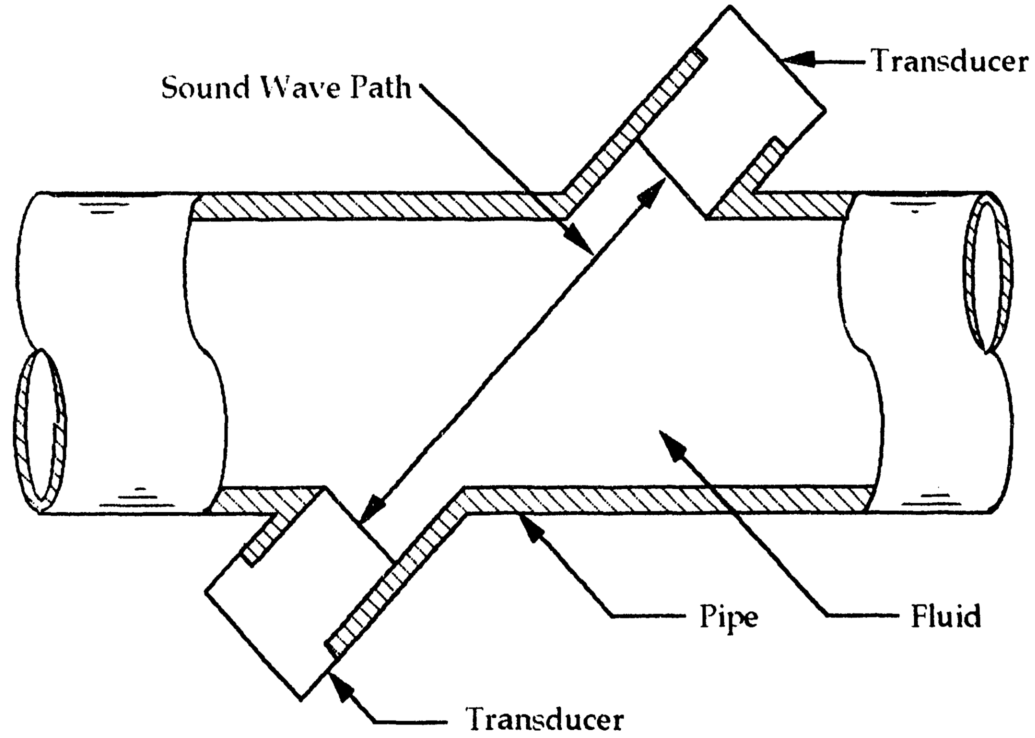

Figure 2.1. Diagonally Offset Flowcell (After Lynnworth, 1989)

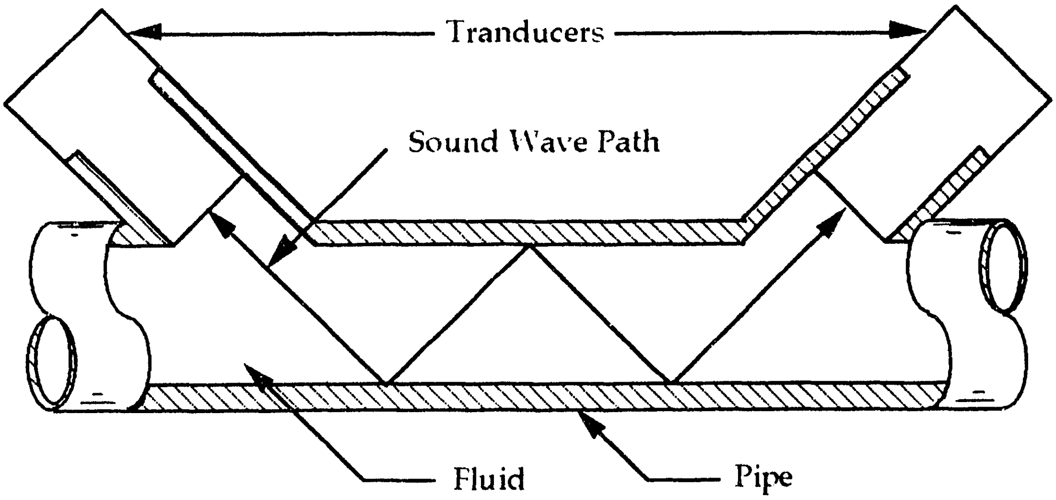

Figure 2.2. Zigzag Flowcell (4 Path) (After Lynnworth, 1989)

Each transducer alternately emits a sound pulse which travels through the fluid and is received by the other transducer. The transit times are recorded by a computer and the fluid velocity calculated.

2.2 Flow Rate Calculations

The transit time of the sound wave depends on the fluid velocity, v_f, the speed of sound in the fluid, c, and the path length between the transducers, L. The transit time measured in the downstream direction, t_d, is:

$$t_d = L/(c + v_f) \tag{2.1}$$

Similarily, the travel time upstream, t_u, is:

$$t_u = L/(c - v_f) \tag{2.2}$$

Solving for v_f in (2.1) and (2.2) gives:

$$v_f = L/t_d - c \tag{2.3}$$

$$v_f = - L/tu + c \tag{2.4}$$

Summing (2.3) and (2.4) and dividing by 2:

$$v_f = (L/2)(1/t_d - 1/t_u) \tag{2.5}$$

This result is very important, for the dependence on the speed of sound cancels out. This means it is possible to measure fluid speeds in media where the sound speed is unknown or variable (McBane et al., 1991).

Due to the difference in fluid path versus sonic path, the measured velocity, v_f, differs from the overall area average velocity, v_a. This can be corrected using a meter factor, K. The meter factor is a functon of the

Reynold's Number and the flow profile and ranges from .75 for laminar flow to 1.3 for highly turbulent flows. The velocities and the meter factor are related by the relationship:

$$v_a = K\, v_f \tag{2.6}$$

The volumetric flow rate, Q, is the average fluid velocity, v_a, multiplied by the cross-sectional area, A, of the pipe or conduit:

$$Q = v_a\, A \tag{2.7}$$

If the density of the fluid, ρ, is known , the mass flow rate, M, can also be calculated:

$$M = \rho\, Q \tag{2.8}$$

The density is a parameter which needs to be known downhole for proper mass flow rate calculation. It can be estimated using ultrasonic means (Section 4.3) or by using traditional production logging tools such as the gradiomanometer tool, the pressure-temperature tool or the nuclear fluid density tool (Lynnworth, 1989 and Schlumberger Cased Log Interpretation Principles/Applications, 1989).

2.3 Experimentation

As previously mentioned, a commercially available contrapropagation flowmeter and flowcell were purchased for testing. The meter was a Panametrics, Inc. Model 6068 Ultrasonic Flowmeter and the cell a 7 path zigzag cross-correlation square flowcell with 2 Mhz transducers. The 2 Mhz transducers are considered ideal for liquid measurement. This emphasis on liquid measurement was because a gas flowmeter has already been tested by the Gas Research Institute (GRI) in 1987 (McBane et al., 1991). See Figure 2.3 for a block diagram of the flowmeter's electronics.

The flowcell was installed in a large flow loop designed for water/nitrogen gas multiphase flow (Figure 2.4). The water flow rate was controlled using a constant head storage tank. With a constant head, the pressure drop and flow rate can be calculated. Nitrogen gas was used as the gas phase and the flow rate was metered with a calibrated gas meter. With both phase rates regulated, it was possible to investigate the accuracy of the ultrasonic flowmeter in both liquid and multiphase flows.

The system had a total capacity of approximately 50 gallons of water. The upper tank, with a capacity of 30 gallons, was 12 feet off the ground, giving a head of near 9 feet. The lower tank had a storage capacity of 55 gallons. The pump had a capacity of 280 gallons/minute.

The flowcell and the test conduit were constructed of transparent acrylic for improved observation. A square flowcell was used for better velocity averaging. The square flowcell was designed so that the ultrasonic signals sample a larger cross-section of the flow profile, thus increasing the accuracy. The one inch square flowcell had a ten inch long entrance to countereffect the entrance effects. The acrylic tubing above and below the flowcell was one inch in diameter.

2.4 Results and Discussions

Tests were performed to determine parameters of the flowmeter. They included:

1. Minimum flow rate. The maximum flow rate was unattainable with this flow loop.
2. Accuracy with regards to single phase water flow.
3. Maximum amount of gas phase present before attenuation of the signal caused measurement to become impossible.
4. Effects of different frequency transducers.

The flowcell was tested and calibrated with a static fluid column. The measurement varied ± .86 B/D with no flow and ± 1.5 B/D at 100 B/D. With

160% error at 1 B/D, 20 % error at 10 B/D and 3% error at 100 B/D, the minimum flow rate measurable was zero flow. Unfortunately, there are no figures available for spinner accuracy at these rates for they are unreliable below 100 B/D (Hill, 1990).

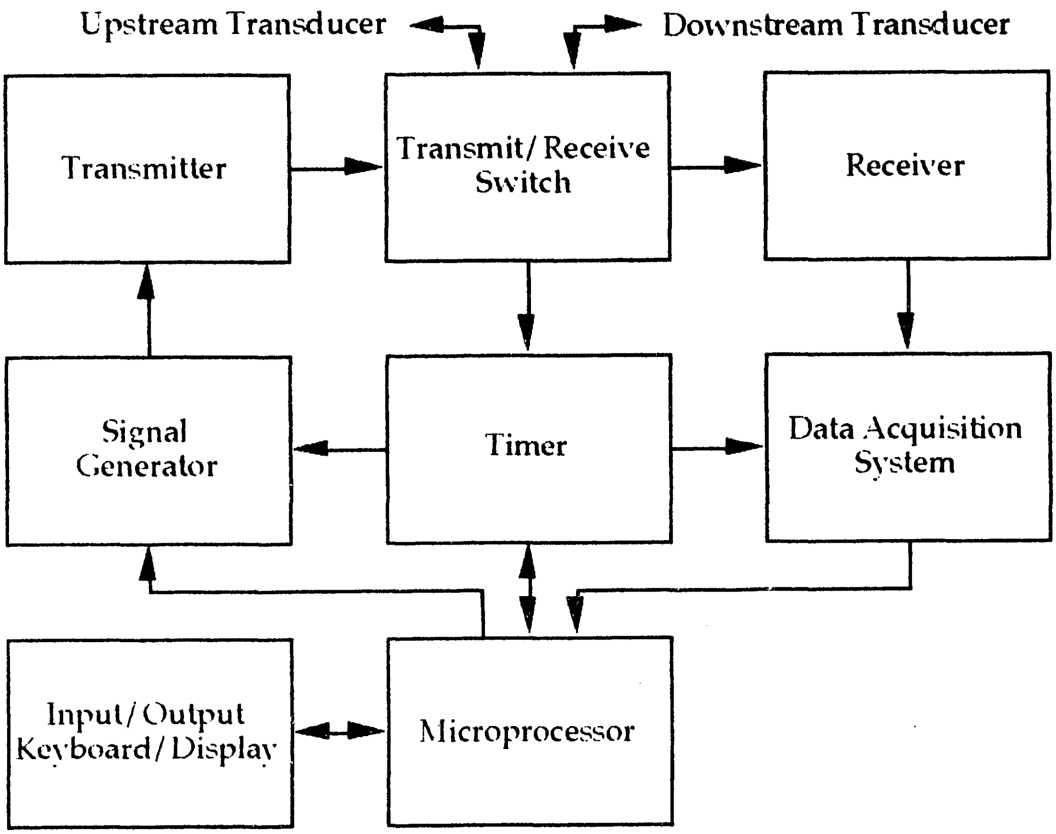

Figure 2.3. Model 6068 system block diagram (After Lynnworth, 1989)

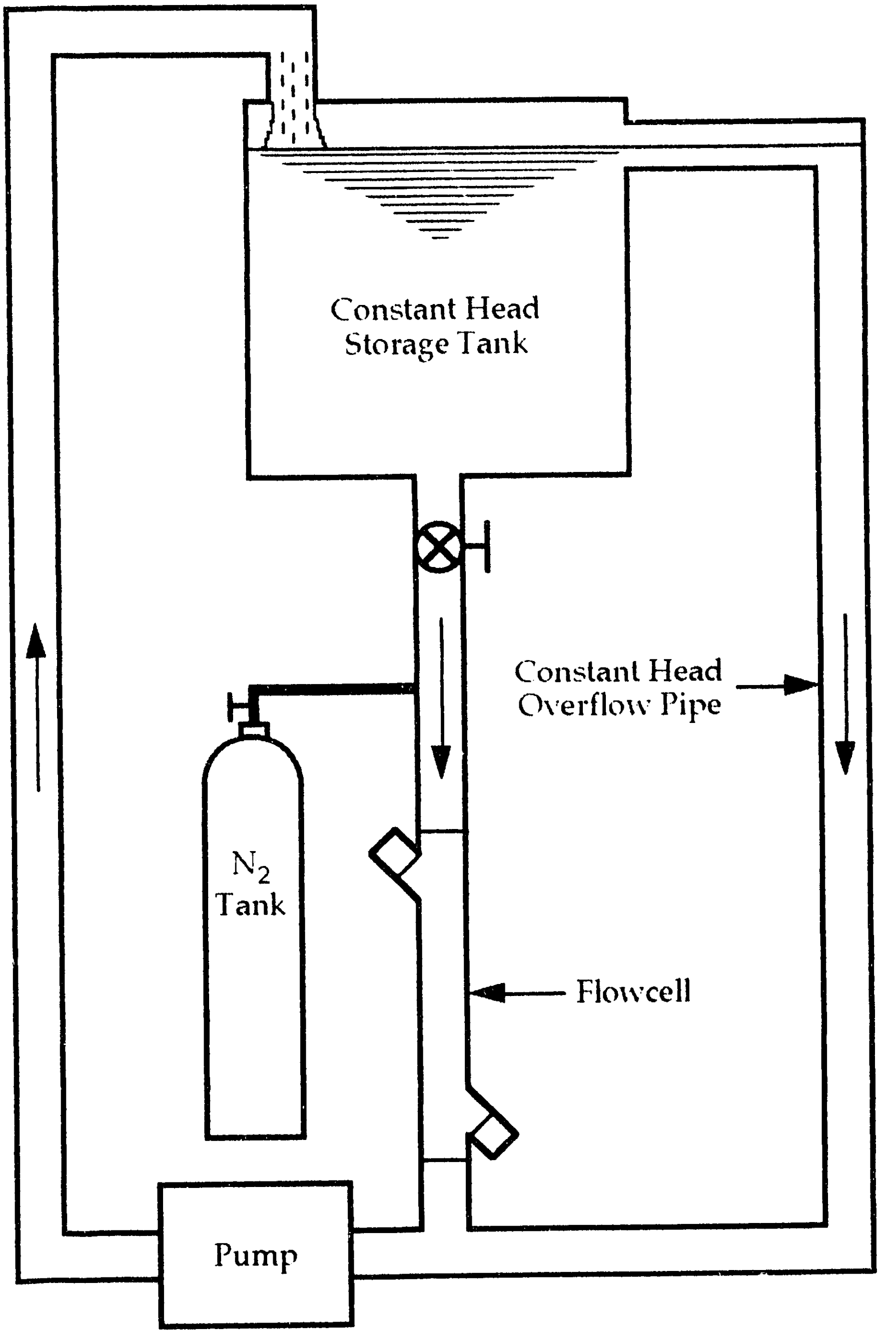

Figure 2.4. Experimental Multi-Phase Water/Nitrogen Gas Flow Loop

The accuracy of the flowmeter was then compared against calculated flow rates. A series of chokes (.25", .5" and .75") were installed in the flow loop for repeatable measurements. The measured and calculated flow rates are plotted in Figure 2.5. Ideally, the two rates should match. This ideal line is also plotted in Figure 2.5 for comparison.

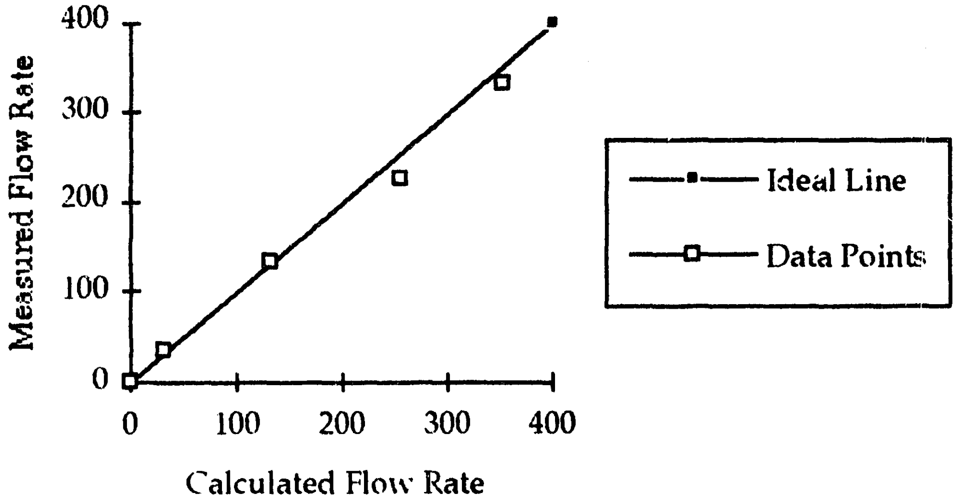

Figure 2.5. Calculated flow rate vs. measured flow rate for single phase water flow. Rates are measured in ft^3/hr.

The data matches the ideal line fairly accurately. The error, approximately 8% at the higher rates, is may be due to calculation errors, for estimating the effects of turbulence is difficult. All four data points are well within the range of turbulent flow, which occurs in flows greater than 20 ft^3/hr.

The inherent problem of ultrasonic measurement in gas is that of sound attenuation. Gas absorbs sound at a rate much higher than liquid, weakening the signal and making measurement difficult. The attenuation of sound, α, is proportional to the square of the frequency, f. Therefore, when using transducers with a frequency an order of magnitude higher, the sound absorption is 100 times greater. Whereas 2 Mhz is ideal for liquids, it is too high for gas measurement. 40, 100, 200 and 212.8 khz have all been used successfully for gas flows (Anderson et al., 1984, Jorden et al., 1986, Lynnworth, 1989 and McBane et al., 1991).

Even a microscopic amount of gas has a great effect on ultrasonic measurement. Logically, the fluid velocity of a gas/liquid mixture would be proportionate to the mixture ratio, but that is not the case. The sound velocity drops rapidly with only a slight percentage of gas in the system and does not increase until there is only a few percent liquid phase left (Figure 2.6) (Gudmundsson and Dong, 1992, Karplus and Clinch, 1964 and Lynnworth, 1989).

Fortunately, as previously shown, the fluid velocity determination does not rely on the speed of sound. Unfortunately, the sonic attenuation still weakens the signal. If the signal strength falls below the sensitivity of the receivers, measurement is infeasible.

The tested flowmeter, at a relatively high frequency of 2 Mhz, is very susceptible to signal attenuation. Tests were run at a variety of liquid flow rates and the gas rate was increased until measurement became impossible. The signal sensitivity was also heightened with a favorable result. The results are plotted in Figure 2.7.

The void space is the ratio of gas volume/total volume. It was calculated by knowing both inflow rates. This plotted ratio was calculated assuming the gas velocity was the same as the water velocity. From observation of the multiphase flow, it was evident that the water velocity was

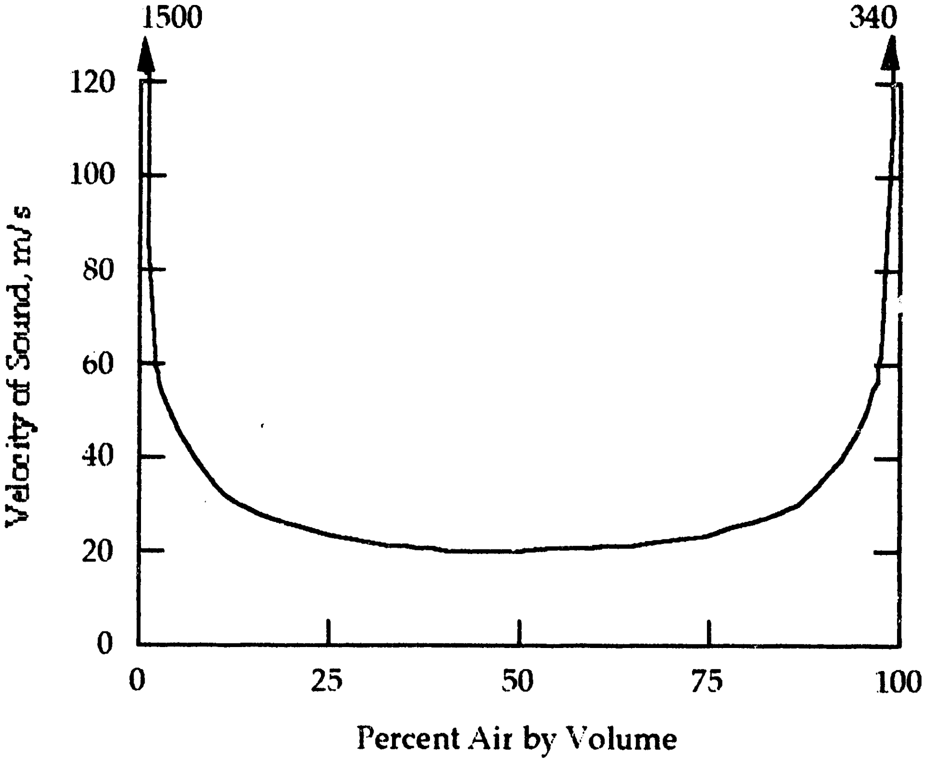

Figure 2.6. Sound Velocity vs. Void Space (After Gudmundsson and Dong, 1992 and Karplus and Clinch, 1964)

greater than the gas velocity due to holdup of the bubbles. This was expected, but direct measurement of the actual void space was impossible with this system. Therefore, high speed photographs (Appendix) were taken and the void space estimated from observation. Depending on the liquid flow rate, the actual void space ranged from 5 to 10 times greater than calculated. Assuming a linear relationship between the correction factor and the liquid flow rate, the data from Figure 2.7 was corrected and replotted in Figure 2.8.

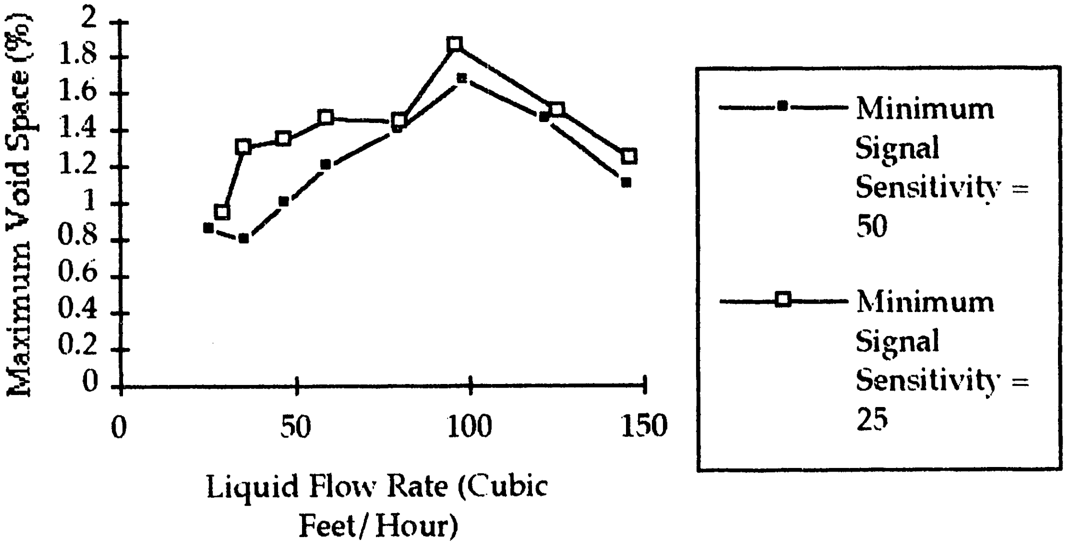

Figure 2.7. Maximum Void Space vs. Liquid Flow Rate

In addition to removing some graphical idiosyncracies, the corrected data shows great promise. 18-20 % void space is considerably more than other flowmeters can tolerate. With further testing of other flowcell designs and the utilization of transducers of other frequencies, it is conceivable that this could be improved upon.

The trends in the data can be explained. The high and low flow rate limits are due to limits of the flow loop. At flow rates lower than 25 or 30 ft^3/hr, gas bubbles gathered in the upstream transducer housing, causing signal attenuation. At liquid flow rates higher than 150 ft^3/hr, the gas meter

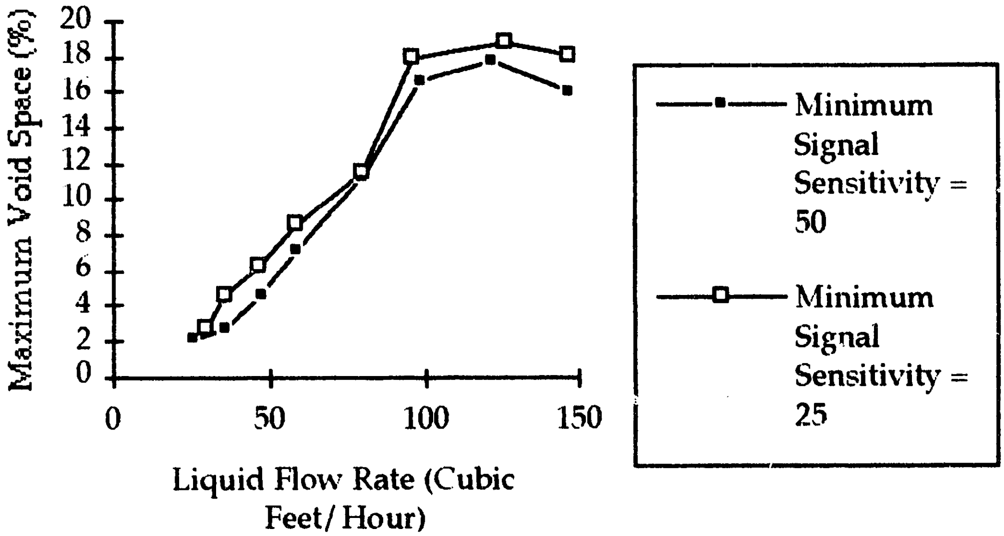

Figure 2.8. Observed Void Space vs. Liquid Flow Rate

was not accurate enough for void space calculations to be reliable. The upward trend of the data to 100 ft^3/hr is explained by the fact that the gas bubble velocity is increasing. When the bubbles are moving faster, there is a better chance that the signal can get to the receiving transducer without excess attenuation. The maximum measurable void space is probably near 18-20%, thus the flattening of the curve above 100 ft^3/hr. Also, due to limitations of the flow loop, microscopic air bubbles were being introduced into the system at high flow rates, probably causing the downturn in the data above 125 ft^3/hr.

As previously mentioned, the described experimental system was not designed to test single phase gas flow, for such a downhole gas tool has already been tested by the GRI. The GRI tool operated at 212.8 khz, an order of magnitude difference from the 2 Mhz used in the flow loop in the previous tests (McBane et al., 1991).

The final test was, in fact, to test the effect of using lower frequency transducers. A set of .5 Mhz transducers were installed in the system and investigated. Remembering that the coefficient of attenuation is proportional to the square of the frequency, attenuation should decrease by a factor of 16 in this case. With the drop in attenuation, it was expected that measurements would be feasible at higher void ratios. Unfortunately, the flowcell was too long for transducers of this frequency and the measurements were not reliable.

2.5 Advantages and Disadvantages

The contrapropagation method shows great promise. Using transit-time measurement, it is possible to measure the velocity and sound speed of a flowing fluid. There is significant error at near zero flows, but contrapropagation measurement can measure these low flow rates much better than mechanical tools. The accuracy of the transit-time velocity calculations also appears excellent

The transit-time method requires that the fluid is sonically transmissive. Measurement becomes impossible when there are to many scatterers in the flow such as a signifigant void space. Slug flow or annular flow seem to be beyond the capability of contrapropagation measurement.

Chapter 3

Doppler Flowmeter

3.1 Theory

The Doppler effect is a familiar one. The pitch of a train's whistle is higher as it approaches than as it moves away. This is because the sound waves emitted from the approaching train are being compressed, the wavelength shortened and the frequency increased. The Doppler equation for an approaching sound source is (Weast et al., 1982):

$$f' = f/[1 - (v_S/c)] \tag{3.1}$$

f is the actual emitted sound frequency, f' is the resultant frequency, v_S is the velocity of the source and c is the speed of sound in the medium. If the speed of sound is known, it is possible to measure the frequency shift and calculate the velocity of the train. Solving for v in (3.1):

$$v_S = c[1-(f/f')] \tag{3.2}$$

In 1916, Chilowski and Langevin proposed "bouncing" a sound wave off a moving object (in this case, a boat) and measuring the frequency shift to deduce the speed. The Highway Patrol use this method today, for "radar" guns are such a device. Doppler theory was not applied to fluid flow until 1969, but quickly resulted in a commercially available flowmeter in 1970.

Instead of a car or boat, the ultrasonic pulses are reflected off impurities or eddies in the fluid and the velocity calculated.

Whereas contrapropagation techniques are more accurate in laminar, clean flows, the Doppler method requires turbulence eddies or a second phase for measurement to be feasible. Eddies or phase boundaries provide the "reflective" surface off which the ultrasonic waves can bounce. A paper presented in 1984 by J. Waller sets out guidelines for Doppler measurement. The most important conditions which must occur for accurate measurement are (Waller, 1984 and Lynnworth, 1989):

1. The measured flow must be a liquid
2. Sonic discontinuities for the reflection of the ultrasonic beam are required.
3. The flow profile must be well developed.
4. The flow should be turbulent if sonic discontinuities are not present.

The most common configuration of the Doppler flowcell is similar to that of the contrapropagation flowcell, but the transducers are both aimed upstream. (Figure 3.1) A second configuration is a two path zigzag cell. (Figure 3.2) The transducers are usually in the range of .6 to 1 Mhz (Lynnworth, 1989).

In gas/liquid flow, the ultrasonic pulse bounces off the phase interface and the resultant frequency measured. The velocity calculated will be that of the bubble and not the liquid, unless they are equal, which is usually not the case in vertical flow. This method also works when the reflctors are particulates or oil/water interfaces.

As imagined, a range of frequencies will be returned due to the flow profile. Simple experimentation with a known flow rate will make it possible to choose the correct frequency for accurate estimation of the overall average fluid velocity.

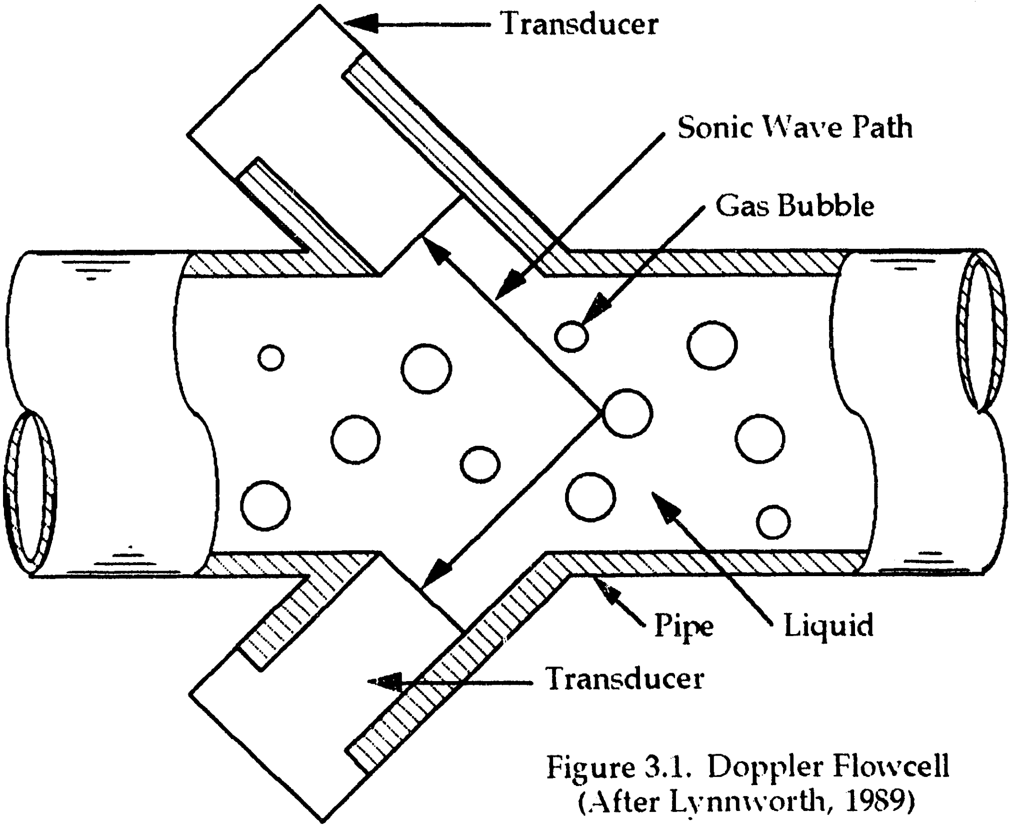

Figure 3.1. Doppler Flowcell
(After Lynnworth, 1989)

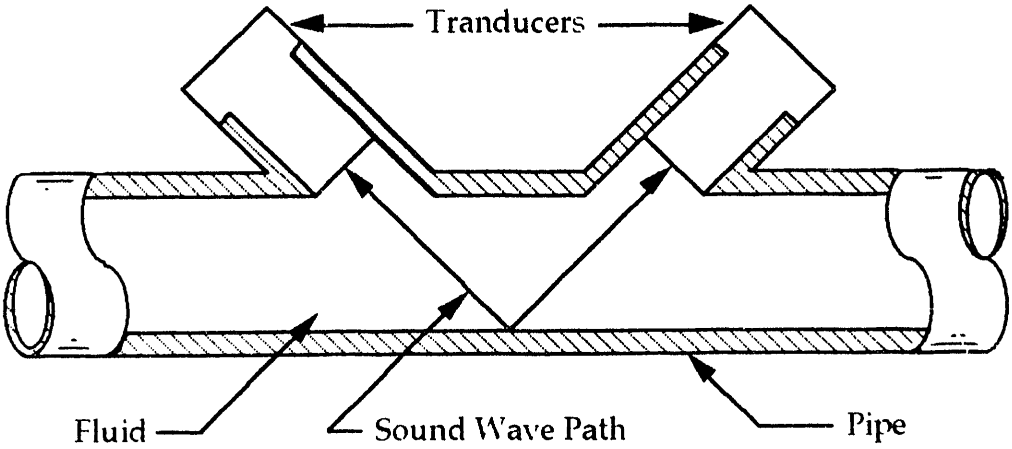

Figure 3.2. Two Path Doppler Zigzag Flowcell (After Lynnworth, 1989)

A Doppler flowmeter was not actually tested during this project, but it is an alternative that needs to be tested in the future. It would increase accuracy and feasibility in the experimental system, especially during multiphase flow.

3.2 Advantages and Disadvantages

The Doppler flowmeter has its advantages and disadvantages. As opposed to the transit-time method, Doppler fluid velocity measurement requires "dirty" fluids, but is not possible in pure single phase laminar flows. In addition, the Doppler method measures the velocity of the second phase present, not the liquid velocity. Also, unlike the contrapropagation method, the velocity calculation is not independent of the speed of sound in the fluid.

Chapter 4

Multiphase Downhole Flowmeter

4.1 Theory

By combining the advantages of both of these methods, it should be possible to build a true multiphase flowmeter. The contrapropagation method would be used to measure the liquid velocity and the Doppler method to measure the velocity of the second phase, whether gas or solid.

A flowcell combining the positive attributes of both methods needs to be constructed. A proposed four transducer flowcell is pictured in Figure 4.1. One pair of transducers (right pair, Figure 4.1) measures transit-times and the liquid velocity, while the other pair (left pair, Figure 4.1) measures the frequency shift and the second phase velocity.

If the transducers could measure transit-times and frequency shift, this flowcell could be built with only two or three transducers.

Ideally, the contrapropagation transducers should be around .5-1 Mhz and the Doppler transducers around 100-200 khz. The diagonally offset flowcell was chosen for transit-time measurement because of the shorter path length. With a short path length, attenuation is decreased because there is a

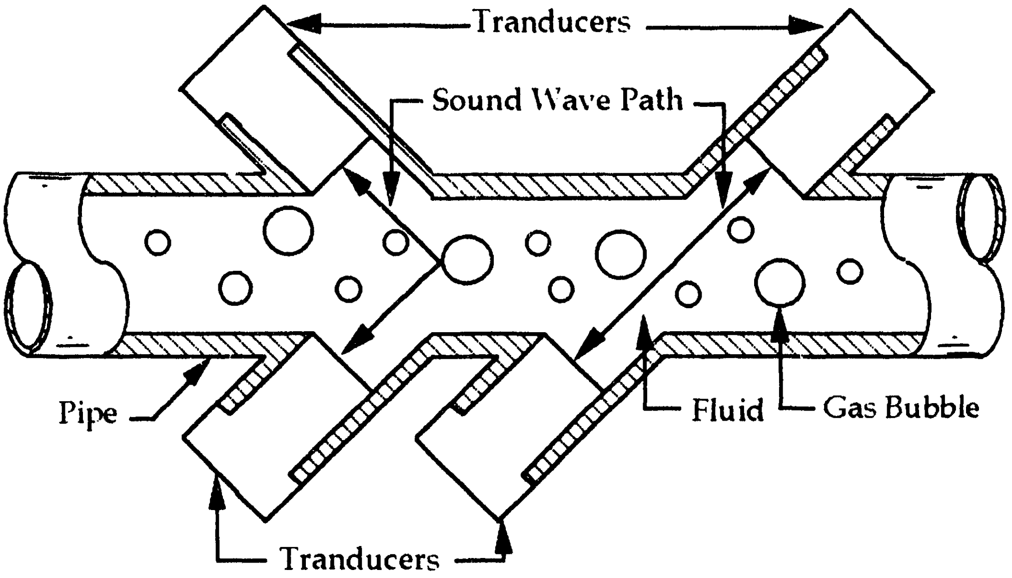

Figure 4.1. Proposed multiphase flowcell utilizing transit-time and Doppler shift ultrasonic measurement

shorter distance over which the attenuation can occur. Using the lower frequency transducers has the same effect.

This benefits of combining both methods are substantial. Doppler velocity calculation is dependent on the sound velocity which the contrapropagation method provides. Doppler measurement fails in clean, laminar flows where transit-time measurement is best. Inversely, Doppler measurement is best in flows where contrapropagation measurement is difficult (Lynnworth, 1989).

This flowcell will be able to calculate the velocity of each phase, but the fractions and densities of each are required for their relative flow rates to be calculated. By using a downhole density tool, the average density and each phase density can be found and the phase fractions calculated. With the densities, fractions and velocities of each phase known, the phase mass flow rates can be determined (Collier and Wallis, 1967 and Govier and Aziz, 1972).

After the proposed flowcell has been tested thoroughly, the flowcell should be inserted into a downhole tool for further testing. This brings up many obstacles such as space constraints and the effects of high temperatures and pressures. The sonde itself will have to have a flow diverter basket similar to that of certain spinner tools to provide for internal flow through the installed flowcell (Figure 4.2).

The basket needs to be retractable for when the sonde is being lowered or raised. Also, in order to measure injection rates, the tool could be inverted, with the basket pointing upwards.

4.2 Advantages

An ultrasonic downhole flowmeter would have many advantages over traditional flowmeters. Besides providing better accuracy in a wider variety of flows, the ultrasonic flowmeter has many attractive features.

Unlike the proposed ultrasonic tool, spinner tools have many mechanical limitations. The spinner flowmeters cannot measure rapidly flucuating flows due to spinner inertial effects. Ultrasonic measurement and calculation are relatively instantaneous, offering a distinct improvement in these cases. Spinner tools also suffer from bearing friction and mechanical breakdown. The proposed flowmeter will not experience any of these mechanical problems, for the measurement method is exclusively electronic, there are no moving parts. The fact that measurement is non-intrusive also means that the tool need not affect the flow profile like a mechanical tool (Hill, 1990).

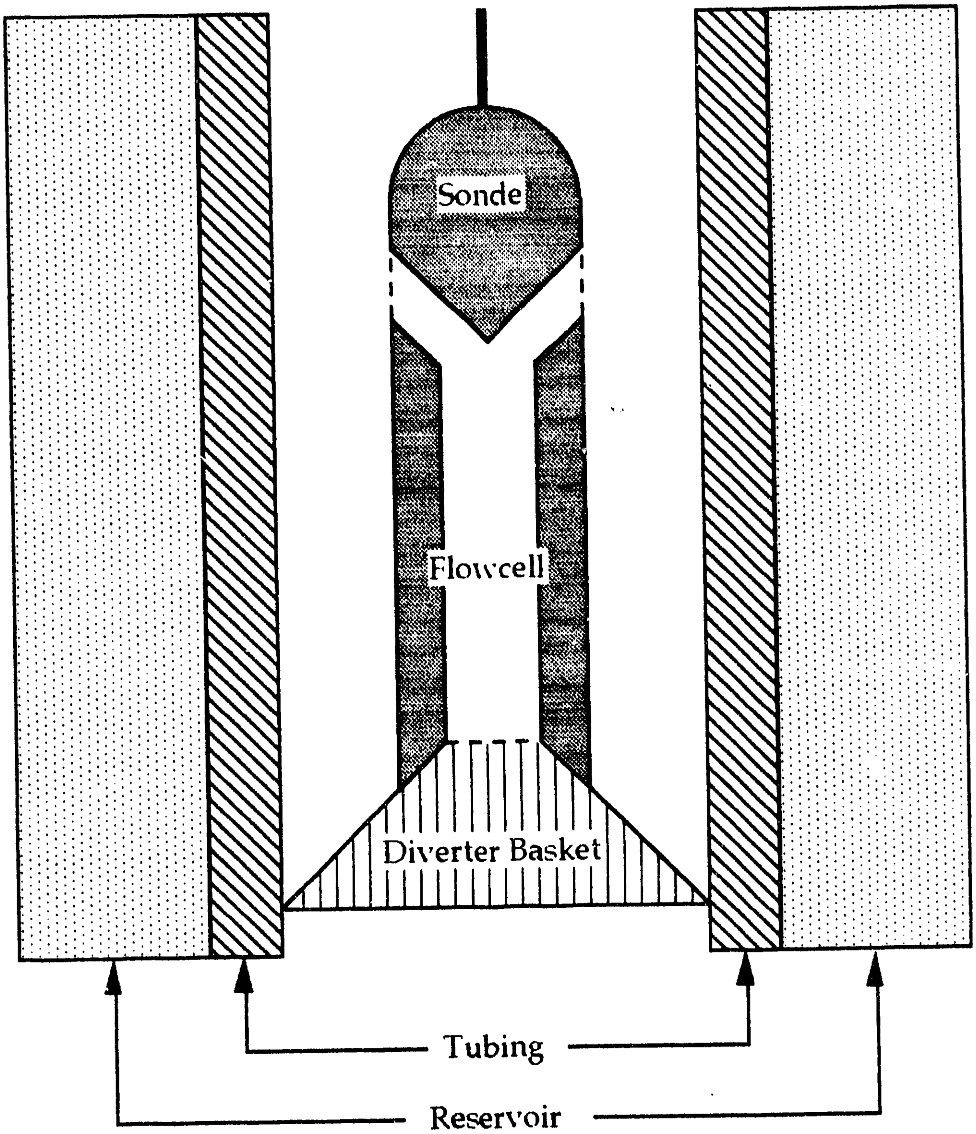

Figure 4.2. Cross-section of the proposed downhole tool in a cased well. The fluid flows into the basket, through the tool and out the ports at top.

Spinner tools usually require at least two passes to actually calculate the flow rates correctly, and even then, the logs contain error. The ultrasonic tool should measure flow rates more accurately in only one pass, saving logging time and expenses (Carlson and Johnston, 1983 and Van Rooy and Vesperman, 1981).

Unlike tracer tools, there is no radioactivity to cope with making the tool safer and more environmentally sound (Bennett et al., 1991 and Hill, 1990).

Chapter 5

Conclusions and Future Research

5.1 Conclusions

Ultrasonic flow rate measurement is feasible and offers an improved method for downhole flow determination. The proposed downhole tool wil have better accuracy at all flow rates than existing tools, particularly when the rates are low or flucuate rapidly.

Except for extreme slug or annular flow, the tool will be able to measure multiphase flow rates. The measurements will provide individual phase velocities and flow rates, something existing tools cannot do at all.

5.2 Future Research

The plans for future research were described throughout the paper. Future projects include the testing of a multiphase flowcell and the construction of a downhole tool. Ultrasonic measurement can be applied to determine other fluid parameters besides flow rates. See the next section for an outline of other ultrasonic investigation possibilities.

5.3 Other Applications of Ultrasonic Logging

Ultasonic testing can be used to determine other fluid parameters than just the velocity and flow rate. In fact, ultrasonic testing is used above ground for many purposes right now. These methods could also be adapted to downhole use.

The contrapropagation flowmeter can measure the speed of sound in the fluid, c, instead of the fluid velocity using the same transit times. Subtracting Equation (2.3) from (2.4) and solving for c:

$$c = (L/2)(1/t_d + 1/t_u) \tag{4.1}$$

Fluid temperature is closely related to the speed of sound. Once the sound speed is known, the temperature, T, of a single phase fluid can be found using the relationship:

$$T = (c/c_{sc})^2 * T_{sc} \tag{4.2}$$

T_{sc} and c_{sc} are the temperature and sound velocity at standard conditions (McBane et al., 1991).

The density and viscosity are in turn closely related to the temperature and can be found using more complicated ultrasonic measurement (Baker et al., 1970). In addition, the Hewlett-Packard pressure guages used downhole today, in fact, utilize ultrasound as the measurement principle (Lynnworth, 1989).

Nomenclature

α = coefficient of sound attenuation

A = conduit/ pipe cross-sectional area

c = speed of sound in medium

c_{sc} = speed of sound in medium at standard conditions

f = Doppler emitted frequency

f' = Doppler resultant frequency

L = transducer spacing

M = mass flow rate

ρ = fluid density

Q = volumetric flow rate

T = temperature

T_{sc} = temperature at standard conditions

t_d = transit-time in downstream direction

t_u = transit-time in upstream direction

v_s = Doppler sonic source velocity

v_f = measured fluid velocity

v_a = average fluid velocity

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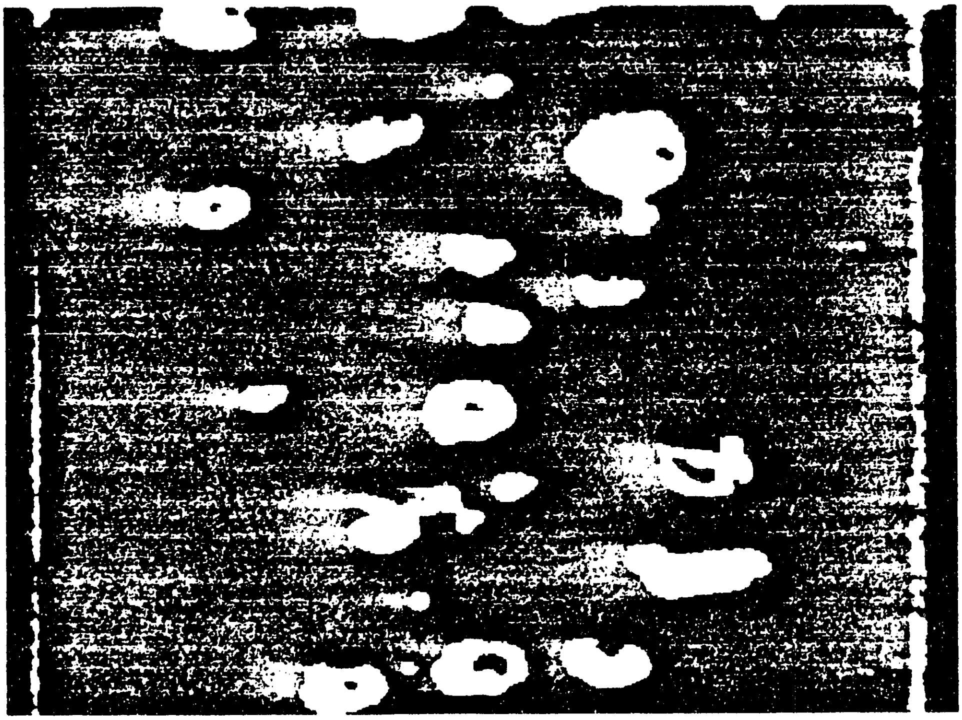
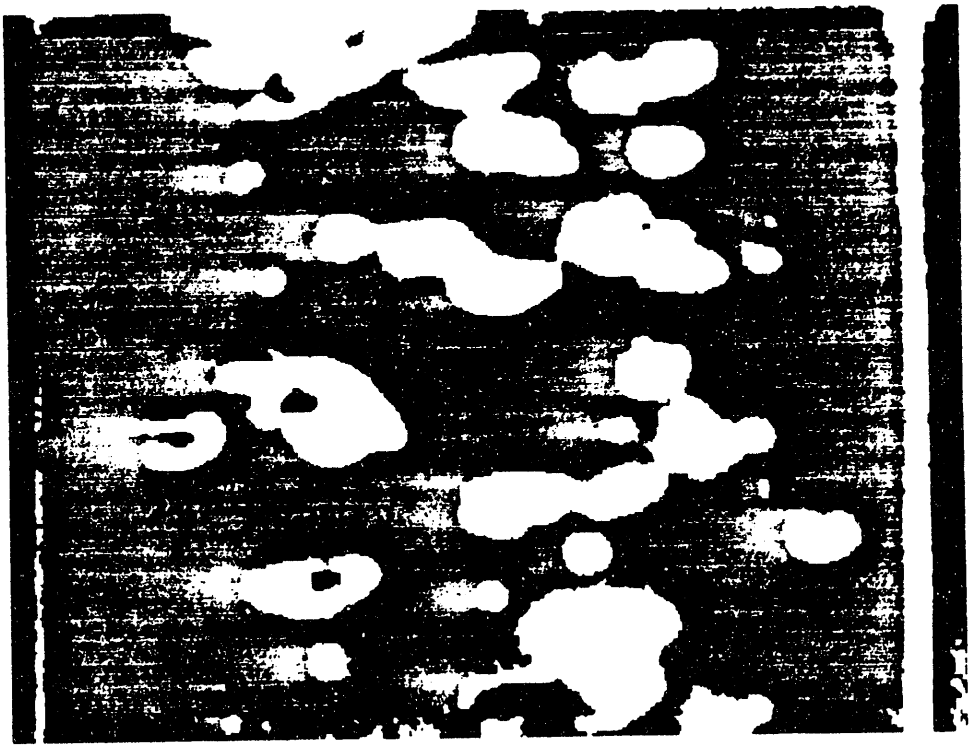
[19] Weast, R.C. and Astle, M.J.: "CRC Handbook of Chemistry and Physics," CRC Press, Boca Raton, Florida (1982).

Appendix: Photographs

The following are scanned images of the photographs. Flow is downwards, and the gas bubbles appear white while the liquid appears black. The scans are enlarged approximately 500 percent.

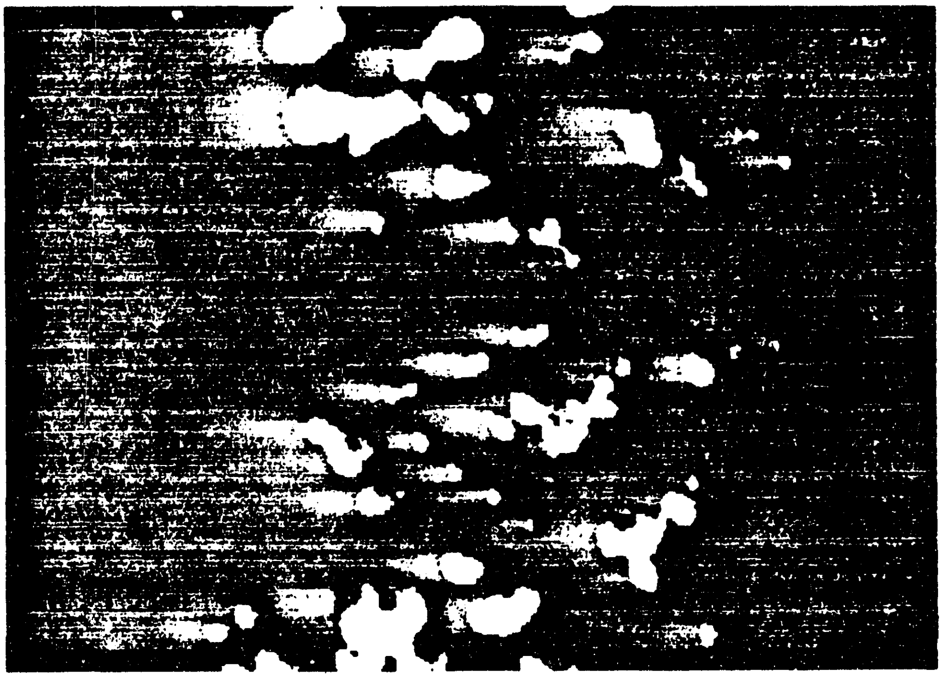


Photograph 1. Water flow rate is 50 ft^3/hr.
Calculated volumetric void space is 1.0 %.
Observed volumetric void space is 4.5 %.



Photograph 2. Water flow rate is 50 ft^3/ hr.
Calculated volumetric void space is 2.0 %.
Observed volumetric void space is 10 %.

Photograph 3. Water flow rate is 50 ft^3/ hr.
Calculated volumetric void space is 3.0 %.
Observed volumetric void space is 15 %.



Photograph 4. Water flow rate is 115 ft^3/ hr.
Calculated volumetric void space is 1.0 %.
Observed volumetric void space is 10 %.

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