MEASUREMENT OF TWO PHASE FLOWS IN GEOTHERMAL PIPELINES USING RADIO FREQUENCY (RF) POWER MEASUREMENTS: EXPERIMENTAL RESULTS

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ABSTRACT

A sensor scheme using radio frequency (RF) power has been investigated for the measurement of two phase flow in geothermal pipelines. The method can provide continual monitoring and be installed into piping in areas of limited pipe runs. The measurement is used to calculate dryness fraction, void fraction, and possibly flow rate in the pipe, and should be independent of temperature. It is accomplished by measurement of RF energy transmitted into the contents of the pipe by antenna, and received by a separate receive antenna. Tests were performed to determine feasibility, investigate antenna designs, and improve transmitter protection schemes. The results and analysis presented in this work show the method has the potential to measure two-phase flow in geothermal pipelines and wells with at least 2% accuracy. It may be used to complement (improve) the accuracy of existing two-phase orifice plates currently in use in geothermal pipelines, or may be used stand-alone, for the measurement of total mass flow rate and enthalpy in geothermal or other pipelines and wells on a continuous basis.

1. INTRODUCTION

1.1 Geothermal steam field management

Development of electrical power from geothermal sources requires continual monitoring and planning to optimize and maintain the energy output from each geothermal well. Maximizing production from a geothermal field with many wells is a balancing act of knowing how the available wells will perform and when to plan for additional wells, and how to determine the most effective time to perform maintenance or other operations. Continuous fluid flow measurement and monitoring may also be a primary condition for resource consent (operation license) and compliance in many countries. The most important parameters to determine from each well are the mass flow rate and enthalpy of the produced fluid, and how these may change over time either by themselves or by interaction with other wells in operation. Various techniques have been devised to determine these two parameters in geothermal fields (see Helbig and Zarrouk, 2012), with most methods complicated by the fact that well production is often two-phase, comprising a mix of steam and water. The techniques do allow determination of the necessary parameters, but are not suited to continual measurement on a minute or hourly basis. The common practice is to perform such tests only quarterly or longer periods, due to expense of testing or the requirement that the test be performed while the well is out of service. Changes occurring in the wells, or interaction between wells, may be missed with such long timespans between test results. The sensor method discussed here can provide data through these long timespans, providing results minute by minute, and may help improve the activity of tuning the steam field system for maximum performance and efficiency.

The sensor measures the fluid contents of a pipe by attenuation of RF signals. A transmit antenna and a receive antenna are installed into the pipe, and a signal is sent from one to the other. Measurement of response provides the necessary data to determine pipe content. The sensors can be placed in relatively close proximity. Initial tests used a distance of one meter for the space between transmit and receive locations, but closer spacing may be possible. A useful configuration would be the use of three antennas, equally spaced 1/2 meter apart. The center antenna would be used for transmit, and the two outer antennas would be for reception.

1.2 One-Dimensional Model

The behavior of a two-phase mixture flowing in a horizontal pipeline can be analysed using a simple one dimensional model. Two important parameters are involved in solving governing equations which are the void fraction (α) and the slip ratio (S). The void fraction is the fractional area occupied by the gas phase:

$$\alpha = A_g/A \tag{1}$$

$$1-\alpha = A_f/A \tag{2}$$

where A_g and A_f are the cross sectional area occupied by the gas and liquid phases respectively while A is the total cross sectional area of the pipe.

The gas ($\dot{m}_g$) and liquid ($\dot{m}_f$) flow rates are:

$$\dot{m}_g = \dot{m}_t\, x = \rho_g\, v_g \alpha \tag{3}$$

$$\dot{m}_f = \dot{m}_t\,(1-x) = \rho_f\, v_f (1-\alpha) \tag{4}$$

where x is the dryness fraction, ρ_g and ρ_f are the densities of gas and liquid respectively, v_g and v_f are the gas and liquid velocities respectively and $\dot{m}_t$ is the total mass flow rate.

By combining equations (3) and (4) we can define the slip ratio (S) as the gas velocity to the liquid velocity:

$$S = \frac{v_g}{v_f} = \left[\frac{x}{(1-x)}\right] \times \left[\frac{(1-\alpha)}{\alpha}\right] \times \frac{\rho_f}{\rho_g} \tag{5}$$

The void fraction can then be expressed as:

$$\alpha = \left\{1 + \left[\frac{(1-x)}{x}\right] \times \left[\frac{\rho_g}{\rho_f}\right] \times S\right\}^{-1} \tag{6}$$

For a homogenous flow where the velocity of gas is the same as that of liquid (i.e. S=1) then equation (6) reduces to:

$$\alpha = \left\{1 + \left[\frac{(1-x)}{x}\right] \times \left[\frac{\rho_g}{\rho_f}\right]\right\}^{-1} \qquad (7)$$

The application of equation (6) for a range of slip ratios in a geothermal pipeline at typical pressure of 10 bar abs for a dryness fraction ranging from 0 to 1 is given in Figure 1 below:

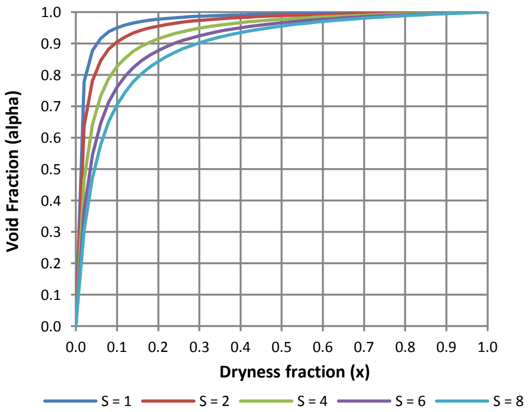

Figure 1. Void fraction vs dryness fraction for a range of slip ratios at a pipeline pressure of 10 bar abs.

Figure 1 shows how void fraction and dryness fraction are related. For a dryness fraction of 0.2 for example, it can be seen that the void fraction will be greater than 0.8 for all slips ratios up to S = 8.

For most dryness fractions of interest in geothermal pipeline flow the volume of the pipe is mostly filled with air/steam and not liquid. A common dryness fraction of interest for geothermal operation would be 0.1 or greater. For values of dryness fraction greater than 0.1 about 70% or more of the pipe internal volume will be filled with air/steam and not liquid. This is important for measurement of water content via RF attenuation. A large portion of the volume being analyzed is effectively empty of liquid, which is useful for this technique as will be demonstrated later in the results.

This analysis shows the advantageous relationship between void fraction and dryness fraction. Being able to ultimately measure the dryness fraction via this sensor will allow the calculation of the enthalpy at a given pipeline pressure:

$$h = h_f + x\, h_{fg} \qquad (8)$$

where: h is the total enthalpy (kJ/kg) at the measured (pressure) location, h_f (kJ/kg) is the liquid enthalpy and h_{fg} (kJ/kg) is the latent heat respectively at the pipeline pressure.

This sensor can potentially provide the necessary information to calculate the enthalpy as shown above. Determining enthalpy without disturbing production flow will be of great benefit to the monitoring of well behavior and give the geothermal steam-field engineers additional valuable information on the performance of wells. Such continual monitoring can also help improve the accuracy of two-phase orifice plates (Helbig and Zarrouk, 2012) when measuring the mass flow rate of two phase flows.
Also, if the sensor is used near in close proximity (downstream) of an orifice plate, the results from the sensor may improve, as the plate forces the steam and water to become an almost homogenous mixture flowing at the same velocity through the orifice plate throat. This homogenous flow may provide for smoother measurement from the senor and less need for averaging, and results in slip ratios near unity.

2. RF MEASUREMENT

2.1 Introduction

This sensor relies on determining the contents of the pipe through the effects the pipe contents have on RF energy. A steel pipe is conductive, and a transmitted signal inside the pipe will reflect off walls in all directions. This phenomenon allows the RF energy transmitted inside a pipe to arrive at the receive antenna in the pipe from many directions. Water and other fluids inside the pipeline attenuate the RF energy. Any water located anywhere in the pipe will have an effect on the overall signal strength received at a receive antenna, and the amount of liquid (water) or gas (steam/air) material can be determined by the amount of attenuation. This will allow the termination of the void fraction and hence can be used to calculate the dryness faction using equations (6) or (7) which is then used to calculate the enthalpy at the pipeline conditions using equation (8).

2.2 Transmit requirements

To accurately measure the attenuation of the signal, the actual RF energy transmitted inside the pipe must be known to a fine degree. The impedance of the environment inside the pipe is a changing phenomenon, as water and steam flow together through the pipe and over the antennas. With such impedance mismatches occurring, RF energy will not entirely be transmitted out the transmit antenna into the pipe itself. Some, or perhaps much, of the RF energy of a transmitter maybe reflect back to the transmitter and not propogate out the antenna. This can be a major problem to the transmitter itself, dependent on signal power levels. Transmitters need protection from such reflected RF power, and the protection method chosen here is the use of a circulator. A circulator can 'redirect' reflected energy, protecting the transmitter output, and shunting the power away to a third port which usually dissipates that energy safely into a properly impedance-matched load. In the case of this sensor the reflected energy will be measured, and therefore the actual forward radiated energy can be determined by comparing the reflected power to the total forward power from the transmitter. This way the dynamic forward power can be determined when transmitting into a variable impedance (i.e. the contents in the pipeline).

2.3 Block diagram

Figure 2 gives a block diagram of the test configuration. For testing, a spectrum analyzer with tracking generator was used as a transmit source, and average power measurements are taken from both RF meters. The received signal from one receive at a time was viewed and measured with the spectrum analyzer. The reflected signal is measured in dBm (sometimes referred to as dB_{mW} or decibel-milliWatts) is an abbreviation for the power ratio in decibels (dB) of the measured power referenced to one milliWatt (mW). These power levels will correspond to amount of water in the pipe, which defines void fraction, and will be used to calculate dryness fraction and then enthalpy using equations (6) and (8).

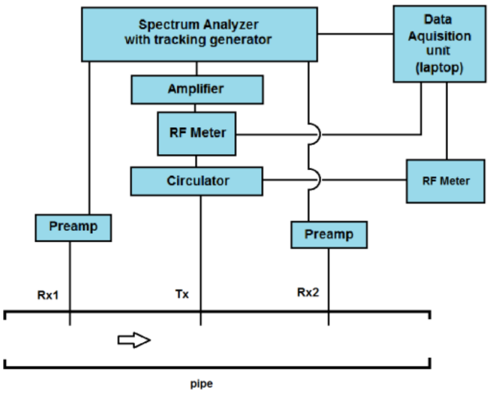

Figure 2: Measurement block diagram

2.4 Test setup

Tests were conducted on a commercial steel pipe with an 8 inch internal diameter, with suitable antennas introduced to the interior through threaded fittings. The test setup is shown in Figures 3 through to 5.

Figure 3: Test setup, using an 8 inch internal diameter steel pipe.

The spectrum analyzer and transmit amplifier can be seen in Figure 3, with the transmit antenna connection on the top of the pipe, shown on the left.

Figure 4: Receive antenna and preamp mounted vertically into pipe from top.

Transmit and receive antennas are positioned vertically in the figures 3 and 4. An alternative 45 degree receive antenna position was also initially tested, as shown in Figure 5 below.

Figure 5: Receive antenna and preamp, mounted into pipe at 45 degree angle.

The antennas were initially mounted in the lower 45 degree positions similar to TFT tap points seen on piping for tracer flow tests. With antennas mounted on vertically out the top, they remained dryer (not flooded by water) till the pipe was more than 60% full of water. This was useful for antenna testing and design, but made little difference to actual readings. In actual field locations, annular flows and other regimes will likely allow most of the water in the pipe to be near the pipe walls on all internal surfaces. The antennas will be flooded regardless of their mount locations, and the transmit design must allow for the variable impedance that will occur.

2.5 Water levels

The amount of water introduced to the pipe is measured on a simple linear scale, as shown in Figures 6 and 7.

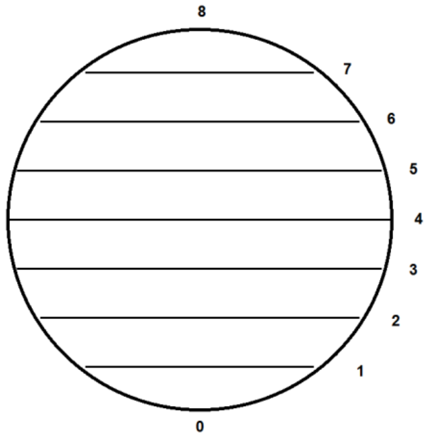

Figure 6: Linear water level scale

Figure 7: Linear scale, shown on vertical tape added to face of view port.

A conversion of these levels to void fraction is shown in Table 1.

Table 1: conversion of water level to void fraction

Water level	Area	Void Frac.
0	0	1.00
1	3.63	0.93
2	15.31	0.70
3	18.29	0.64
4	20.57	0.59
5	22.33	0.56
6	44.44	0.12
7	46.64	0.07
8	50.27	0.00

To avoid a reflective surface and to better duplicate geothermal flow conditions, a bubbler was added that introduces air into the pipe from a nozzle with multiple ports down the length of the pipe, as shown in figure 8.

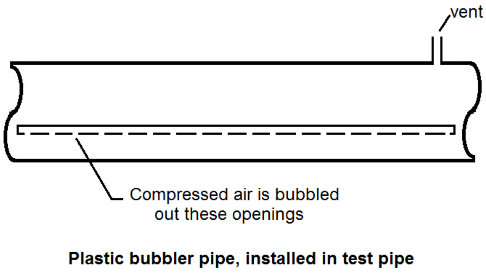

Figure 8: bubbler pipe

The pipe is vented at the top to allow for escape of the excess air, thereby leaving the percentage of water-to-air the same regardless of whether the bubbler was on or off. The bubble action was sufficient to make the water in the pipe entirely chaotic, filling the full pipe volume with a mixture of air and water at most water levels, with the exception of perhaps when testing level 1 (Figure 6). At this level the bubble action served to spread the water around the lower 40% of the pipe, and definitely did not allow the water to remain pooled in the bottom of the pipe volume, or to have a smooth reflective surface.

2.6 Test procedure

For each test, water was introduced to the pipe and allowed to settle so a ‘level’ could be determined. Then the test began using the tracking generator as signal source, and amplification added as needed, up to 1 Watt of microwave power output initially, and additional amplification added in later tests.

Results were taken with ‘flat’ water at first, and all equipment checked for correct operation and readings, then the bubbler was enabled allowing the water in the pipe to be more chaotic. This caused readings to be chaotic as well, and averaging of power levels became necessary. Averages of 30 seconds and one minute were used, but generally it was found that average times greater than about 15 seconds were sufficient to obtain a stable power reading. After this was determined, no more 1 minute averages were used, and results were averaged for 30 seconds.

After readings at each water, the bubbler was turned off and more water was introduced to the pipe, allowed to settle for a correct level reading, and the procedure repeated. This was done for all water levels up to level 8, where the pipe is fully filled with water.

2.7 Iterations and trials, discussion

Many tests were performed with water levels of 2 to 5. During this part of the analysis, antenna designs were changed, tuned for length and different sealing materials, and the transmit power levels were modified. In general much testing was done to determine methods that would help to protect the ‘health’ of the transmitter, and measurements taken to help determine the variance in impedance. Balance tests were performed to determine the accuracy of the two power meters, and their locations swapped and compared, before full testing was allowed to proceed.

3. TEST RESULTS

3.1 Initial results

Many trials were conducted. Results of four tests, labeled 1 through 4, will be presented here. Each of these tests served a different purpose, and helped to develop and constrain the various parameters that come into play in development of this technique.

3.2 Test 1

Test 1 parameters:

- Transmit power: 1 Watt forward.
- Antenna spacing: 1 meter
- Initial antenna design

Test 1 (Figure 9) shows typical results from one of the initial tests. The transmit and receive antennas are placed 1 meter apart at the 45 degree position (Figure 5) off the lower portion of the pipe. They are entirely under the standing water when the water level is greater than that of levels 5 or 6. Transmit power output was 1 Watt.

3.3 Test 2

Test 2 parameters:

- Transmit power: 1 Watt forward.
- Antenna spacing: 0.5 meter
- Initial antenna design

Tests 2 (Figure 9) shows typical results when the spacing between transmit and receive antennas is 0.5 meter. Results show that received signals are able to be measured with greater water levels, but the full 'dynamic range' of the results is not as large as in Test 1.

3.4 Test 3

Test 3 parameters:

- Transmit power: <u>6 Watts</u> forward.
- Antenna spacing: 1.0 meter
- Initial antenna design

Test 3 (Figure 9) used higher transmit power, and also has the antennas positioned in the vertical position, protruding out the top of the pipe, in an attempt to increase the measurement dynamic range.

3.5 Test 4

Test 4 parameters:

- Transmit power: <u>2.4 Watts</u> forward.
- Antenna spacing: 1.0 meter
- Modified antenna design

Test 4 (Figure 9) shows results of antenna redesign and tuning. The power level is not as high as in Test 3, yet the response shows a greater received signal even at high water levels. This test shows the potential improvements possible with proper antenna impedance designs for the internal pipe environment.

Results of all four tests are summarized in Table 2 below, and shown in Figure 9.

Table 2: test results. Tests 1-4

Void Frac.	Test 1	Test 2	Test 3	Test 4
	dBm	dBm	dBm	dBm
1.00	55		70	
0.93	43	57	66	
0.70	17	10	50	
0.64	3	0	18	
0.59	-5	-2	6	54
0.56	-15	-8	-3.8	45
0.12	-30	-12	-21	-10
0.07	-30	-13.5	-28	-12
0.00	-30	-15	-30	-15

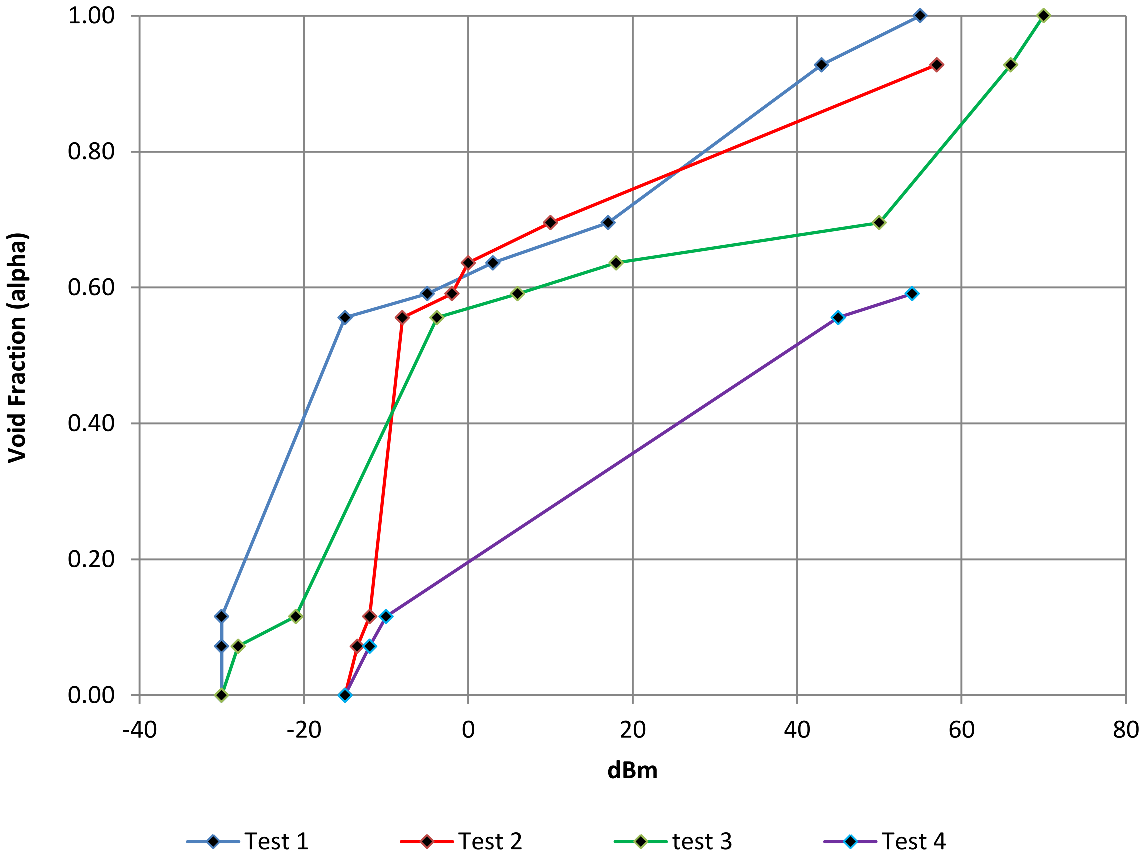

Figure 9: Test results. Tests 1-4

3.6 Test results initial discussion

The four tests presented help explain aspects of this method.

Test 1 shows that the received signal level is too small for accurate reception of power level when the pipe if filled to level 6 (Figure 6) and above. This corresponds to a void fraction of 0.12 or less. However, reception in the more common void fraction range of 1.0 to 0.7 shows good performance, even with only 1 Watt transmit power.

Test 2 shows that accurate reception of power levels can be accomplished even with pipes very full of water by using closer antenna spacing. At spacing of 0.5 meter a received signal was high enough to be above the noise floor and power levels could be determined, yet this appeared to also show an overall decrease in dynamic range.

Test 3 shows the effect of higher transmit power. The microwave amplification used produced 6 Watts transmit power, and appears to show that power levels can be determined at high water content without sacrificing overall dynamic range as seen in Test 2.

Test 4 shows the effects possible by better evaluation of antenna design. The test uses a lesser power level of 2.4 Watts transmit power and shows the effect antenna tuning can have on the performance when the antenna is matched to the expected impedance of certain ranges of water content in the pipe. It also shows that an antenna design made to more properly match the expected impedance of the water-air mixture allows for a more efficient transmission of power, and a more efficient reception capability.

3.7 Tuning the sensor for specific performance.

For the RF sensor to be useful for the geothermal industry, it must accurately measure small differences in dryness fraction at the levels of dryness fraction that are normally expected. Accurate determination of dryness fraction when the pipe is filled with 70% or greater amounts of water may be of less interest in geothermal applications. Therefore the dynamic range of the sensor at water levels of 0-4, or void fractions of between 1.0 and 0.7, may be of primary interest.

This initial testing has shown that a sensor based on less than 10 Watt transmit power and a transmit/receive antenna spacing of no more than 1 meter would be able to make an effective device for measurement of the expected dryness fraction with acceptable accuracy. Such a design is well within the capability of compact electronics and field-installable equipment.

4. CONCEPTS FOR FIELD INSTALLATION

4.1 Installation of the antennas into the pipe.

These preliminary tests do not fully replicate actual field conditions. Most actual piping may be larger in diameter, which in some ways may help make this method work even better. The results from Test 1 and 2 show that transmission of the RF power through a larger volume of the mixture has the advantage of increasing dynamic range, so a pipe of larger diameter may provide much the same advantageous effect. A distance of 0.5 meter between antennas may work well with a larger diameter pipe, and is recommended for initial testing in actual field locations. Three tap ports are recommended, for a total length requirement of 1 meter (Figure 10). If such spacing is not available, other distances could likely be made to work as effectively.

Installation of the antennas into the pipe must allow access for maintenance and support to take place without disruption to the flow in service. The antennas must be able to be inserted and removed while the flow is under pressure, which leads to the need for an insertion method that includes a method to control pressure, such as a valve. A standard (1 inch) tap such as that used for Tracer Flow testing and sampling could be used for antenna insertion, and as a permanent mount. It also has the advantage of already having been designed to meet most piping agency approvals. Figures 10 and 11 show details of a potential method for antenna installations.

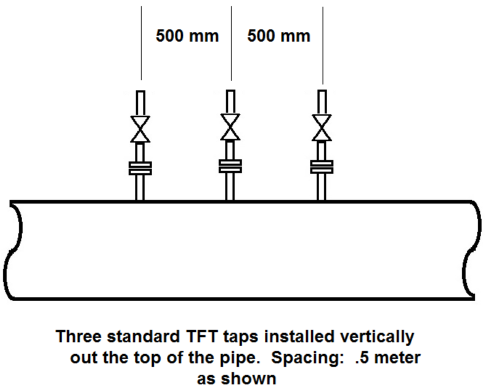

Figure 10: tap ports for installation of 3 antennas

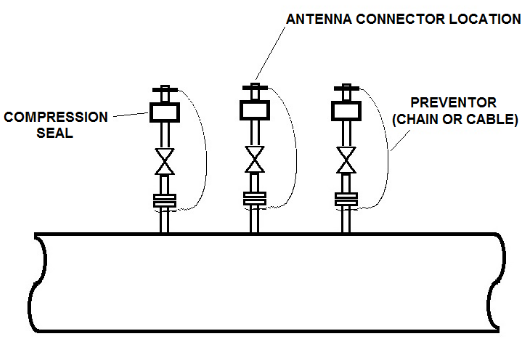

Figure 11: Antenna assemblies inserted through tap ports.

Three ports are recommended, as this gives the opportunity to provide additional services and some redundancy:

1) Dynamic circuitry can allow antennas to be switched from one circuit to another. With switching, any antenna could be used for transmit or receive. With three antennas, failure of one antenna would allow continued operation until the failed antenna can be replaced.

2) The use of three antennas allows for a potential to measure more phenomenon than just dryness fraction. With the center antenna as the transmitter, and the two end antennas as receive antennas, it may be possible to determine velocity of the flow. This would be done by comparison of the two received signals.

5 CONCLUSION

Tests have been performed to analyze a sensor method that has the potential to provide continuous measurement of the two-phase contents of a pipe using RF power. The initial tests show good response with suitable dynamic range without requiring high power levels or a long section of pipeline. A possible mounting scheme with minimal impact on field piping and approvals is proposed that would also allow for additional data to be taken that may provide the necessary information to determine flow rate as well as dryness fraction. The sensor method allows for continuous measurement by sensing the flow in a minimal length of piping, and with specific calibration may also be able to be mounted near bends, orifice plates, or other disturbances to flow without degradation of the sensors performance.

Field testing and further work are needed to develop calibration plans to accurately provide values of dryness fraction from the measured received signals. Such testing may be enhanced by mounting the sensor in close proximity (downstream) of existing two-phase orifice plates, as the more homogeneous flow in that region will simplify calculation and may provide a smoother response. This will simplify the operation of the RF method, and complement the measurements of the two-phase orifice plate with an independently determined enthalpy.

REFERENCES

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