PROCEEDINGS, Twenty-Seventh Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 28-30, 2002
SGP-TR-171

CONTINUOUS ENTHALPY QUANTIFICATION FROM RESISTIVITY MEASUREMENT OF TWO-PHASE FLOW IN A PIPELINE

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ABSTRACT

The resistivity of a steam-water mixture flowing in a pipeline can be measured and used to quantify the enthalpy of production from a geothermal well continuously in real time (patent applied for).

INTRODUCTION

A resistivity measurement can be used for continuous measurement of the volume fractions of two-phase mixtures flowing in a pipe. This can be used to determine the enthalpy of a steam-water mixture, the oil-water ratios of an emulsion, or the fractions of any two-phase mixture with a resistivity contrast between the phases.

Several experiments have been performed at the Coso Geothermal Project to test the theory and the practicality of resistivity measurement of two-phase steam-water flow in a pipeline. The experiments indicate that resistivity can be measured in a pipeline and that liquid volume fraction (LVF), steam flash fraction, and enthalpy can be determined from the result. Work continues to improve the reliability and accuracy of the meter.

THEORY

Volume resistivity can be measured with a four-electrode resistivity meter. This method is commonly used to measure soil resistivity, water conductivity, and the resistivity of many other bulk materials. The resistivity of the fluid in a pipeline can be measured by causing a current to flow through two electrodes at the top and the bottom of the pipeline and measuring the voltage with two electrodes located on the side of the pipeline as shown in Figure 1. The inside of the pipeline should be electrically insulated so that the current only flows in the fluid.

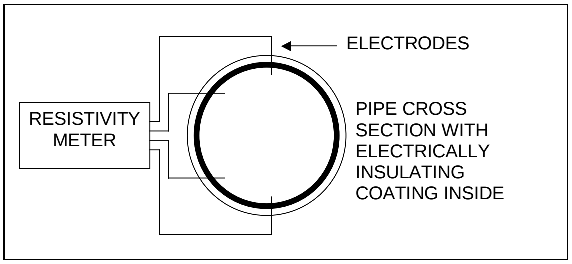

Figure 1. Pipeline resistivity measurement.

Liquid volume fraction can be calculated from the resistivity of a two-phase mixture if the resistivities of the phases are different. The resistivity of water depends on its salt content, while steam is non-conductive. The Archie formula for relating formation resistivity to porosity can be used to relate two-phase resistivity to liquid volume fraction. Liquid volume fraction (V_L) is equal to the square root of water resistivity (R_W) divided by two-phase mixture resistivity (R_{TP}) from the resistivity meter.

Equation 1. $$V_L = \sqrt{\frac{R_W}{R_{TP}}}$$

Steam mass fraction or quality (X) is related to liquid volume fraction by the density of the liquid (D_L) and the density of the steam (D_S), which can be determined from steam tables using the pressure or temperature.

Equation 2. $$X = \frac{(1-V_L)D_S}{(1-V_L)D_S + V_L D_L}$$

The enthalpy of a water and steam mixture can be calculated from liquid volume fraction and pressure. The enthalpy of the two-phase mixture (h) is related to flash fraction by the enthalpy of the liquid (h_L) and of the steam (h_S), which can be determined from steam tables using the pressure or temperature.

Equation 3. $$h = (1-X)h_L + Xh_S$$

EXPERIMENTS

Several experiments have been performed at the Coso Geothermal Project measuring the resistivity of two-phase steam-water flow under different conditions and by different methods.

Meter Set Ups

The first test was set up on an injection line carrying 223.5°F brine. The resistive enthalpy meter consisted of 8 inch plastic lined pipe discharging to atmosphere. Resistivity was measured using a soil resistivity meter attached to Teflon coated thermocouple wires inserted through flanges. The brine was flashed to 15.2 psia in the meter section. Enthalpy calculated directly from the unflashed liquid temperature is a reliable reference to determine the accuracy of the resistive enthalpy measurement.

For the second test, the same resistive enthalpy meter section was attached to an HP separator brine outlet at 326°F and discharged to atmosphere. Valves at the inlet and outlet of the test section controlled the pressure. With the outlet valve open, the inlet valve was opened in steps to measure enthalpy at increasing pressure. When the inlet valve was full open, the outlet valve was closed in steps to increase the pressure further until the test section was at the HP brine pressure and full of liquid. Enthalpy calculated directly from the unflashed liquid temperature is a reliable reference.

The third test was conducted on the flow line of a geothermal well producing from a two-phase reservoir. The resistivity measurement was made in a venturi meter to reduce liquid holdup and to measure flow rate at the same time using the James method for two-phase flow through orifices. Thermocouple wires were held in a groove in the center of the venture with epoxy and the inside of the venturi was coated with epoxy. Resistivity was measured by a water conductivity meter with a data logging function. The venturi-enthalpy meter worked for three days, until the epoxy was washed away by the flow. Enthalpy calculated from resistivity was compared to enthalpy measured by the tracer dilution method. This is a less reliable reference than a liquid temperature measurement because the tracer dilution test was not conducted at the same time as the resistive LVF measurement and production enthalpy from a two-phase reservoir can be highly variable.

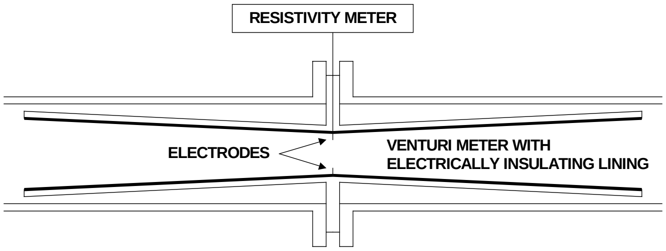

Figure 2. Venturi-resistivity meter for flow and liquid volume fraction measurement.

A fourth test was conducted using spark plugs as electrodes in a James tube well test flowline. The side electrodes were removed from the plugs and the base was covered with epoxy. Four holes were drilled and tapped in the wall of 12” pipe at 6

Table 1. Comparisons of reference and measured liquid volume fraction, flash fraction, and enthalpy.

Test	Temperature (F)	Pressure (psia)	Reference LVF	Meter LVF	Error	Reference Flash Fraction	Resistive Flash Fraction	Error	Reference Enthalpy (Btu/lbm)	Meter Enthalpy (Btu/lbm)	Error
Inj. Brine	214	15.2	0.0572	0.1331	132%	0.0105	0.0042	-60%	191.9	185.8	-3%
HP Brine	211	14.2	0.0043	0.0333	668%	0.1217	0.0172	-86%	296.7	195.2	-34%
	218	16.5	0.0053	0.0368	589%	0.1145	0.0179	-84%	296.7	203.3	-31%
	242	26.1	0.0108	0.0457	323%	0.0901	0.0221	-75%	296.7	232.0	-22%
	256	33.4	0.0165	0.0533	223%	0.0758	0.0238	-69%	296.7	247.7	-16%
	265	38.9	0.0218	0.0475	117%	0.0665	0.0309	-53%	296.7	263.4	-11%
	274	45.1	0.0294	0.0550	87%	0.0571	0.0306	-46%	296.7	272.0	-8%
	297	64.4	0.0717	0.0967	35%	0.0325	0.0237	-27%	296.7	288.6	-3%
	312	80.2	0.1662	0.3688	122%	0.0159	0.0055	-66%	296.7	287.3	-3%
	324	94.9	0.6319	0.9841	56%	0.0022	0.0001	-97%	296.7	294.7	-1%
	325	96.3	0.7851	0.9385	20%	0.0011	0.0003	-76%	296.7	295.9	0%
Well Flow	312	80.2	0.0032	0.0034	6%	0.5011	0.4871	-3%	733.9	721.2	-2%
JT Test	255	32.5	0.0061	0.0103	68%	0.1777	0.1137	-36%	391.0	330.7	-15%

o'clock, 8 o'clock, 10 o'clock, and 12 o'clock positions. There was no insulating coating inside the pipe. Resistivity was measured with a data logger set up to apply current, measure voltage, and record resistivity continuously. The resistive enthalpy measured by the spark plugs was compared to the enthalpy determined from the James tube.

A fifth test was attempted using a venturi-resistivity meter with a ceramic insert to hold the electrodes, however the electrodes shorted out immediately so no data was collected.

Test Data

Table 1 shows comparisons of reference and measured liquid volume fraction, flash fraction, and enthalpy for the four successful tests.

The liquid volume fraction and flash fraction measurements in the first test on injection brine show large errors. But the enthalpy shows a much smaller error.

The second test on HP brine shows large errors below 34 psia and lower errors above 34 psia. This may be due to the nature of the flow through the meter. At low pressure the inlet valve was mostly closed and flow was entering at a high velocity. There may have been stratified flow in the test section with a stagnant liquid strata causing the liquid volume fraction to read high. At 34 psia the inlet valve may have been open far enough to change the flow regime in the meter to annular flow. Errors were larger for the LVF and the flash fraction than for the enthalpy, as with the injection brine.

The third test on high enthalpy well flow shows good agreement between reference and measured liquid volume fraction, flash fraction, and enthalpy. This well produces from a two-phase reservoir so the enthalpy is well above liquid enthalpy at the measurement pressure. Still, the liquid volume fraction error is larger than the flash fraction error, which is larger than the enthalpy error.

The fourth test on the James tube well test facility shows high errors. The liquid volume fraction is high while the flash fraction and enthalpy are low. Again, the liquid volume fraction error is larger than the flash fraction error, which is larger than the enthalpy error. The lack of insulating coating on the inside of the pipe probably contributed to the error.

Analysis

Figure 3 shows the correlation between reference and measured LVF, with logarithmic scales to spread out the smaller values. The measured LVF is higher than the reference LVF for all the data.

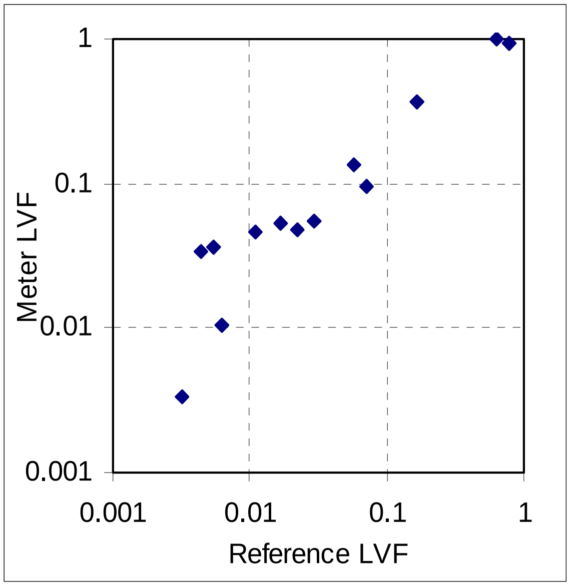

Figure 3. Liquid Volume Fraction Correlation.

Figure 4 shows the correlation between reference and measured flash fraction, with logarithmic scales. The measured flash fraction is lower than the reference flash fraction for all the data, especially from 0.05 to 0.15 reference flash fraction which corresponds to the low pressure HP brine that may have been affected by stratified flow, as discussed above.

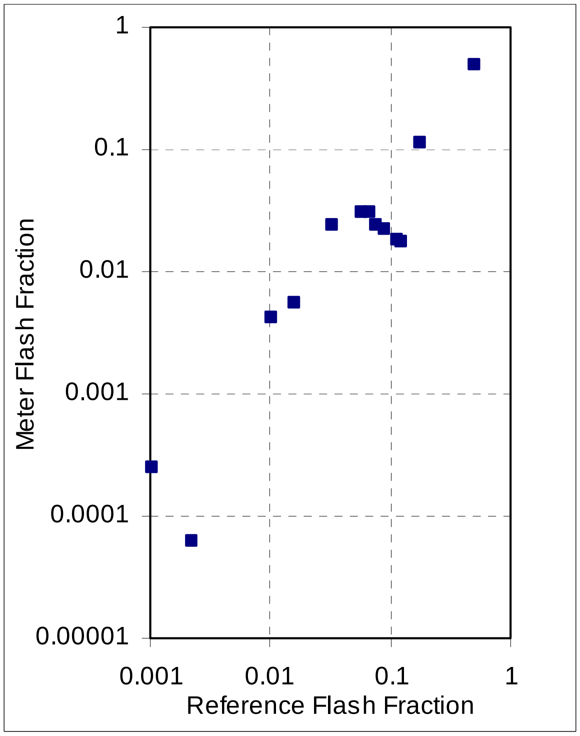

Figure 4. Flash Fraction Correlation.

Figure 5 shows the correlation between reference and measured enthalpy. The measured enthalpy is close to the reference enthalpy except for the low pressure HP brine, as discussed above.

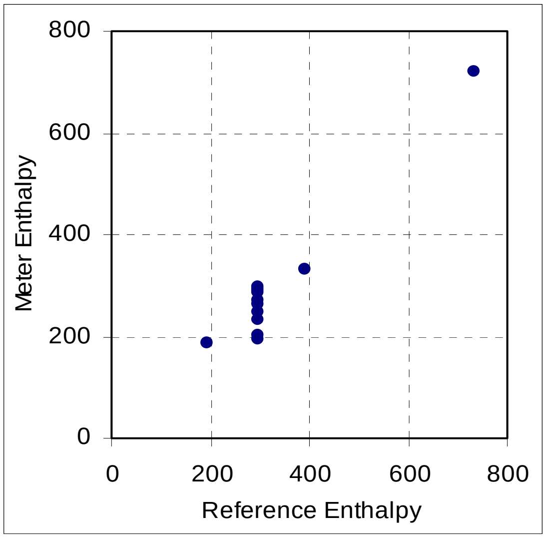

Figure 5. Enthalpy Correlation.

There are two main sources of error in the determination of enthalpy from measurement of liquid volume fraction by resistivity – liquid holdup and electric current leakage. Both tend to cause high LVF indication and, therefore, low enthalpy readings.

Liquid holdup causes the ratio of liquid to vapor in the meter section to be higher than the ratio of liquid to vapor flowing through the meter. Ideally the steam and water are thoroughly mixed and moving at the same velocity. This is the case for high velocity flow where the water is dispersed in the steam as small drops. At lower velocities there is an annular ring of liquid flowing along the wall of the pipe at a slower velocity than the steam and water mixture in the center of the pipe. The placement of the current electrodes at the top and bottom of the pipe and the voltage electrodes above and below the vertical midpoint of the pipe concentrates the resistivity measurement in the center of the pipe where most of the flow occurs, but a large annular liquid layer will divert the current through the liquid and increase the LVF reading. At even lower velocities the flow becomes stratified with the water flowing along the bottom of the pipe and steam flowing faster along the top of the pipe. In this condition the resistivity LVF reading will also be too high.

The resistivity reading itself may also be affected by errors that tend to elevate the LVF reading. The resistivity of the two-phase flow is high compared to liquid water or steel. So any breakdown in the insulation lining the pipe, or the electrodes, or the wires leading to electrodes will divert some of the current through the pipe, reduce the resistivity reading, and cause the LVF to read high. This would certainly be the case in the test with sparkplugs inserted in pipe without any insulating coating.

The measurement error needs to be reduced but some error in the measurement of LVF can be tolerated in the determination of enthalpy. The error in enthalpy is consistently less than the error in the steam fraction, which is generally also less than the error in the LVF. This is due to the large difference in specific volume of steam and water. When a small amount of the liquid is flashed to steam at 100 psig its volume increases 200 times. So a small change in the flash fraction causes a large change in the LVF especially at low enthalpies when the flash fraction is small. Also, at low enthalpies there is a small difference between the total enthalpy and the flashed liquid enthalpy so a large error in flash fraction produces a relatively smaller error in the enthalpy of the two-phase mixture.

The error of the resistive LVF measurement can be reduced by various means. Two-phase flow correlations could be used to predict the liquid hold-up and correct the LVF. The meter can have a reduced flow area like a venturi to increase the velocity and reduce liquid holdup. The LVF may also require some adjustment factors based on flow regime. Better materials and construction will reduce error due to current leakage.

CONCLUSION

The resistivity of a steam-water mixture flowing in a pipeline can be measured and used to quantify the enthalpy of production from a geothermal well in real time and continuously. Work continues to improve reliability and accuracy of the meter.

The design and construction of the meter needs to be improved so it can withstand the severe environment of two-phase geothermal flow. A durable meter could be used to track trends in the enthalpy of production from geothermal wells but the error of the measurement needs to be reduced before it can be used as a primary enthalpy measurement device.

More data needs to be collected over a wide range of flow conditions to quantify the errors in the LVF measurement and enthalpy calculation. Analysis of the data will probably indicate methods to reduce the error through meter design, correlation adjustment factors, and two-phase flow liquid holdup corrections.

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