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DOWNHOLE ENTHALPY MEASUREMENT WITH FIBER OPTICS

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ABSTRACT

Studies investigating ways to measure enthalpy down hole have been in progress at Stanford University for the last three years. So far, the void fraction and the dispersed-phase velocity, which are the two essential factors required for calculation of flowing enthalpy, were determined by using resistivity and photo-sensors. Currently, research efforts have been oriented toward measuring down hole enthalpy by fiber optics. After discussing the applicability of using horizontal or vertical fiber tips, this paper describes the usage of normal reflection probe with the tip surface cut at a right angle to the fiber axis to investigate the void fraction initially in water-air flow then in water-steam flow. The calibration curve was obtained by correlating the void fraction given by the fractional flow ratio detector (FFRD) and the calculated local void fraction. Successful results were obtained for the slow bubble flow case. Future work includes determining the bubble velocity, and testing the device in a model wellbore.

INTRODUCTION

In geothermal reservoirs, rock is the main source of heat energy. Unlike oil and gas reservoirs in which the energy resource is the fluid itself, geothermal fluid is simply a carrier of the energy. The principle value of a geothermal reservoir to a developer lies in the thermal energy it contains; the fluid is useful only in bringing that energy to the surface.

The thermal energy contained within a substance is measured in terms of its energy content per unit mass, namely the "enthalpy". In thermodynamics, enthalpy can be defined as the thermodynamic quantity equal to the internal energy of a system plus the product of its volume and pressure. Since the energy content of the flowing geothermal fluid is one of the main concerns of the geothermal industry, measuring down hole enthalpy would be very valuable.

The accurate estimation of down hole enthalpy is a significant challenge because the reservoir environment is particularly hostile to down hole tools. High temperatures and corrosive chemicals can cause failure of tools and thus measurements obtained may be unreliable or for a short duration only. Recent developments of optical fiber technology have brought new ways to measure pressure and temperature down hole but a means to quantify the additional flow parameters needed to directly determine the enthalpy is not available. To have a direct measurement of the enthalpy rate of a two-phase flow, temperature, pressure, void faction and mass flow rates of both phases need to be quantified.

Until now several types of optical devices have been proposed to measure the local void fraction. Optical probes are basically free of corrosion while electrical and thermal probes frequently encounter corrosion. Optical probe developments have been described in a review paper by Cartellier and Achard (1991) and the working principles of optical probes will be explained in the next section.

Once void fraction, mass flow rate of one of the phases, temperature and pressure are measured than flowing down hole enthalpy could be determined. Temperature and pressure values are needed in order to find specific enthalpies of water and steam from steam tables.

THEORY

Down hole enthalpy:

General definition of enthalpy or in other words heat content can be defined as follows:

$$h = u + Pv \quad (1)$$

where h is the enthalpy per unit mass, u is the internal energy per unit mass, P is the pressure and v is the specific volume.

In geothermal wells at saturated conditions, in-place enthalpy and flowing enthalpy can be calculated as follows:
In-place enthalpy:

$$h_{static} = xh_s + (1-x)h_w \quad (2)$$

Flowing enthalpy:

$$h_{flowing} = \frac{W_w h_w + W_s h_s}{W_w + W_s} \quad (3)$$

Where *x* is the mass fraction between steam and water, *hs* and *hw* are specific enthalpies of steam and water (they can be found from steam tables with *T* and *P* data), *Ww* and *Ws* are mass flow rates of water and steam ($W = q * \rho$). What we are interested in is the determination of flowing down hole enthalpy; therefore we will focus on Equation (3):
If the void fraction of a two-phase fluid is known then the volumetric flow rate of each phase can be calculated as follows:

$$q_{gas} = u_{gas} * A * \alpha \quad (4)$$

$$q_{liquid} = u_{liquid} * A * (1-\alpha) \quad (5)$$

Then, the flowing enthalpy can be determined as in Equation (6).

$$h_{flowing} = \frac{[u_w * (1-\alpha) * \rho_w * h_w] + [u_s * \alpha * \rho_s * h_s]}{u_w * (1-\alpha) * \rho_w + u_s * \alpha * \rho_s} \quad (6)$$

Hence in order to determine the down hole enthalpy what we need to measure (by using the fiber optics) is void fraction and velocity of the dispersed phase. Then the mass flow rate of steam could be calculated, and since it is easy to measure the total mass flow rate at the surface, water flow rate could be obtained from the equation: $W_{total} = W_s + W_w$.

Fiber optics for phase detection:

It is now well known that optical techniques can be used for phase detection. Such techniques are usually based on Snell's law and take advantage of the fact that the indices of refraction of the liquid and vapor phases are quite different.

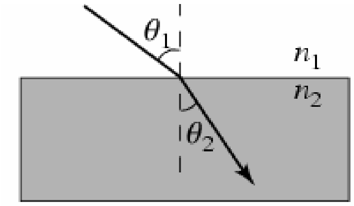

Figure 1: Refraction of light at an interface between two materials.

Snell's law gives the relationship between angles of incidence and refraction for a wave impinging on an interface between two media with different indices of refraction. The law follows from the boundary condition that a wave is continuous across a boundary, which requires that the phase of the wave be constant on any given plane, resulting in:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \quad (7)$$

where θ_1 and θ_2 are the angles from the normal of the incident and refracted waves, respectively.

Depending on the refraction index of the medium in which the fiber optic probes are placed, more or less of the emitted light returns to the receiving fiber. When placed in water, most of the light leaves the fiber and is dispersed in the water, while when immersed in air most of the light is refracted back into the receiving fiber.

Different configurations of optical probes have been reported, most of them were based on the Snell-Descartes refraction law and they had a restriction on the phase index of the flowing mixture.

The normal reflection probe with the tip surface cut at a right angle to the fiber axis had no restriction on the indices of the flowing mixture. Two investigations of gas-liquid flows and one liquid-liquid flow with this probe type have been described (Sekoguchi *et al.* 1984, Morris *et al.* 1987 and Hamad *et al.* 1997), but the current investigation represents the first normal cut optical probe investigation of gas-liquid flow for high temperature void fraction determination.

The principle of this probe is based on the variation in the reflection coefficient (the Fresnel coefficient) at the probe tip with the index of each fluid (Morris *et al.* 1987). The Fresnel coefficient R for a normal light incidence at the interface between the fiber and the surrounding fluid is

$$R = \left(\frac{n_0 - n}{n_0 + n}\right)^2 \quad (8)$$

Local Void Fraction Measurement

In our study the main property to measure is the void fraction, which is a direct measurement of the relative time the dispersed phase is present at the measuring point.

Using the definition given by Hamad et al. (1997) the local void fraction can be measured by using the following equation.

$$\alpha(x,t) = \frac{1}{T}\int_{t-T/2}^{t+T/2} M(x,t')dt' \quad (9)$$

Alternatively the local void fraction can also be determined by a time-averaging procedure as:

$$\alpha(x) = \lim_{T-->\infty}\left(\sum T_G / T\right) \quad (10)$$

Where T is the total measurement time and $\sum T_G$ is the total time the dispersed phase was present at the selected measuring point.

FIBER POSITION

Initially the applicability of using horizontal or vertical fiber tips was investigated. For this purpose, a horizontal and a vertical fiber tip were placed as close as possible to each other as seen in Figure 2 this ensures that they can detect the same bubble at the same time.

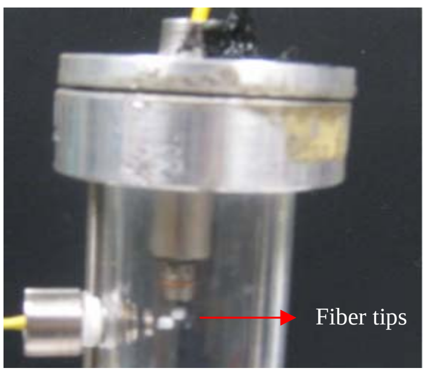

Figure 2: Placement of fiber tips.

A vertical fiber tip was found to be more efficient than the horizontal one since it detected more bubbles. Hence, we pursued our experiments by using the vertical fiber tip.

EXPERIMENTAL SETUP

The optical monomode fiber with a normal cut was placed inside stainless steel tube, which was used to hold the fiber rigid. The steel tube was inserted vertically inside a plexiglass tube that was 4 inch in length and had 1 ¼ inch ID. A schematic diagram of the experiment is shown in Figure 4. A Fiber Optic Laser Diode Source (FOSS-01-3S-9/125-1310-S-1 from Ozoptics) with 1310 nm wavelength, 1 mW output, for 9/125µm core/cladding, singlemode fiber, with super FC/PC receptacle was used to provide invisible light.The light was transmitted through a 1x2 singlemode coupler (F-CPL-S12151 from Newport Electronics). Input light was sent to the probe tip and 90% of the light reflected at the tip was coupled back to a detector (D400FC InGaAs from Thorlabs) placed on the other side of the coupler. The current signal coming from the coupler was converted into voltage signal and also amplified inside the detector.

The whole system was connected to a computer by a data acquisition system. The terminal block and data acquisition card used were SCB-68 and NI-6281, respectively. LabView 8.2 was used to digitize the voltage signals; the VI used was "Cont Acq&Graph Voltage-Write Data to File (TDMS).vi" which is one of the sample VIs available in the LabView 8.2 software. The program recorded the signals simultaneously at 1 kHz and output the results to a scaled TDMS file for further data processing.

After water-air test runs, the air tube was removed and water supply was heated by a coil and two gas burners as seen in Figure 3 to obtain water-steam flow.

Figure 3: Water-steam supplier

Fractional Flow Ratio Detector (FFRD) (Figure 5) developed by Chen et al. (2004) was used at the exit of the water-air flow. The FFRD consisted of an infrared phototransistor on one side of a transparent 1/8 inch tube and an infrared LED on the opposite side.

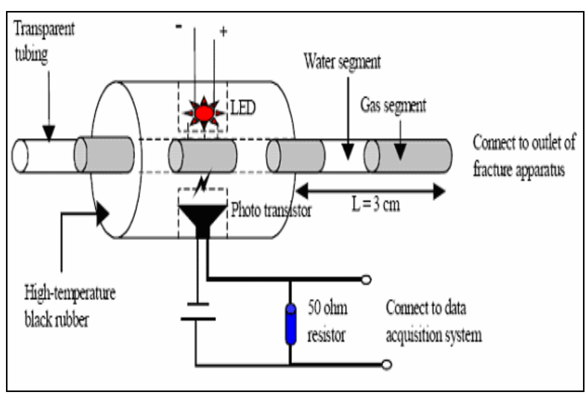

Figure 5: Schematic view of FFRD, from Chen et al. (2004).

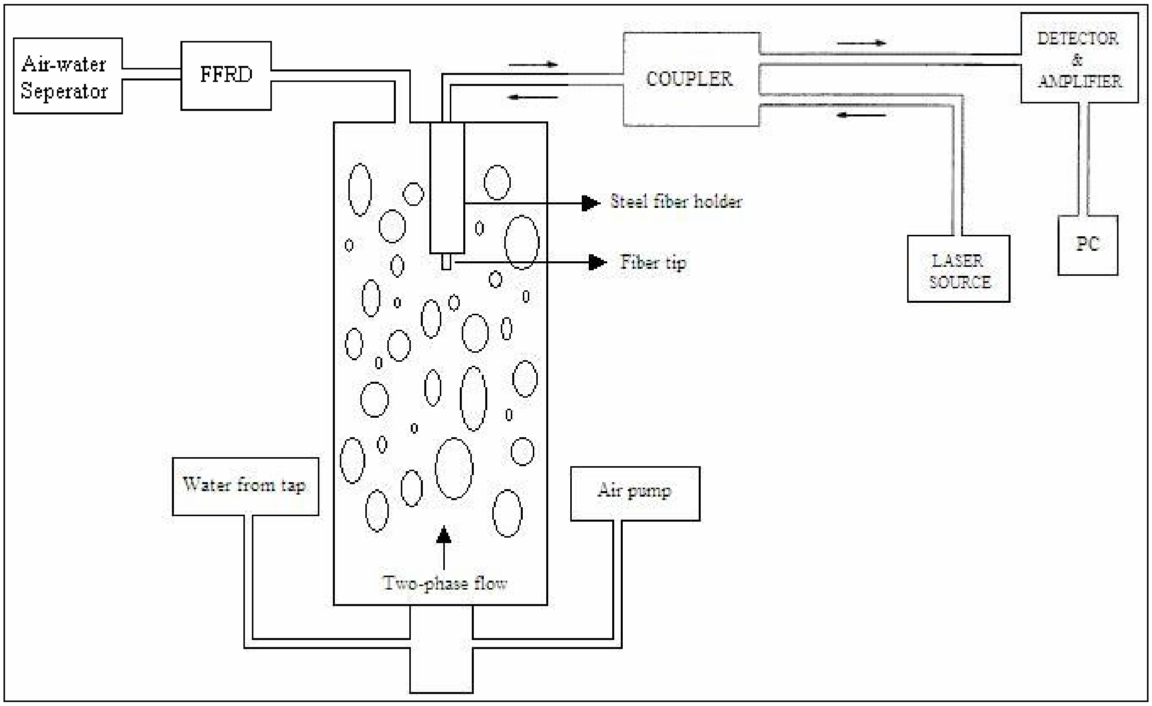

Figure 4: Schematic of experimental apparatus.

DATA ANALYSIS AND RESULTS

Moving average threshold

A threshold line that varied in time was drawn based on local variations in the signal. The moving average threshold method works well for slow bubble flow, but during the fast bubble flow (when void fraction is above 75%) the method did not work well. Therefore, the transition between air and water was not dictated correctly for fast bubble flow.

Calibration

The FFRD technique was used to calibrate the local void fraction measurement in water-air flow and water-steam flow. The calibration curve was obtained by correlating the void fraction given by the FFRD and the local void fraction calculated by:

$$\alpha(x) = \lim_{T \to \infty} \left(\sum_i T_{Gi} / T\right) \qquad (11)$$

Since the FFRD was located at the exit of the plexiglass tube, it detected every bubble that passed through the tube. However, fiber probe only detected the bubbles that touched its surface as seen in Figure 6. Hence, the void fraction value obtained from FFRD was higher than the value obtained from the fiber probe. 15 data sets for slow bubble flow and 20 data sets (each of them lasted for one second) for fast bubble flows were recorded. The average ratio between void fraction obtained from FFRD and void fraction obtained from fiber probe was determined. It was found that values from the FFRD were 33 times higher than the values from the fiber probe during slow bubble flow and 10 times higher during the fast bubble flow. In water-steam flow, since it was not possible to adjust the rate of steam bubbles, we had only one fixed steam rate once the water started boiling. It was found that FFRD values of void fraction were on an average 9.4 times higher than fiber probe values.

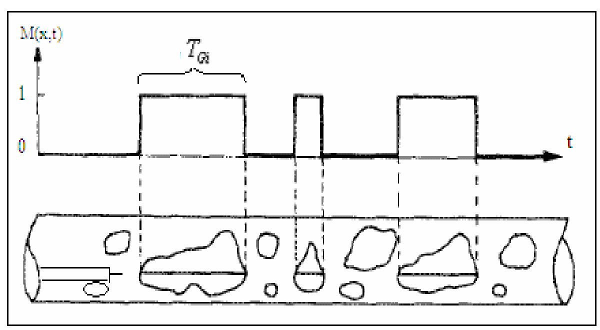

Figure 6: Typical signal schematic in bubble flow.

Results

The calibration curve for the slow bubble flow closely follows the 1:1 line, which indicates a fairly good confidence level in the probe response (Figure 7). However, in fast bubble flow the same pattern was not observed (Figure 8) due to the poor results obtained from moving average threshold. In boiling water, the calibration curve closely followed the 1:1 line.

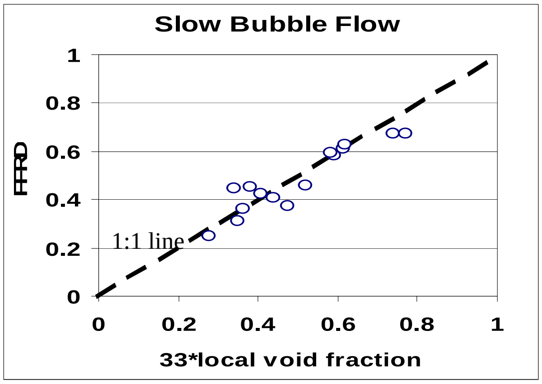

Figure 7: Relationship between FFRD-inferred and fiber-inferred void fraction values for slow bubble flow.

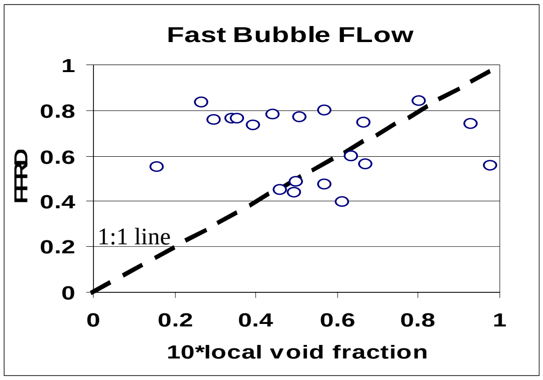

Figure 8: Relationship between FFRD-inferred and fiber-inferred void fraction values for fast bubble flow.

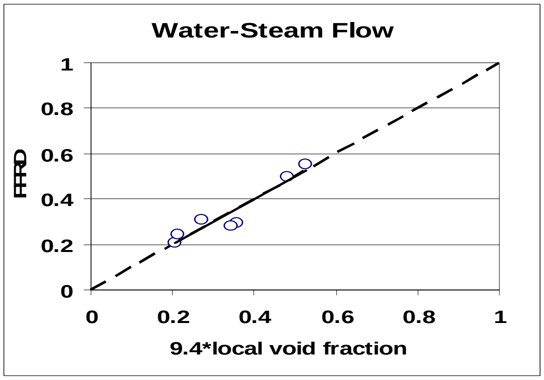

Figure 9: Relationship between FFRD-inferred and fiber-inferred void fraction values for water-steam flow.

CONCLUSION

The set of experiments done in this study has shown that the normal cut fiber optic probe can be used to measure local void fraction which is an essential factor to determine enthalpy down hole.

The correlation between the fiber probe and FFRD was much better in water-steam flow than in water-air flow due to the difference of refraction indices between air and steam. A good correlation between the FFRD and fiber-derived estimates of void fraction was obtained for slow bubble flow. For fast bubble flow, the FFRD did not give satisfactory results, so a new method of comparative measurement is under investigation.

Future work includes determining the bubble velocity by designing a new fiber probe (Figure 10) which has two separate fibers with different length, and testing the device in a model wellbore.

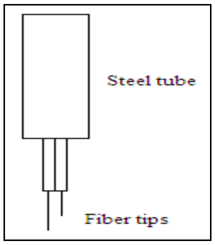

Figure 10: Fiber probe design to measure bubble velocity.

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