DOWNHOLE ENTHALPY MEASUREMENT IN GEOTHERMAL WELLS WITH FIBER OPTICS

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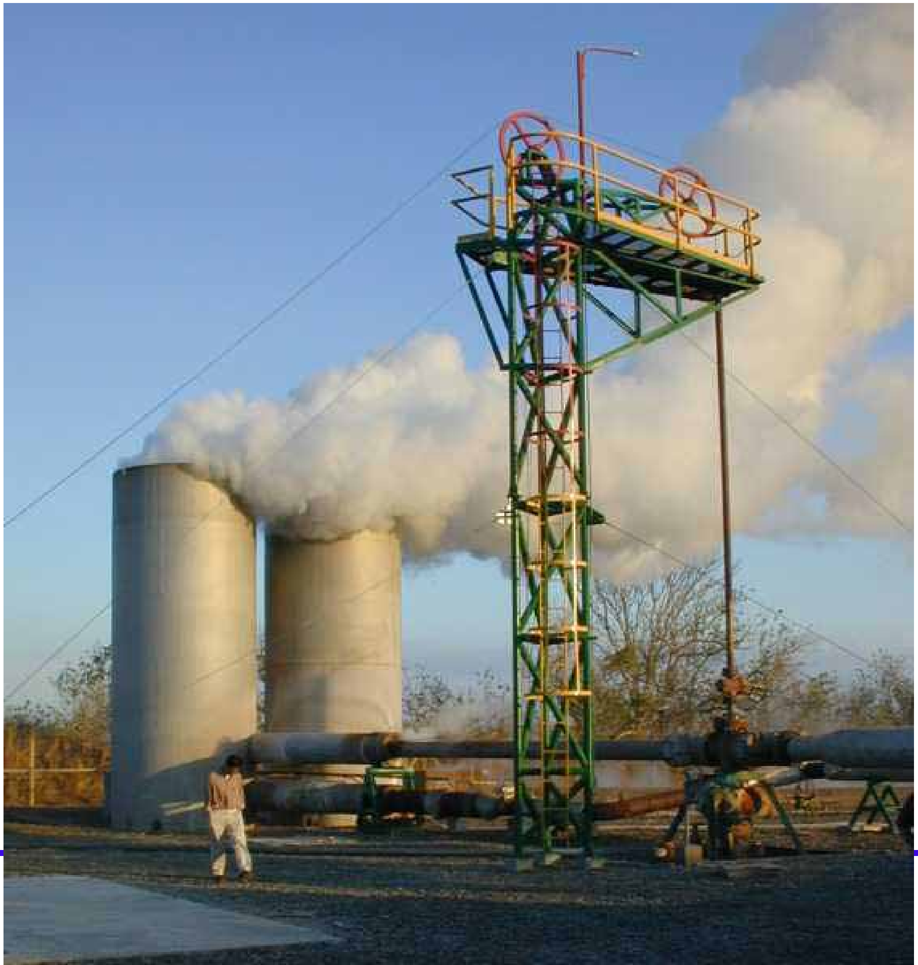
OBJECTIVE

Finding a way to measure enthalpy down hole.



OBJECTIVE

Finding a way to measure enthalpy down hole.

Down hole enthalpy measurements useful for:

- **Fracture characterization**
- **Reservoir modeling**
- **Validating results from wellbore simulators**
- **Earlier estimates of power produced by a well**

PARAMETERS NEEDED for DOWNHOLE ENTHALPY MEASUREMENT

Flowing enthalpy: $h_{flowing} = \dfrac{W_w h_w + W_s h_s}{W_w + W_s}$

Mass flow rate: $W = q * \rho$

Void fraction

Volumetric flow rate of each phase:

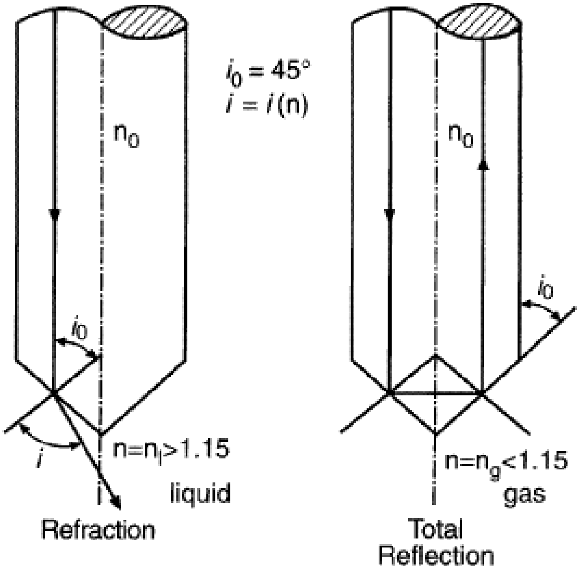
$$q_{gas} = u_{gas} * A * \alpha$$

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

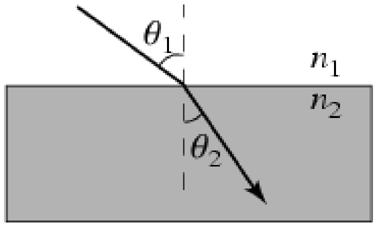
$$h_{flowing} = \frac{\left[u_w * (1-\alpha) * \rho_w * h_w\right] + \left[u_s * \alpha * \rho_s * h_s\right]}{u_w * (1-\alpha) * \rho_w + u_s * \alpha * \rho_s}$$

FIBER OPTICS FOR PHASE DETECTION

The working principle of most fiber optic probes is based on the Snell-Descartes refraction law:

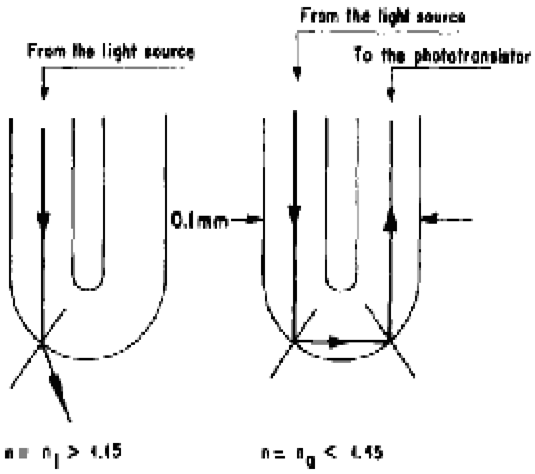


Hamad *et al.* 1997



$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

Liquid-gas interfaces passing by the tip of the probe cause the system to change from a refraction state to a total reflection state.



Danel & Delhaye 1971

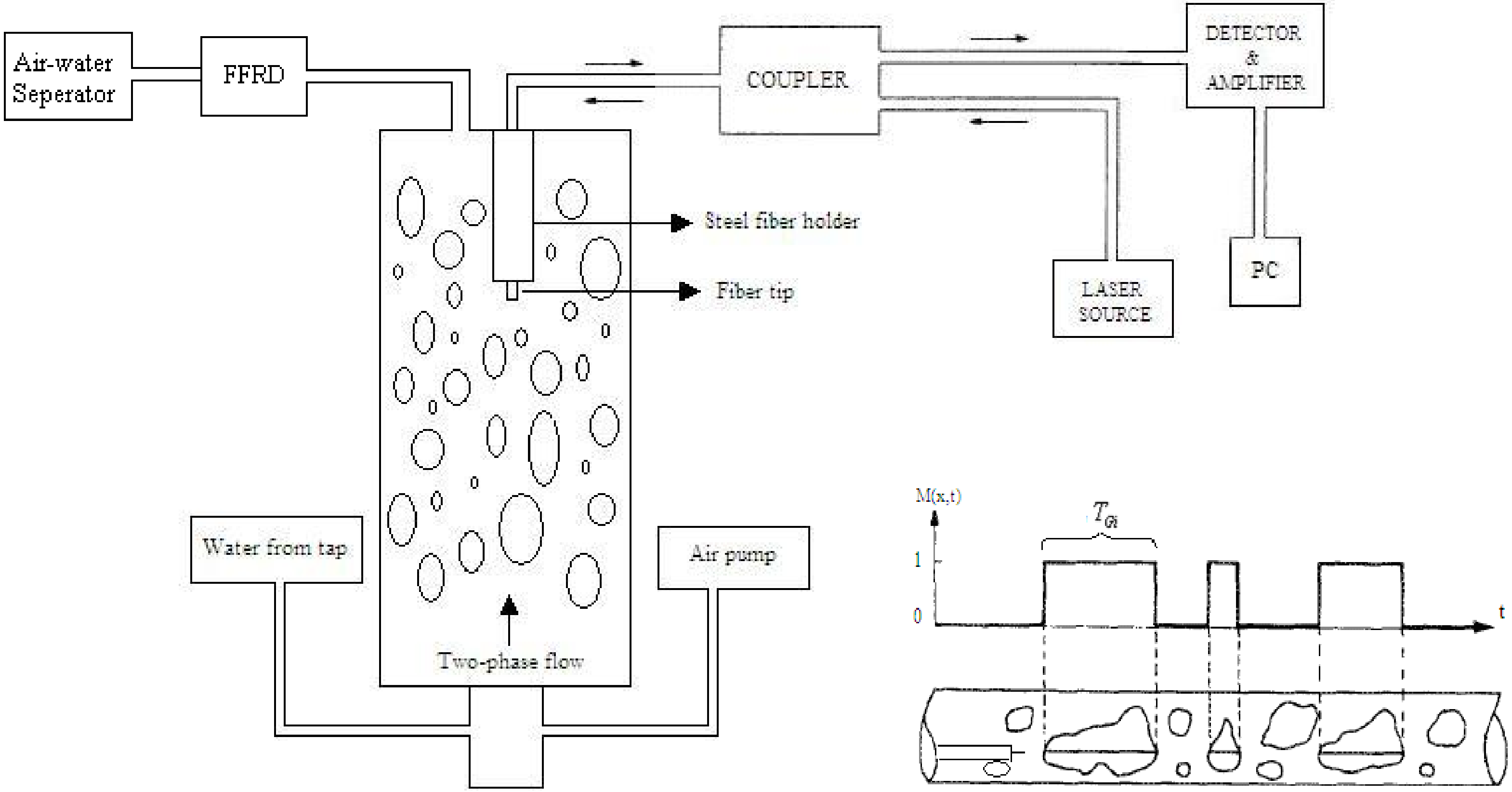
THE NORMAL REFLECTION PROBE

- 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. The Fresnel coefficient for a normal light incidence at the interface between the fiber and the surrounding fluid is:

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

- The important changes in the reflection coefficient ensure a relatively easy way of detecting the bubble’s interfaces.

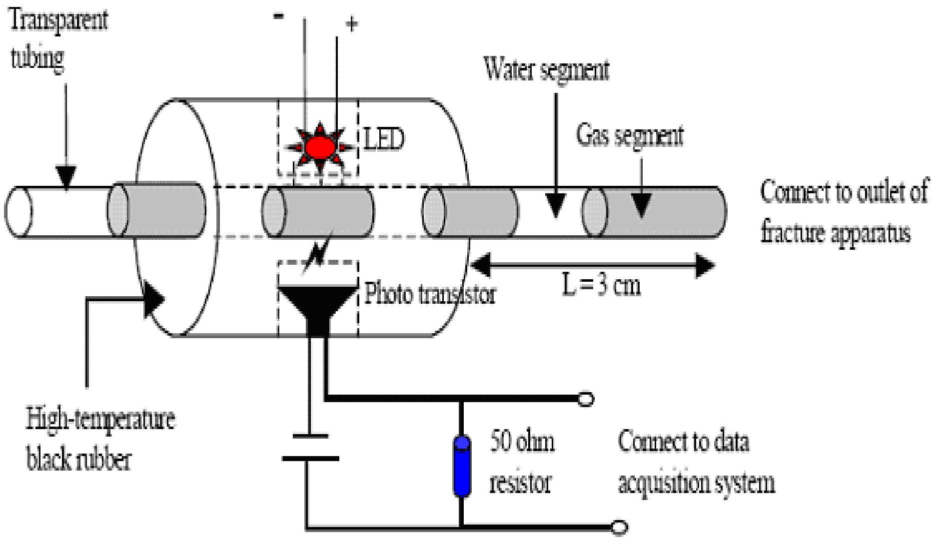
SCHEMATIC OF EXPERIMENTAL APPARATUS



Allain Cartellier (1989)

COMPARISON MEASUREMENT

- The FFRD technique was used for correlation during the void fraction measurement experiments.
- The phototransistor inside the FFRD produces different voltages when sensing different strengths of light.

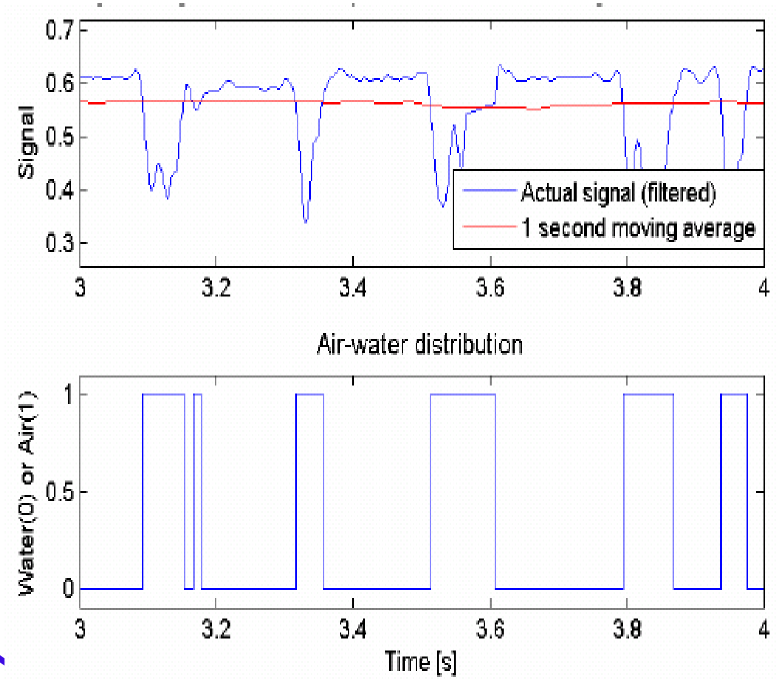


Fractional Flow Ratio Detector

(Chen *et al.* 2004)

LOCAL VOID FRACTION CALCULATION

In our study void fraction is defined as the direct measurement of the relative time the dispersed phase is present at the measuring point.

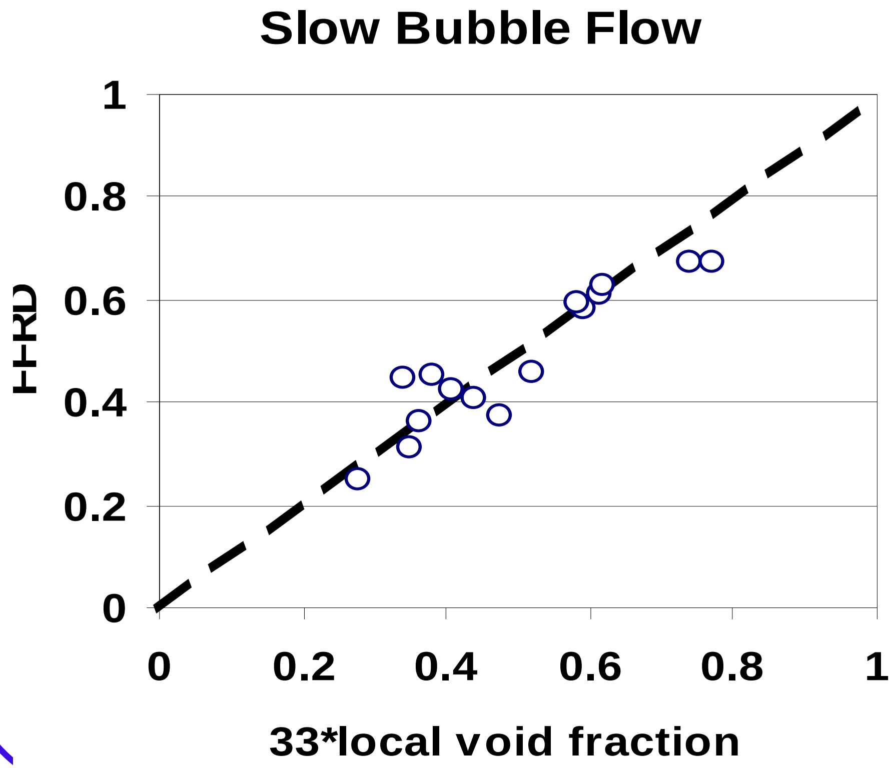


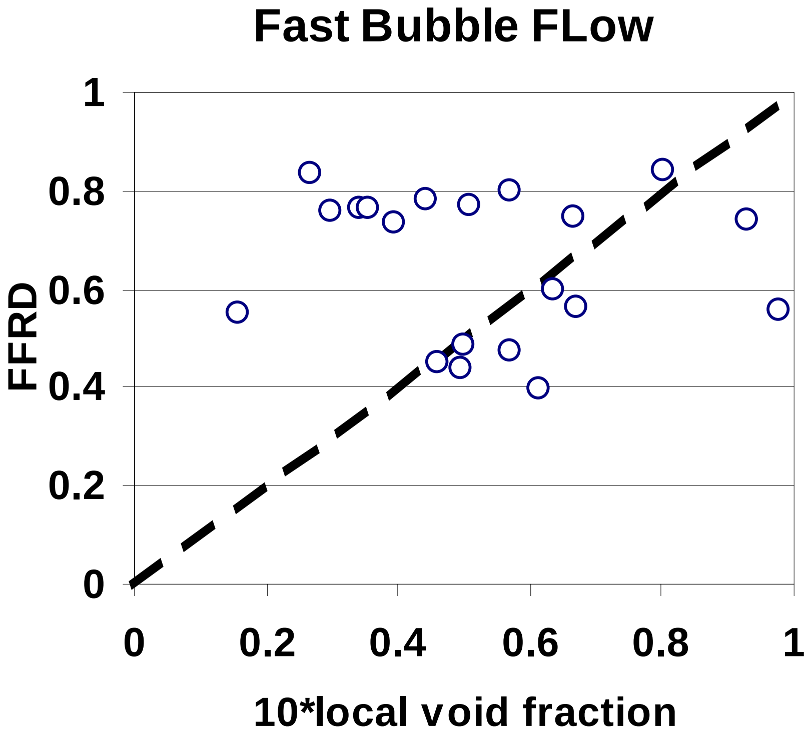
$$\alpha(x,t) = \frac{1}{T}\int_{t-T/2}^{t+T/2} M(x,t')\,dt'$$

$$M(x,t') \begin{cases} \text{1, If x is in the dispersed phase at time t} \\ \text{0, otherwise (in water).} \end{cases}$$

EXPERIMENTAL RESULTS

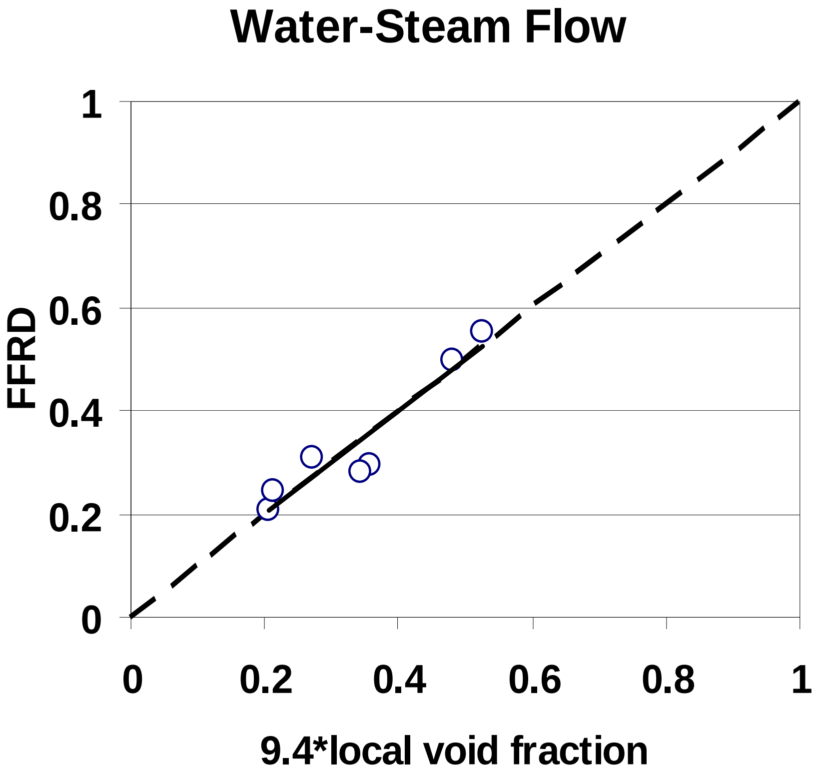
Correlation curves for water-air flow



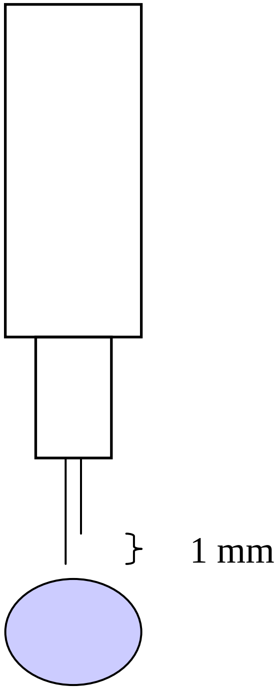


EXPERIMENTAL RESULTS

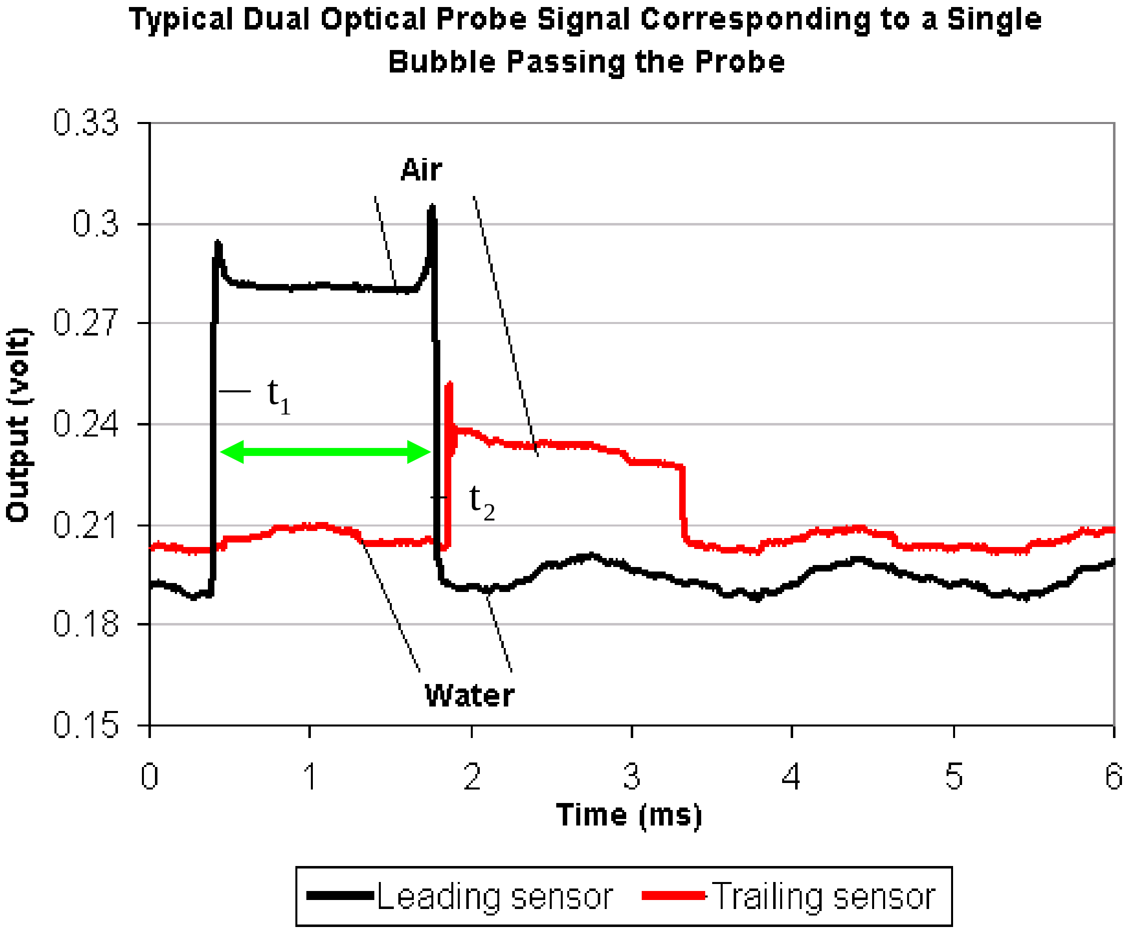
Correlation curve for water-steam flow



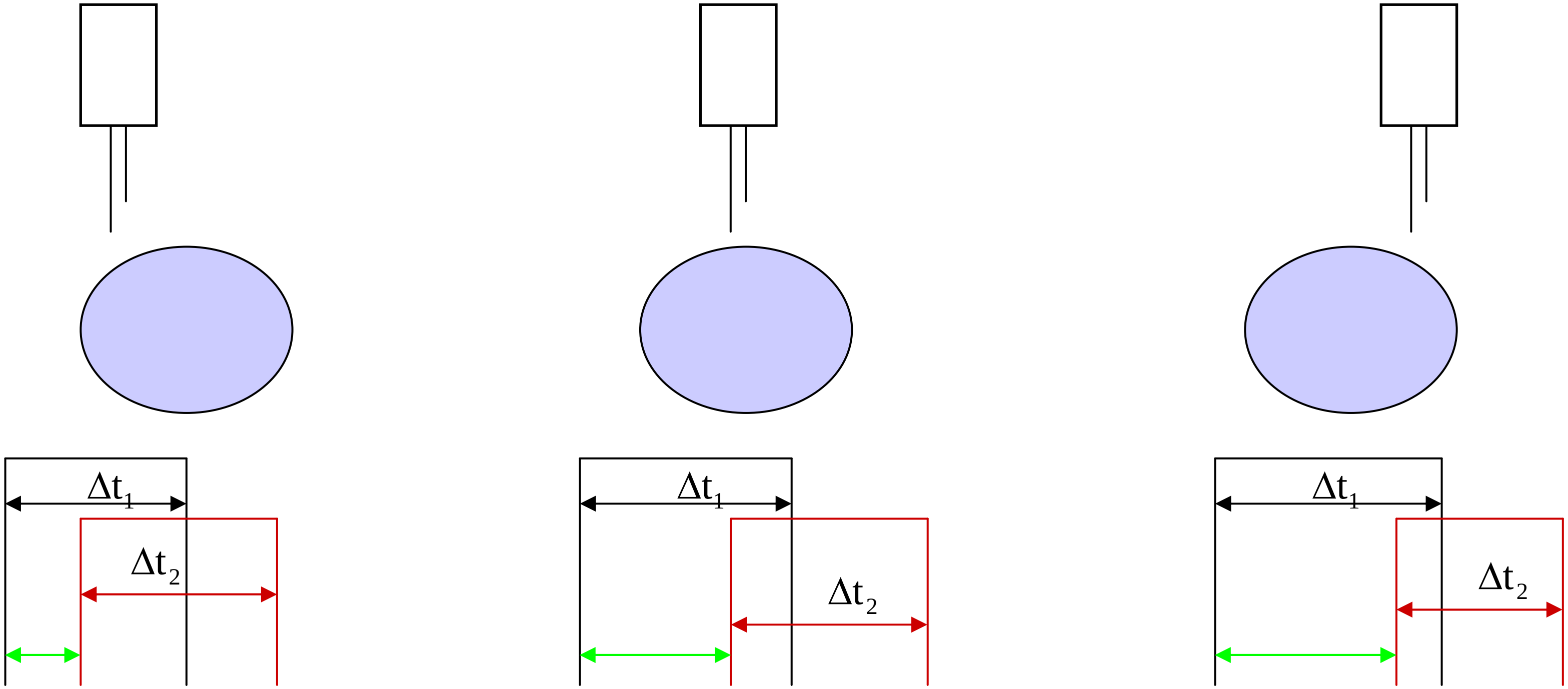
DISPERSED PHASE VELOCITY MEASUREMENT



$$U_b = \frac{1}{t_2 - t_1}$$


Typical Dual Optical Probe Signal Corresponding to a Single Bubble Passing the Probe

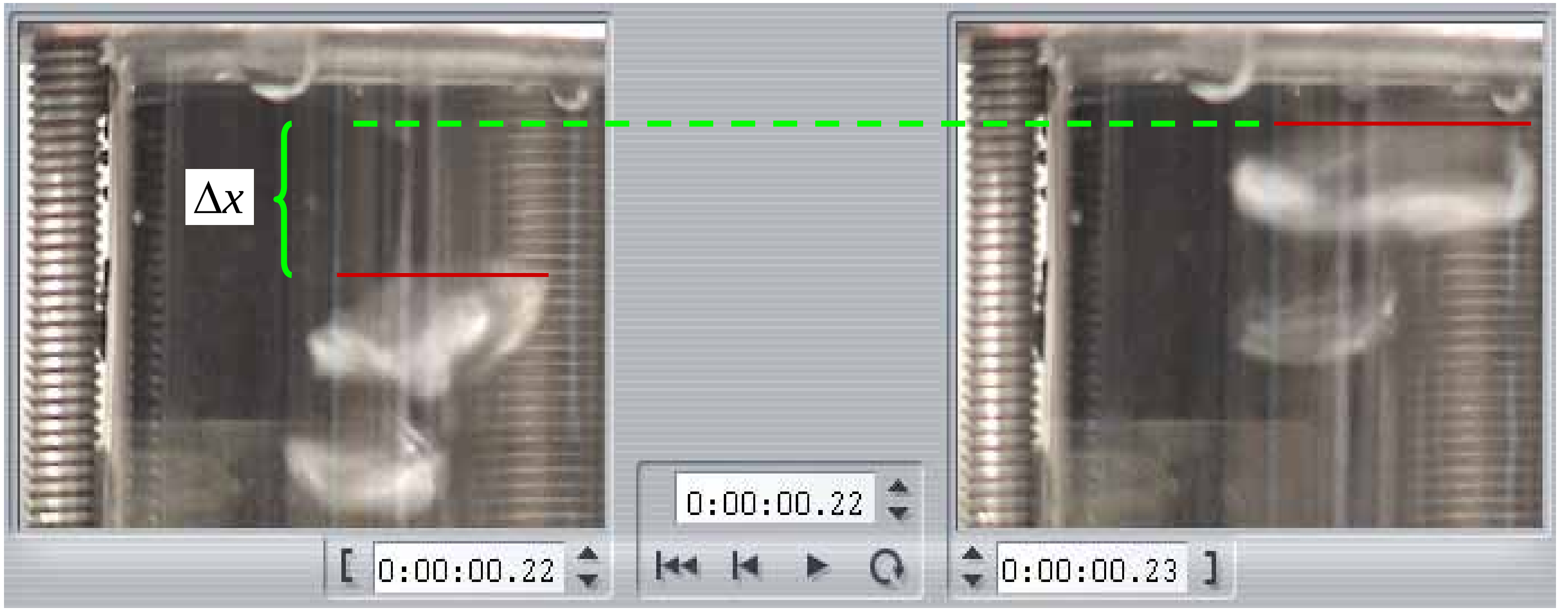
DIFFERING STRIKE LOCATIONS



$\Delta t_1 < \Delta t_2$ $\Delta t_1 = \Delta t_2$ $\Delta t_1 > \Delta t_2$

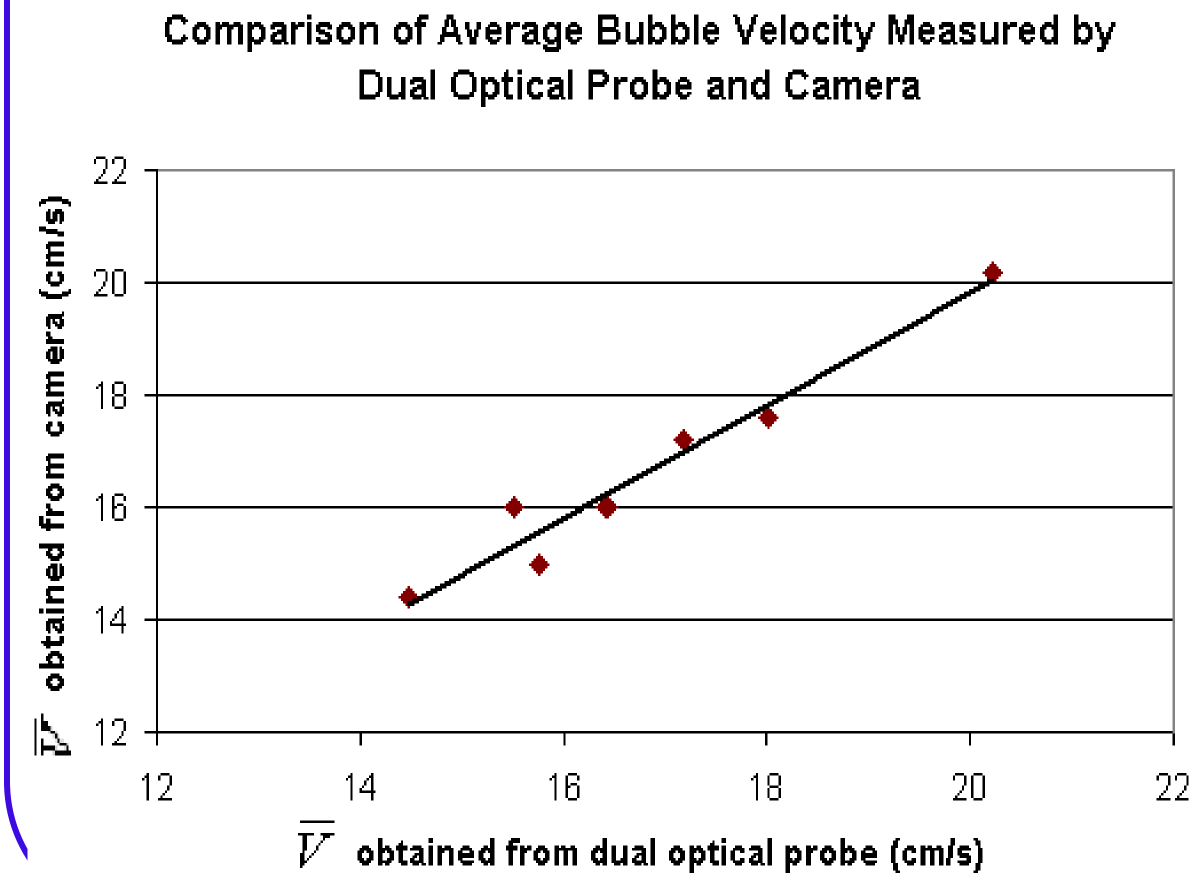
Δt_1 and Δt_2 represent residence times of the two optical fibers inside the bubble

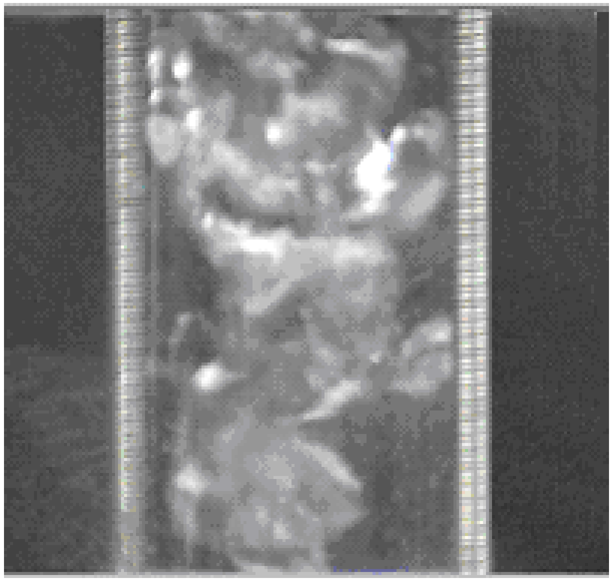
COMPARISON MEASUREMENT TECHNIQUE



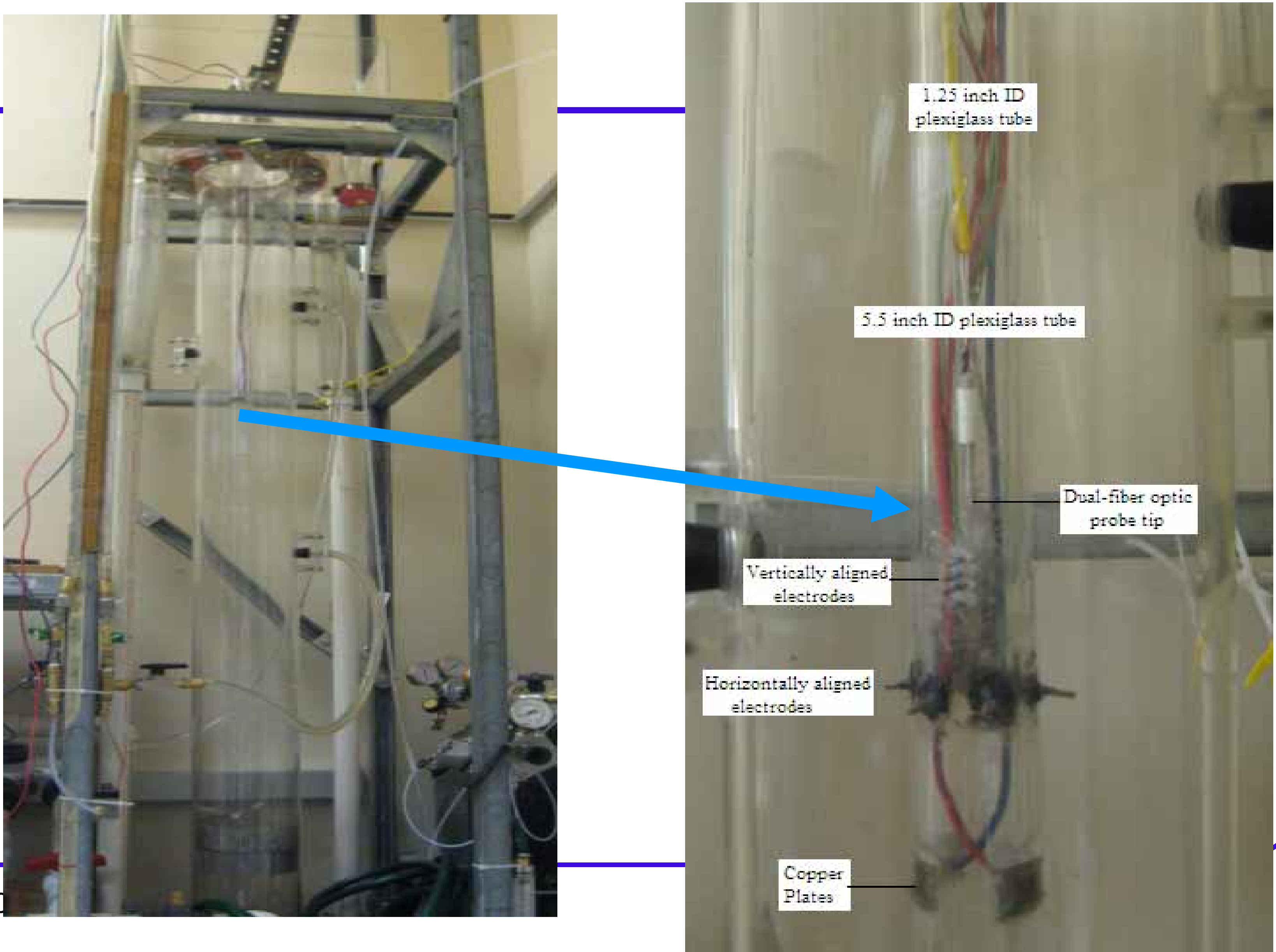
$$U_b = \frac{\Delta_x}{33.33}$$

EXPERIMENTAL RESULTS



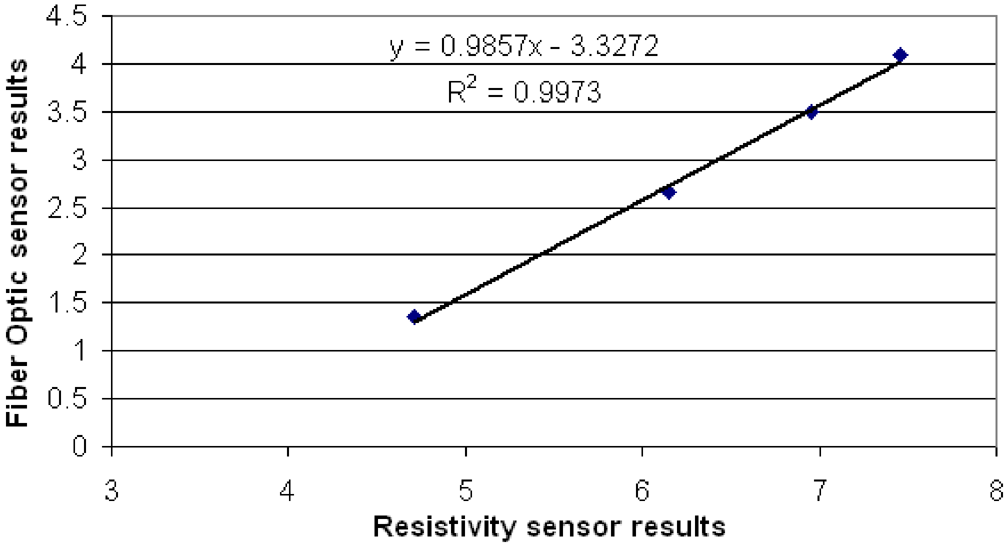


EXPERIMENTS in THE MODEL WELL



EXPERIMENTAL RESULTS

Air injection pressure (psi)	Average void fraction from resistivity sensor (%)	Average void fraction from fiber optic sensor (%)	Ratio between resistivity and fiber optic sensor results
7	4.71	1.35	3.49
10	6.15	2.67	2.31
12	6.95	3.49	1.99
20	7.46	4.09	1.83



CONCLUSION

- Normal cut fiber optic probe can be used to measure local void fraction and dispersed phase velocity, which are essential factors to determine enthalpy downhole.

- A good correlation between the FFRD and fiber-derived estimates of void fraction was obtained for (slow) water-air bubble flow and (fast and slow) water-steam flow.

- For slow water-air flow a good correlation was obtained between the dual optical probe and the camera-inferred velocities. The fiber optic probe also appeared to be working well in fast water-air flows, however we did not have a successful secondary measurement to confirm this.

- In the model wellbore, the fiber-inferred void fractions were correlated with those from resistivity measurements.

ACKNOWLEDGEMENTS

- We are grateful for funding through Idaho National Lab.
- Thanks also to Stanford University for support of undergraduate research.
- Earlier resistivity measurements by Egill Juliusson.
- Model wellbore designed by Manoj Kumar.

QUESTIONS

QUESTION & ANSWER

FIBER PROBE DESIGN for DOWNHOLE