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INSTRUMENTATION FOR TWO-PHASE GEOTHERMAL FLOW

C. A. Calder

ABSTRACT

A brief review of approaches to general two-phase flow instrumentation is given and suggestions are made for development of instrumentation techniques that have promise of being suitable for the characterization of two-phase geothermal flow in the field. Various types of instrumentation will be studied and developed using a test spool installed at the Geothermal Test Facility at LLL.

Accurate measurement of temperature, pressure, and steam quality are of initial primary concern with secondary efforts to be employed to further define and characterize other relevant flow parameters.

INTRODUCTION

In support of the LLL program for development of geothermal resources using the total flow concept, instrumentation is being designed and developed to characterize the important flow parameters of the geothermal fluid. The approach is one of a growing capability with early emphasis being placed on designated high priority measurement requirements. Instrumentation will be initially developed and evaluated using a test spool at the LLL geothermal test facility. The facility will approximately provide well-head thermodynamic conditions using clean water. Although the possible corrosion, scaling and solid particle erosion characteristics of the geothermal fluid will not be duplicated in the facility, this severe field environment will certainly influence the selection and design of experimentation to be employed.

Flow measurement parameters of interest, listed in an approximate order of priority, are:

1. Temperature
2. Pressure
3. Quality of steam (vapor mass fraction)
4. Flow velocity, distribution (each phase)
5. Flow rate
6. Uniformity of liquid distribution across flow section

7. Void fraction, droplet size
8. Suspended solids

Other flow parameters may be added as the program develops.

GENERAL TWO-PHASE FLOW INSTRUMENTATION

Liquid-gas two-phase flow can take on numerous connotations. Two-phase flow may be described in such terms (flow regimes) as slug flow, bubbly flow, mist (fog) flow, annular flow, etc. The desired flow regime for the low quality geothermal steam entering the nozzle-turbine system would probably be best described as well-mixed mist or fog flow. In this flow, the liquid fraction is carried as miniscule droplets evenly distributed throughout the gas phase. The velocity of both phases will not be the same if slip occurs.

Significant research has been carried out in the last two decades on two-phase gas-liquid flow with several books¹⁻³ and a periodical⁴ now available. Recent reviews on the state of the art may be found in Refs. 5 & 6. A compilation of papers presented at a session of the 11th National Heat Transfer Conference⁷ deals directly with two-phase flow instrumentation and is especially relevant. A recent review of single phase techniques is found in Ref. 8.

Much of the two-phase instrumentation presently in use relies heavily on the successful and well-established techniques of single-phase flow such as the orifice meter, pitot tube, venturi and hot wire anemometer. Under certain conditions, these techniques are entirely adequate but often their use requires considerable interpretation or judgement. Frequently the data is strictly qualitative but can be a real value in understanding the flow character. Various optical and radiation techniques have been widely employed including the recently developed Laser Doppler Velocimeter (LDV) system.

Possible Techniques Adaptable to Two-Phase Geothermal Flow

Some of the techniques for flow instrumentation which appear to the writer to be especially suited to the low quality steam situation in geothermal flow are discussed in this section. Because of anticipated severe scaling and erosion problems, emphasis is given to non-intrusive type instrumentation. However, certain probing and sampling techniques which disturb the flow will be considered. Representative references describing the relevant techniques are categorized in the Bibliography in the back of the report.

Optical Techniques

Flow photography is an extensively applied technique for the characterization of two-phase flow. Methods used in visual studies of two-phase flow include direct illumination, shadow graph, and Schlieren photography. The more recent laser based optical techniques such as holography also utilize photographic data recording.

These techniques all require a transparent flow section or transparent windows in the pipe. Transparent flow sections for flow in large diameter pipe, say greater than one inch, at relatively high pressures and temperatures is not practical in most cases. Optically clear pipe of such diameter is not readily available from commercial outlets and fabrication difficulties and cost would be unreasonable. Due to the susceptibility of glass and similar materials to stress concentrations and tensile loading, the pressure ratings are very low for relatively thick walled glass pipe. The use of windows mounted in the pipe wall would appear best suited for the geothermal flow situation in most applications of optical techniques. Chemical reaction, erosion, and scaling problems inherent in the field may cause difficulty in maintaining adequate optical properties of the windows.

Shadowgraph photography, where the light source is located on the opposite side of the pipe from the camera, is by far the most popular illumination technique and can provide information on thermal gradients as well as density gradients. In addition, time related phenomena such as flow velocity can be measured. The real value of photography, however, is the qualitative insight that can be gained about the flow field.

The LDV technique, available only the last few years, utilizes the doppler shift of laser light reflected from particulate in the flow to give extremely accurate flow velocity profiles. Several variations of the technique are available so that either one or two windows or a transparent flow channel may be used. This technique might be especially useful for two-phase flow in that velocities of both phases can be measured giving an evaluation of the slip present. This approach might require seeding so that velocity of the gas phase can be measured. It might also be possible to get a handle on the approximate droplet size and associated velocities using LDV. Cost of such a system lies in the \$15-\$25K range and might not be convenient or suitable for field use.

Laser beam - photosensor systems have been applied to two-phase flow to measure such items as void fraction, bubble size and velocity, and flow

particulate. These systems utilize the reflection, refraction, and absorption of the laser beam passing through the flow. Intuitively, it would appear that a laser beam - photodiode system might be used for an indication of droplet size as well as steam quality.

Steam at 100% quality is clear but when quality decreases, it becomes progressively more foggy and would greatly attenuate a laser light beam at low quality conditions. Therefore, a measurement of laser beam transmittance or reflection and refraction through the flow would be related to steam quality.

Radiation Techniques

High energy radiation of beta, gamma, or x-rays have been used to measure certain properties of two-phase flows. Most applications deal with measurement of the beam attenuation to evaluate the void fraction of the flow. The system is similar to the laser beam attenuation system discussed previously, but the restriction for optically transparent walls is removed.

Ultrasonic Techniques

The ultrasonic velocity meter has been in use since the 50's for measuring average flow velocity in liquids. The application is based on a measurement of the difference in transit time of a downstream and an upstream traveling ultrasonic pulse. Or, similarly, the difference in frequency at downstream and upstream stations of a continuous source is measured. Its use in gas and two-phase flows is considerably more difficult due to the high attenuation and dispersion of the sound. However, ultrasonic velocity systems can be designed and optimized for a particular application to provide accurate velocity measurements. This approach can also provide sonic velocity and density of the medium.

Piezoelectric Flowmeters

Flowmeters utilizing a piezoelectric sensor on the pipe wall have been employed but rely on calibration for the particular application. A voltage output is achieved when the acoustic wave stresses the piezoelectric crystal causing it to become electrically polarized. These flow generated acoustic signals are monitored and related to the velocity or mass flow rate.

Probes

Probing techniques have a definite disadvantage for application in Salton Sea type geothermal environments. The severe scaling, corrosion, and erosion environments makes intrusive instrumentation less desirable. However, some probing such as flow sampling will no doubt have to be done and probing does permit profile type measurements whereas most non-intrusive techniques give average values.

Hot wire and hot film anemometers have been widely used in single phase gas and liquid flows. They have also been somewhat successfully applied to two-phase gas/liquid flows but results must necessarily be interpreted for the particular situation. They are extremely delicate instruments and do not appear at all suitable for field use at the time.

Impact and drag force type probes are used to characterize certain flow parameters. The impact probe consists of a small piezoelectric crystal subjected to the flow impact and can be used to measure transient pressure conditions and detect particulates in the flow. For geothermal flow considerations, such a probe might be of use in evaluating droplet size, the presence of solid particulates and their size, and determining the distribution of droplets in the flow. Drag force probes usually consist of a cantilever beam with a drag body in the flow. The beam is instrumented with strain gages to determine drag force on the body.

Numerous other probes, many commercially available, have been designed for, or might be considered for, application in two-phase flow. They are used to measure such parameters as droplet size, flow rate, velocity, film thickness, void fraction, etc. In some devices it is possible to purge the probe so instruments such as the pitot tube can be used without plugging.

Magnetic Flowmeter

The magnetic flowmeter is non-penetrating and is based upon the voltage generated when the flow passes through a magnetic field. Relatively high fluid conductivities are required and the flow tube must be non-magnetic. If non-magnetic metal tubes are used, then the inside wall has to be electrically insulated. Their use in geothermal flow is questionable due to the conductivity requirement but they can be operated at conductivities as low as that of distilled water.

Fig. 1 Instrumentation Schematic For Test Spool

GEOHERMAL INSTRUMENTATION TEST SPOOL

A schematic layout of the test spool design is shown in Fig. 1. The test spool is 2 inch schedule 80, SS304 pipe 50 inches long with 300# flanges at both ends, and is part of the Geothermal Test Facility. The layout shows the flow instrumentation that will be evaluated in initial work with future efforts expected to be towards more sophisticated instrumentation and development of various additional techniques to further characterize and define the flow. The test spool is viewed, therefore, as a growing capability program.

The Geothermal Test Facility is designed to provide low quality steam which approximately matches the thermodynamic conditions found in the field except that clean water is used. This is done by flashing water at 550°F and 1000 psi through a valve at approximately constant enthalpy to the desired conditions as shown on the T-S diagram in Fig. 2.

Fig. 2 T-S Entropy Diagram Illustrates Isenthalpic Expansion for Test Spool

For example, an isenthalpic expansion from 1000 psi (550°F) at point A to 280 psi (410°F) at point B results in a steam quality of about 20%. Thus, instrumentation can be developed using a wide range of low quality steam conditions.

As shown in Fig. 1, the instrumentation planned for initial testing and evaluation including the following:

1. Pressure and temperature measurements
2. A piezoelectric flowmeter
3. Steam quality heat exchanger
4. Light attenuation/scattering
5. Impact transducer
6. Ultrasonic velocity meter
7. Flow photography

The details of each measurement device will now be separately discussed along with a statement of the status at the time of this writing.

Pressure and Temperature Instrumentation

Accurate measurements of pressure and temperature of the two-phase flow are not expected to be a significant problem. Static pressure will be monitored at two locations near the fore and aft end of the test spool using two channels of a 500 psi scanning transducer system. Taps for the pressure tubing are located on the top side of the pipe and purging of the lines using nitrogen can be done after each reading.

Temperature will be recorded at the fore and aft end of the pipe using pipe wall mounted chromel-alumel thermocouples. A rough calculation of Reynolds number indicates the flow will be turbulent, providing sufficient heat transfer so the use of thermowells should not be necessary. The pipe wall will have to be well insulated over the thermocouples and along the entire length where the insulation does not interfere with instrumentation.

Status: Bosses with pressure taps have been welded to the pipe at each location and intrinsic thermocouples mounted on the pipe wall.

Piezoelectric Flowmeter

This simple device consists of a piezoelectric crystal mounted on the pipe wall to sense the acoustic signals generated by the flow. The amount and level of acoustic emission is related to the flow rate. If extraneous acoustic signals reach the sensor through the plumbing, it may be necessary to acoustically isolate the transducer and mount it in a "wetted" condition in actual contact with the flow. This type of transducer must be calibrated for the actual application but can provide an extremely simple means of flow rate measurement.

Status: Acoustic sensor is on order.

Quality Measurement System

Steam quality is one of the most important measurements needed to characterize the low-quality geothermal fluid at the well head. Throttling and separating calorimeters have long been used to measure quality in high quality steam but are not suitable at low qualities. Commercial instruments for measuring the quality of very wet steam apparently are not available. Therefore, it was necessary to design a system for quality measurement which is suitable for low quality steam.

The design of the proposed method is sketched in Fig. 3 and consists of two heat exchangers, a sampling probe, and associated tubing and thermocouple instrumentation. The second heat exchanger, a subcooler, also requires a cooling water source. A representative sample of the fluid is passed through the first H.E. and condensed to total liquid flow. The liquid is then sub-cooled by the second H.E. and used as the coolant in the first H.E.

Fig. 3 Design of Quality Measurement System

Temperatures are recorded at the inlet and outlet locations (four) of the first heat exchanger by pipe wall mounted thermocouples. The governing equation for quality is determined by making an energy balance on the carefully insulated heat exchanger, i.e., the heat absorbed by the coolant is equal to the

heat given up by the condensed steam and the subsequent heat loss of the liquid. Using the traditional symbols for quality (x), mass flow rate ($\dot{m}$) and enthalpy (h), the heat balance can be written as:

$$\dot{m} \Delta h_{f34} = \dot{m} x (\Delta h_{f12} + h_{fg12}) + \dot{m} (1 - x) \Delta h_{f12}$$

It follows that the quality can be expressed as:

$$x = \frac{\Delta h_{f34} - \Delta h_{f12}}{h_{fg12}}$$

or letting c_p be the specific heat and T the temperature gives

$$x = \frac{c_{p34} \Delta T_{34} - c_{p12} \Delta T_{12}}{h_{fg12}}$$

In the present design, the condenser and subcooler will utilize the same model H. E. It is very compact and is a concentric tube type permitting use with the relatively large pressures encountered on both the primary and secondary side in the present application. The system must be well insulated and pressure transducers installed to insure that large pressure drops do not occur. The sampling probe is designed to permit traversing across the vertical diameter with valving adjusted to achieve isokinetic sampling. Thermocouples will be mounted on the tube wall adjacent to the inlet/outlet locations.

This relatively simple design for steam quality measurement leads to an evaluation of quality using only the four temperature measurements and calculated or measured thermodynamic properties of the geothermal fluid. Flow measurement of the sample and cooling water is not required but might be of value for other purposes. As noted in Ref. 9, this system is limited to some maximum quality depending on the particular conditions. For a typical case of 440°F steam and 80°F cooling water, the design is limited to about 40% quality for

relatively pure water and somewhat less than that for high salinity brines. When qualities encountered exceed the system capacity, it should still be possible to use this approach by feeding the cooling water directly into the condenser and measuring flow rates of the condensed brine and cooling water.

Status: System is completely fabricated with pressure taps and thermocouples installed. High temperature foam insulation which sets up from a liquid state was used to insulate the system. A photograph of the system without insulation is shown in Fig. 4.

SUBCOOLING
HEAT EXCHANGER

CONDENSING
HEAT EXCHANGER

Fig. 4 Dual Heat Exchanger System For Steam Quality Measurement

Light Attenuation

As steam becomes less foggy with increasing quality, the measurement of light attenuation or possibly scattering and refraction, should be some indication of the quality level. This setup consists of a small, 5 mW laser and associated photodiode with the laser beam passed through small transparent windows on opposite ends of the pipe diameter. Calibration would be required for the particular application.

Status: System is complete and ready for use. The one-half inch diameter glass windows have been mounted in the pipe wall as shown in Fig. 5. This self-seating design results in an extremely strong but yet very simple window arrangement. The windows were ground from 2" diameter glass pipe and sealed in place using a high temperature RTV silicone rubber.

Fig. 5 Cross-sectional View of Self-Seating Window Design

Impact Transducer

A 5 MHz, 1/8-inch diameter quartz crystal mounted on the end of a probe and facing the flow will give a response to impact from droplets and particulate in the flow. The character of the signal should be indicative of the droplet or particulate size, velocity, and mass. The probe is fed through a Conax fitting in the pipe wall and can be traversed across the diameter. The transducer is strictly dynamic and will not be sensitive to steady state type input such as the dynamic pressure. An impact on the crystal induces a stress

state which results in electric polarization of the crystal. The output voltage V is given by the relation¹⁰

$$V = \frac{K\sigma A}{C}$$

where σ , K , A , and C are the stress, piezoelectric constant of the crystal, crystal area, and total capacitance, respectively.

Status: An impact transducer has been fabricated and is ready for testing. The traces shown in Fig. 6 illustrate the response characteristics of the transducer to low velocity impact from small particles and from water droplets released from a hypodermic needle in a vertical drop. Note the greater than three order of magnitude difference in sweep rate used between the particles and water droplets.

Fig. 6 Oscilloscope Traces of Impact Transducer Response to Particle and Water Droplet Impact

Ultrasonic Velocity System

Through a number of discussions and a formal consultation visit with Panametrics personnel, an ultrasonic velocity meter system design was decided upon. The system will be developed under contract to Panametrics and will

utilize several of their recent innovations in optimizing the design. As mentioned previously, ultrasonic velocity meters have been widely used in liquid flow but their application in highly attenuating media such as gas and two phase flows is much more difficult. Two high temperature ultrasonic transducers will be mounted in line on the pipe wall at 45° to the pipe axis. Isolation mounts will be incorporated to minimize short circuiting problems and increase the S/N ratio. The system will use a pulser-receiver and a preamp with data being recorded on a high speed storage oscilloscope.

A schematic of the setup is shown in Fig. 7. If V is the average flow velocity, C the sound velocity in the static fluid, and d the transducer spacing at 45° to the pipe axis, then the downstream travel time t_d for an ultrasonic pulse will be:

$$t_d = \frac{d}{C+V \cos 45^\circ}$$

and the upstream travel time t_u will be

$$t_u = \frac{d}{C-V \cos 45^\circ}$$

These relations can be solved simultaneously to get the flow velocity and sound speed from the measurements of t_d and t_u :

$$V = \frac{d}{\sqrt{2}} \left(\frac{1}{t_d} - \frac{1}{t_u} \right)$$

$$C = \frac{d}{2} \left(\frac{1}{t_d} + \frac{1}{t_u} \right)$$

Fig. 7 Schematic of Ultrasonic Velocity Meter

Small corrections can be made for flow profile and the recessed zero velocity region at the transducer face. As an example, take the two-phase sound velocity to be 600 ft/sec and the flow velocity to be 15 ft/sec in a two-inch pipe (approximate Geothermal Test Facility conditions), then

$$t_d = 386.0 \text{ } \mu\text{sec and } t_u = 399.9 \text{ } \mu\text{sec}$$

An additional application of ultrasonics would be the evaluation of density and mass flow rate through impedance (pc) measurement of the flow. This is more difficult to achieve accurately and will not be attempted initially.

If successful, the ultrasonic velocity system will provide a convenient means of measuring average flow velocity in the field without disturbing the flow.

Status: Contract for development of ultrasonic velocity system has been let.

Photography

A five inch length of transparent pipe section has been designed into the test spool, shown in Fig. 1, for photographic applications as well as other methods requiring a transparent or non-conductive wall. The section will be constructed from a five inch long, two-inch diameter spacer pipe with a 1/3 inch wall thickness and will be compressed in place between two flanges. The design will be pressure tested to failure in the high pressure facility before its incorporation into the test spool.

Status: Spacer pipe was ordered in October, 1974 but has still not been received.

System Safety

A safety note has been written for the geothermal test spool, Ref. 11. At the time of this report, circular and rectangular pyrex glass window designs and the quality measurement system have been pressure tested. The self-seating window designs were tested to 1720 psi at a temperature of 450°F when the rectangular window failed by cracking and permitting gas leakage. This is

almost five times the maximum pressure anticipated in use. The quality measurement system was pressure tested to twice the maximum pressure expected without leakage or any signs of weakness or potential failure. The glass spacer pipe design will be tested at 1.5 times expected pressure before its incorporation into the test spool.

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