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**Advanced Two-Phase
Flow Instrumentation Program
Quarterly Progress Report for
January-March 1980**

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ADVANCED TWO-PHASE FLOW INSTRUMENTATION PROGRAM QUARTERLY PROGRESS REPORT FOR JANUARY-MARCH 1980

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ADVANCED TWO-PHASE FLOW INSTRUMENTATION PROGRAM QUARTERLY
PROGRESS REPORT FOR JANUARY-MARCH 1980

K. G. Turnage R. L. Anderson*
C. E. Davis G. N. Miller*

ABSTRACT

Work performed to develop reliable liquid level sensors for in-vessel use in pressurized water reactors is described. During this period, an improved heated thermocouple level sensor was fabricated and techniques for separating thermocouple output signals from superimposed ac voltages were developed. Experiments that were performed with a thermal-type level sensor in natural convection to saturated water and steam are described. Pressures in those tests ranged from 0.1 to 10 MPa (15 to 1500 psia). Acoustic techniques using pulse transit times along a waveguide were studied. A single waveguide was used to obtain accurate measurements of liquid level at room temperature and to compensate for temperature variations over a 10°C temperature range.

1. INTRODUCTION

During the accident at the Three Mile Island (TMI) nuclear power plant, a condition of low water level in the reactor vessel and inadequate core cooling existed and was not recognized for a long period of time. A review of the accident was conducted by the U.S. Nuclear Regulatory Commission (NRC) TMI-2 Lessons Learned Task Force.¹ Their report recommended that improved instrumentation systems, including reactor vessel liquid level (coolant) sensors, be developed and implemented in all pressurized water reactors (PWRs) in the United States. The coolant sensors are intended to provide an unambiguous indication of the adequacy of core cooling. They must survive in accident conditions, and they must work under both natural and forced convection flow conditions.²

The Advanced Two-Phase Flow Instrumentation (ATPI) Program at Oak Ridge National Laboratory (ORNL) has been funded by the U.S. NRC Division of Reactor Safety Research to evaluate instrumentation systems for this

*Instrumentation and Controls Division.

purpose. As part of this effort, two concepts are being pursued concurrently: (1) thermal-type sensors, such as heated junction thermocouples (TCs), and (2) acoustic sensors. Test sensors are being designed and fabricated at ORNL and procured from outside sources. A variety of experiments are being run to evaluate the devices for power reactor use.

2. THERMAL DEVICES

2.1 Sensor Design and Development

Thermal devices being tested use pairs of K-type (Chromel vs Alumel) TCs to sense the cooling capacity of the medium surrounding the device. One of the TCs is heated by an electric current passed through a separate wire; the other is primarily influenced by the fluid temperature. The difference between the temperatures of the heated and unheated points (ΔT) is monitored to compensate for variations in the system fluid temperature. For a given heater power, with good cooling conditions (liquid or rapidly flowing two-phase mixtures), the ΔT is relatively low; with poor heat transfer (e.g., stagnant steam), the temperature at the heated junction increases greatly, making the ΔT higher.

During the current report period, a second heated thermocouple (HTC) coolant sensor was fabricated (Fig. 1). (This probe will be referred to

Fig. 1. HTC coolant sensor (ORNL II) fabricated by Fuel Rod Simulator Fabrication Group.

as ORNL II.) The probe was built by the Fuel Rod Simulator Fabrication Group at ORNL. Components used for the new probe are like those used in the first differential HTC, described previously.³ However, the new probe has two distinct design improvements. First, the HTC junction is located directly under the heater windings, instead of just outside the windings along the probe axis, as it was in the first prototype. Compared with the earlier version, more heating of the hot junction will result, making the probe more sensitive to degradation of the surface heat transfer condition. Second, location of the heater coil nearer the probe tip and closer spacing between the heated and reference TC junctions (separation distance of 5 cm) will allow use of the probe in a horizontal orientation in a 9-cm-ID pipe. Tests are planned for the HTC in 9-cm-ID pipe in the Advanced Instrumentation for Reflood Studies (AIRS) Test Stand, a forced convection steam-water instrument test facility. When the probe is used in vertical orientation, closer spacing of the junctions will help to ensure that there is little difference in the fluid conditions adjacent to the two junctions. X rays were made of the probe to verify the location of internal elements.

Another method using ordinary TCs (no separate heater) as sensors was tested. The TC wires were heated by an ac current, and, at the same time, the TC emf was read using a filtered circuit. A schematic of this system is shown in Fig. 2. A blocking capacitor is placed in the output of the Variac to prevent the dc emf from the TC from being shorted through the windings of the Variac. The TC emf is filtered to remove the ac, is buffered, and may be displayed on a meter. A test of the ac HTC probe was performed using a container of water at room temperature. Figure 3 is a plot of the difference in indicated temperature between the covered and the uncovered states vs the ac heating current. These data indicate that this method to detect liquid level can be used in cases where TCs are in contact with the fluid. Successful application may require some prior knowledge of the temperature rise in the covered and uncovered states in the particular location where the TC is installed. This method may be useful as a diagnostic tool, and the instrumentation should be relatively inexpensive.

Fig. 2. Schematic of system used for self-heating tests of K-type TCs as a liquid level sensor.

Fig. 3. Difference between covered and uncovered TC output recorded in room-temperature self-heating test and plotted vs ac heating current.

2.2 Testing of Heated Thermocouples

During January and February, experiments were performed with an ORNL-fabricated HTC probe in the pressurizer of the Transient Instrument Test Facility (TITF).⁴ The test sensor (ORNL I), which is described in the previous quarterly report,³ incorporates both heated and reference TC junctions in a single sheath. (Test results reported previously³ were from an HTC probe that used a separately sheathed TC mounted ~15 cm above the probe as a reference.)

For level probe testing, the TITF is pressurized using strip heaters on the pressurizer body. Then, the level sensors under test are covered and uncovered with saturated water using system letdown valves and a high pressure injection pump. An accurate measurement of the liquid level in the pressurizer is obtained independently of the test sensor by using a differential pressure transducer.

For each test point, a constant dc power was supplied to the 6.5- Ω probe heater. Differential TC output voltages were obtained with heater currents ranging from 350 to 1600 mA. Four series of tests were conducted with three locations of the HTC probe along a (horizontal) radius of the pressurizer, about halfway from top to bottom of the vessel (Fig. 4). The ranges of data taken during the test series are indicated in Table 1. A digital voltmeter and a continuous chart recorder were used to record the output signal of the differential TC during testing. Figure 5 shows the recorded ΔT s obtained during these test series. Each graph includes

Table 1. Test matrix with ORNL HTC No. 1

Test series	Date of test (1980)	Distance ^a (cm)	Heater current range (mA)	Pressure range (MPa)
1	1/14	5.0	63-500	0.1-10.2
2	1/15	0.2	115-750	0.1-1.5
3	1/16	0.8	400-750	0.1-3.6
4	2/5-6	0.8	400-1640	0.1-4.2

^aDistance between probe tip and vessel wall.

Fig. 4. Schematic showing location of HTC sensor ORNL I in TITF pressurizer for natural convection experiments.

data for a particular pressure and temperature range. Each data point represents a mean ΔT reading obtained after the TC output was judged to have reached a steady-state value.

Data show that at a given heater current the steady-state ΔT s recorded when the test sensor was immersed in saturated steam were always greater than the ΔT s recorded when the probe was covered with liquid. The sequence of plots at successively higher ambient pressures and temperatures shows that changes in ΔT from covered to uncovered states decrease with increasing pressure. This is largely due to the improvement in natural convection heat transfer to saturated steam at higher steam pressures and densities.

The variation in recorded ΔT s from run to run may be due to the change in location of the probe with respect to a structure inside the vessel (Fig. 4) that formed a cover or hood over part of the HTC. The hood is part of the pressurizer assembly itself and was installed several years ago when the pressurizer was used with another facility.

Additional tests are needed to establish repeatability of probe performance, particularly at pressures above 3.4 MPa (500 psia). An improvement in probe performance is expected with the removal of the internal structures in the vicinity of the probe. Further tests are to be run with the same sensor, after the modified pressurizer is reinstalled in the TITF.

An example of the sensor time-response observed during these tests is shown in Fig. 6. During the test period heater power was 1.0 W, corresponding to a local surface heat flux of 0.35 W/cm^2 ($0.11 \text{ Btu/h}\cdot\text{ft}^2$).

Fig. 6. Transient response of HTC ORNL I recorded during test series 3 (see Table 1); heater power = 1.0 W, temperature in vessel = 100°C , pressure in vessel = 100 kPa.

The curve indicates that, after the probe was uncovered, ~70 s were required for ΔT to reach 63% of its maximum. On recovering the probe, less than 2 s were required for the output temperature to fall to 37% of maximum ΔT .

2.3 TITF Pressurizer Modifications

Following the completion of the HTC tests, the pressurizer's instrumentation and piping connections were disconnected and the pressurizer body was removed from the system. The spherical top end cap was cut off, and all internal structures were machined from the pressurizer body. Penetrations and fittings added to the pressurizer for future probe testing are shown in Fig. 7. The flat top for the pressurizer includes locations for insertion of an HTC level sensor borrowed from the U.S. Navy. Locations for insertion of 3.2- and 1.6-cm-OD HTC probes and for a 1.27-cm-OD ultrasonic level sensor were included in the upper end cap. These devices are to be tested in the pressurizer in a vertical orientation. In addition, a 1-in. threaded fitting was added to the side of the pressurizer body as shown to accommodate the heated resistance temperature device (RTD) on order from Fluid Components Incorporated.

2.4 HTC as Flowmeter

The second prototype heated junction TC probe, ORNL II (see Sect. 2.1), was installed in a low-flow calibration loop at room temperature, and the change in the output was recorded as a function of flow rate. Results are shown in Fig. 8. The minimum flow of 0.03 m/s (0.09 ft/s) produced a change in temperature of about 3°C from the static, no-flow condition. At a higher flow velocity of about 0.8 m/s (2.6 ft/s), the change in temperature was about 13°C. During natural convection cooling of a pressurized water reactor (PWR) core by subcooled or saturated liquid water, the convection flow velocity is expected to be about 0.3 m/s (1 ft/s) or greater.

Fig. 7. TITF pressurizer after modifications were complete for testing of new thermal and acoustic level sensors.

Fig. 8. Change in temperature from output recorded at zero flow to that recorded at a given water velocity. Test was performed using device shown in Fig. 3 in low-flow-rate calibration loop at room temperature.

3. ACOUSTIC LIQUID LEVEL PROBE DEVELOPMENT

3.1 Background

Of the possible ways to use acoustic techniques to measure liquid level in a reactor vessel, the torsional-wave ultrasonic sensor seems to hold the most promise. Some potential advantages are that: (1) only a steel (or other suitable material) ribbon would be exposed in the reactor vessel, (2) fluid density and temperature profiles could be sensed along the probe, and (3) the torsional-wave ultrasonic sensor would provide a continuous readout of liquid level along the probe.

The principle of the torsional-wave ultrasonic liquid level sensor is illustrated in Fig. 9. A torsional acoustic pulse traveling down a flattened ribbon suspended in free air will be reflected from the end and returned to the transducer with a transit time that may be measured, for example, with an oscilloscope. When the ribbon is immersed in a liquid medium, the velocity of propagation of the torsional wave is slowed so that, if a portion of the ribbon is immersed (as shown), then the reflection of the pulse is delayed. An oscilloscope display of these measurements might appear like the traces shown at the top of Fig. 9.

The velocity of a torsional wave in a rectangular waveguide is given by

$$v = K \sqrt{\frac{\mu}{\rho}} \left[1 + \frac{\rho}{2\rho_s} \left(1 - \frac{1}{K} \right) \right],$$

where

ρ = density of surrounding medium,

ρ_s = density of sensor material,

μ = shear modulus,

K = a shape constant dependent on waveguide geometry.

Thus, the velocity of torsional waves in a waveguide is affected by the density of the surrounding medium, by the waveguide's shear modulus (temperature dependent), and by the waveguide's density (temperature dependent).

Fig. 9. Principle of torsional-wave acoustic liquid level sensor.

The velocity of an extensional acoustic wave in the waveguide is given by

$$V_{\text{extensional}} = \sqrt{\frac{Y_0}{\rho_s}},$$

where Y_0 is Young's modulus. Note that $V_{\text{extensional}}$ does not depend on the density of the surrounding medium. Thus, in theory, information on the velocity of propagation of extensional waves in a sensor may be used to correct the information from torsional waves for the effects of temperature, yielding information on density only. One goal of the current experimental program is to evaluate the usefulness of this technique in practice, first in a room-temperature level facility (Fig. 10) and then in high-temperature and flowing environments.

3.2 Experimental Methods and Results

During the current report period, experiments were conducted with a 3-m-long wave guide sensor and with transducers suitable for exciting torsional and extensional waves in the sensor. The active region of the probe consists of a flattened stainless steel ribbon with a cross section of 1 by 2 mm. In that flattened region are three equally spaced notches. The transducers act on a length of magnetostrictive material of circular cross section that is attached to the end of the flattened region. The exciting coils are also used to detect reflected waves. For these tests, transit times were measured using an oscilloscope.

Results of experimental measurements of water level in the laboratory over a 225-cm height are shown in Fig. 11. The error over the entire length of the probe was about $\pm 0.5\%$ of full scale at constant temperature. A 10° change in temperature, however, introduced about a $\pm 3\%$ error into the level measurements. Measurements of the temperature at a single point in the column and at four points along the column did not improve the results.

Experimental measurements of the velocities of propagation in air and water were made as a function of temperature for both the torsional and extensional waves in the waveguide. Results of these experiments

Fig. 10. Liquid level facility used for testing of acoustic sensors.

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Fig. 11. Error in liquid level measured over a 225-cm range using torsional-wave acoustic level sensor at room temperature. Temperature variation during test was less than 1°C .

(Fig. 12) show that, over a limited range of temperature, the effects are linear.

Figure 13 shows the level measurement data taken with a 10°C temperature change, both uncompensated and compensated, using extensional waves to measure the temperature of the probe. Because of reduction in errors

ORNL-DWG 80-5458 ETD

Fig. 12. Propagation times of torsional and extensional waves plotted as function of sensor temperature.

Fig. 13. Error in liquid level measurements made using acoustic level sensor with both torsional and extensional waves.

in the measured level, the temperature of the probe as measured by extensional waves probably can be used to correct the temperature effects on the level measured with torsional-wave signals.

3.3 Ultrasonic Probe Procurement

A purchase order was placed with Panametrics, Inc. of Waltham, Massachusetts, for a prototype torsional/extensional level sensor, suitable for testing at high temperatures and pressures (up to 10 MPa). Delivery is expected in May 1980.

4. CONTACTS WITH REACTOR VENDORS

As part of the effort to develop useful PWR coolant sensors, ATPI Program personnel continued working to contact those in the industry who would be most likely to use the results of this research. Key vendor personnel involved in the information transfer effort are C. W. Connell, Jr., Babcock and Wilcox; R. E. Bryan, Combustion Engineering; and W. G. Lyman, Westinghouse.

Meetings have been scheduled for April 1980 with the three PWR vendors in the United States to inform them of our program in sensor development and to solicit their advice on the direction future research should take.

5. SUMMARY

During the current report period, progress was made in the development of thermal and acoustic liquid level (coolant) sensors intended for use in PWR vessels.

An improved HTC level sensor was fabricated, and techniques for separating TC output signals from superimposed ac voltages were developed. Experiments were performed with a thermal-type level sensor in natural convection to saturated water and steam at temperatures up to 300°C. There was significant variation from run to run in recorded ΔT at a given system pressure, heater current, and phase condition (liquid or vapor). However, for a given heater current and pressure below 2.8 MPa (400 psia), all the ΔT s recorded for the vapor conditions lie well above the range of ΔT s recorded for the liquid conditions.

The pressurizer was removed from the TITF and modified for future testing. A number of internal components that may have affected HTC performance were removed from the pressurizer. Also several penetrations were added to allow testing of thermal-type level devices and an ultrasonic device with vertical orientation.

Experiments were performed in a room-temperature level facility with a steel ribbon modulated with torsional and extensional waves at ultrasonic frequencies. The work has shown that pulse reflections can be timed to yield level readings accurate within a few percent. Additionally, temperature data derived from effects on the longitudinal waves have been used to correct the level readings to better than 1% accuracy. Tests to date have covered only a 10°C temperature range; future tests are intended to cover a wider temperature range.

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