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304P
GEAP-10114
AEC RESEARCH AND
DEVELOPMENT REPORT
OCTOBER 1969

RECEIVED BY DTIC MAY 11 1970

**TWO-PHASE FLOW
AND HEAT TRANSFER
IN MULTIROD GEOMETRIES
SIXTEENTH
QUARTERLY PROGRESS REPORT
JULY 1 - SEPTEMBER 30, 1969**

U.S. ATOMIC ENERGY COMMISSION
CONTRACT AT(04-3)-189
PROJECT AGREEMENT 44

ATOMIC POWER EQUIPMENT DEPARTMENT
GENERAL ELECTRIC
SAN JOSE, CALIFORNIA

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GEAP-10114
AEC Research and
Development Report
October 1969

TWO-PHASE FLOW AND HEAT TRANSFER IN MULTIROD GEOMETRIES

Sixteenth Quarterly Progress Report
July 1–September 30, 1969

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U. S. Atomic Energy Commission
Contract AT(03-4)-189
Project Agreement 44

Printed in U.S.A. Available from the
Clearing House for Federal Scientific and Technical Information
National Bureau of Standards, U. S. Department of Commerce
Springfield, Virginia
Price: \$3.00 per copy

6012-Dev.Eng.-19
115 - AG - 1/70

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ACKNOWLEDGMENTS

This program is sponsored by the Atomic Energy Commission and conducted by the General Electric Company, with the following individuals contributing to the program during the current reporting period:

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SUMMARY

Task C

The circular tube test section, which was built specially for the measurement of developing two-phase flow, is described.

1. INTRODUCTION

This is the sixteenth quarterly report on the work done under Contract AT(04-3)-189, Project Agreement No. 44, and covers the period from July 1 to September 30, 1969.

The objectives for Phase 1 of the program were as follows.

Task A

1. Obtain detailed measurements of flow structure (pressure drop, liquid film thickness, wall shear stress, local mass flux, local impact pressure) for air-water and steam-water mixtures.
2. Carry on an analytical effort in parallel with the air-water tests.

Task B

1. Measure the critical heat flux for a vertical nine-rod geometry, under forced convection conditions, with water at high pressure (600 to 1400 psia) and flow upward. Tests should be performed with a "clean" multirod geometry (as little disturbance as possible to the flow by the provisions for maintaining the rods in correct relative alignment).
2. Investigate the effect of certain parameters; specifically, quality, flow rate, heated length, pressure, and rod-wall spacing.
3. Use the results to evaluate one or more computer models as a basis for CHF prediction.

The work under Phase 1 has been reported in Quarterly Reports Nos. 1 through 10, plus certain topical reports and summary reports, either issued or to be issued soon.

The objectives for Phase 2 are as follows.

Task C

1. Make measurements of both fully-developed and developing two-phase flow (steam-water at 600 to 1400 psia, adiabatic and with heat addition, flow vertical upward) from which can be determined rates of mass and energy transfer in the transverse direction, such measurements to be made in a circular tube, eccentric annulus, and nine-rod channel. The nine-rod channel measurements should include representative measurements of subchannel flow and enthalpy from which can be deduced information concerning cross flow and mixing.
2. Determine the relationships between rate and driving potential, or potential gradient, and the effect of certain parameters (e.g., total flow, pressure, local void) on these relationships. In particular, determine the effect of grid-type spacers in the nine-rod channel.
3. Analyze the results to evaluate existing models of two-phase flow. Endeavor to develop an improved model in light of the results. Such a model should be useful in the prediction of flow structure, pressure drop, and critical heat flux in developing two-phase flow in multirod geometries, both "clean" and with grid-type spacers.

Task D

1. Measure critical heat flux in a nine-rod channel fitted with grid-type spacers characteristic of modern water-cooled reactors.

2. Determine, if possible, whether, and to what degree, the effect of spacers on the CHF is caused by a redistribution of the flow among the various subchannels, or by a highly localized disturbance which might, for example, disrupt the liquid film.
3. Modify the prediction methods developed in Task C as appropriate, and check them against the data obtained under Item 1.

Subchannel measurements under Task C were continued in the nine-rod test section during July and part of August. These measurements were made with the heat flux nonuniform in the radial direction, in contrast with the

earlier measurements for which the heat flux was uniform. These, plus the earlier subchannel results given in References 1 and 2, will be presented in detail in a topical report to be issued soon. No further description of the subchannel work will be given here.

The circular tube test section for the measurement of fully-developed and developing two-phase flow under Task C was completed and put into service in September. Some data were obtained but have not been reduced. Comments in this report will be confined to only a description of the test section.

2. DESCRIPTION OF CIRCULAR TUBE TEST SECTION

The circular tube test section shown in Figures 1 and 2 was designed and built specially for the measurement of developing two-phase flow. It has an inside diameter of 0.683 inch, and has various points of attachment for the electrical power leads so that measurements may be made either at the end of the heated length or at various distances past the end of the heated length. The different possible arrangements are:

<i>Heated Length (ft)</i>	<i>Distance from Heated Length to Exit End of Tube (ft)</i>
15.8	8
4	4
6	2
8	0

2.1 SETUP NO. 1

The flow at the exit end of the tube can be divided by means of a concentric cylindrical flow splitter into an inner zone and an outer zone, which in an annular flow regime correspond approximately to the core region and the film region, respectively. This setup with flow splitter in place is shown in Figures 3 through 6, and is hereinafter referred to as Setup No. 1.

Static pressure taps located on the wall and on the centerline at the leading edge of the splitter are used to adjust the flow in the outer zone so that the flow at the leading edge is "isokinetic". The flow is presumed to be isokinetic (i.e., unchanged by the means used to measure it) when the static pressures on the wall and centerline are equal. Three different diameter splitters are used in order to traverse the film region. The annular clearance between the largest diameter splitter (No. 1) and the tube wall is 0.01 inch. The annular clearances for the other two splitters (Nos. 2 and 3) are 0.02 inch and 0.03 inch, respectively.

Setup No. 1 also includes the eight static pressure taps shown in Figure 1 for static pressure gradient determination.

The inner-zone and outer-zone flows—which will be referred to, respectively, as the main flow and the sample flow in the following discussion—leave the test section through concentric passageways (see Figure 3). The main flow is in the outer passage and acts as a steam-water jacket around the sample flow, to minimize heat loss from the sample. The main flow then goes to an afterheater and steam drum and the sample goes to a mixer-type calorimeter, as shown in Figure 4. The sample is mixed with a measured rate of cold water which condenses any steam in the sample. The rate and enthalpy of the mixture and the increase in enthalpy of the cold water in going through the calorimeter, are sufficient to determine the sample rate and enthalpy. A slight correction is necessary to account for heat loss from the calorimeter itself.

The quantities that are measured in Setup No. 1 are:

- System pressure (at exit end of test section)
- Total flow rate (just ahead of test section inlet)
- Inlet temperature
- Power to test section
- Exit temperature
- Cold water flow rate
- Cold water temperature
- Mixture (cold water plus sample) flow rate
- Mixture temperature
- Static pressure profile over the last eight feet ahead of the exit.

Various values of inlet temperature and power are used in combination with the various splitters and points of power lead attachment, to determine the effect of mass rate, quality, and distance from the end of the heated length, on the sample flow in three different annular zones and on the static pressure gradient.

Figure 1. Circular Tube Test Section

Figure 2. Segment of Test Section between Power Lead Attachment Points E_2 and E_3 . (Foil insulation, ordinarily in place, was removed for this photo.)

Figure 3. Setup No. 1

Figure 4. Schematic of Loop with Setup No. 1

Figure 5. Top of Test Section with Setup No. 1. (Foil insulation was removed for this photo.)

LINE TO STATIC PRESSURE PROBE

TUBE FROM SAMPLE COLLECTING RING
TO EXIT FROM TEST SECTION

TWO STATIC LINES FOR
ISOKINETIC SETTING

Figure 6. Closeup of Top and Test Section with Setup No. 1, Top Closure Removed

2.2 SETUP NO. 2

The thickness of the liquid film* at the exit end of the tube under conditions of annular flow can be measured by two different schemes, both dependent on the fact that the liquid phase is a much better electrical conductor than the vapor phase. The essential element in the first scheme will be referred to as a conductivity cell, and in the second as a conductivity probe.

The cell method has been developed and used particularly by the British at Harwell.^{3,4,5,6} It consists essentially of two electrodes embedded in and flush with the wall of the channel. The wall in the vicinity of the electrodes must be of a nonconducting material. Electrical conductance is established between the two electrodes when a continuous film of liquid bridges the gap between them. If the thickness of the liquid film increases, the conductance also increases. If the conductivity cell has been calibrated and the specific conductivity of the liquid is known or constant, the problem of measuring film thickness is reduced to the problem of measuring electrical conductance. The cell method gives a value for film thickness which is equal to the thickness of a uniform liquid film (no vapor entrained) having the same conductance.

The probe method has been developed and used by McManus,⁷ Hewitt, et al.,⁵ and Bergles, et al.⁸ It consists of a conducting probe which is inserted through one wall of a channel so that it can traverse normal to the opposite wall. When fully inserted, it must make electrical contact with the opposite wall; hence, that wall must be an electrical conductor at the point of contact. As the probe is withdrawn, it first loses direct contact with the wall, but maintains contact via a continuous bridge of liquid in the film. As the probe is further withdrawn, the bridge of liquid becomes discontinuous (as though the probe has encountered the troughs of occasional passing waves), and finally—provided the flow regime is truly annular—there is no bridge at all (as though the probe has cleared the crests of all passing waves). Following McManus,⁷ the average thickness of the film is taken as the distance that the probe travels from the wall before the probe loses contact with the liquid bridge 50% of the time.

It is expected that the probe method will give values for film thickness which are greater than the cell method. The reason is that entrained vapor bubbles will, in effect, reduce the specific conductivity of the liquid in the film. The film must necessarily be thicker than is indicated by the cell method in order to have the same conductance as a liquid film free of entrained vapor bubbles.

* This is a generally accepted concept of the annular and annular-dispersed flow regimes. However, the "liquid film" is known to carry entrained vapor, and the interface between liquid and vapor is often very poorly defined. The idea of a film is an oversimplification which is often used in models of these flow regimes.

Setup No. 2, with the conductivity probe and five conductivity cells in place, is shown in Figure 7. The conductivity probe and the first cell are at Station No. 1. The remaining four cells are at Stations Nos. 2 through 5. The sectional view of a typical conductivity cell shows that each cell is actually four cells, each of the four covering a 90-degree sector. Thus, any substantial circumferential variations in film thickness can be detected. Moreover, the axial disposition of the conductivity cell permits detailed determination of thickness variation in the axial direction.

Each of the conductivity cells consists of a ceramic cylinder, with 0.029-inch-diameter stainless steel electrodes which pass through its wall from the outside. The electrodes are brazed to the ceramic and ground flush on the inside. A 0.063-inch-o.d. stainless steel tube is brazed to the outside of the cylinder concentric with each electrode, and the space between each electrode and its tube is filled with insulating material. The tubes are then led out through glands in the wall of the test vessel.

When the conductivity probe is in use for film thickness measurement, one of the conductivity cell electrodes is used in conjunction with it to make the wall a conductor at the point of contact where the probe is fully inserted. A sectional view of the probe is shown in Figure 8. It passes through a water-cooled O-ring gland, and is driven in or out by means of a micrometer screw, with its dial graduated in thousandths of an inch. The center of the probe is an electrically conducting rod, insulated from the surroundings except for a small, sharp point on the inside end and a terminal on the outside end, external to the test section. In use, this terminal is connected to an oscillograph via suitable circuit, to indicate whether or not a continuous bridge of water exists between the probe and the channel wall.

In summary, the liquid film thickness can be measured by either or both methods at the following distances from the end of the heated length:

Distance from Heated Length to Point of Measurement		Method of Measurement	
(inches)	(feet)	Cell	Probe
0.75		X	X
2.75		X	
5.5		X	
11.0		X	
22.0		X	
	2	X	X
	4	X	X
	8	X	X

The quantities that are measured in Setup No. 2, then, are:

- System pressure
- Total flow rate

Figure 7. Setup No. 2

Figure 8. Conductivity Probe

- Inlet temperature
- Power to test section
- Exit temperature
- Conductivity cell conductance (time average and versus time)
- Conductivity probe conductance (versus time)

Various values of inlet temperature and power are used in combination with the various points of power lead

attachment, to set the same conditions for which data were obtained in Setup No. 1. The effect on film thickness (as measured by two different methods) is then determined for mass rate, quality, and distance from the end of the heated length. The results can be correlated with the sample flow and pressure gradient measurements made with Setup No. 1.

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