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MASTER

**TWO-PHASE FLOW
AND HEAT TRANSFER
IN MULTIROD GEOMETRIES
EIGHTEENTH
QUARTERLY PROGRESS REPORT
JANUARY 1 - MARCH 31, 1970**

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

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AEC Research and
Development Report
April 1970

**TWO-PHASE FLOW AND HEAT TRANSFER
IN MULTIROD GEOMETRIES**

**Eighteenth Quarterly Progress Report
January 1 -- March 31, 1970**

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TABLE OF CONTENTS

Acknowledgments	1
Summary	1
1 Introduction	1
2 Description of Circular Tube Test Section	2
2.1 Setup No. 2	2
2.2 Description of Conductivity Probe	5
2.3 Principle of Operation	5
2.4 Calibration of Conductivity Probe	5
2.5 Other Quantities Measured in Setup No. 2	5
3 Test Procedure	7
4 Results, Setup No. 2	9
5 Nonisokinetic Results, Setup No. 1	26
6 Pressure Drop Results	26
Appendix. Recirculation Pump Performance Tests	33
Nomenclature	40
References	41
Distribution	43

LIST OF ILLUSTRATIONS

Figure	Title	Page
1	Circular Tube Test Section	3
2	Conductivity Probe	6
3	Conductivity Probe Circuit	7
4	Typical Oscilloscope Photos Used to Judge When the Probe Was "Seeing" a Continuous Liquid Film Bridge to the Wall 50% of the Time (Run No. 40.5)	8
5	Bubbly Region 0.06 Inch from Wall to Centerline Near Zero Quality (Run No. 36, $L_U = 0$, $G = 1.02 \times 10^6$ lb/h-ft ² , $\phi = 0.56 \times 10^6$ Btu/h-ft ² , $\bar{X} = 0.003$).	13
6	Bubble Region 0.06 Inch from Wall to 0.20 Inch from Wall, Transition Region 0.20 Inch from Wall to Centerline (Run No. 37, $L_U = 0$, $G = 1.03 \times 10^6$ lb/h-ft ² , $\phi = 0.57 \times 10^6$ Btu/h-ft ² , $\bar{X} = 0.050$)	15
7	Annular/Dispersed Flow (Run No. 56, $L_U = 0$, $G = 1.02 \times 10^6$ lb/h-ft ² , $\phi = 0.57 \times 10^6$ Btu/h-ft ² , $\bar{X} = 0.157$)	17
8	Evidence of Slug Flow Diminishes as Quality Increases (Probe On Centerline, $L_U = 8$ ft, $G = 1.02 \times 10^6$ lb/h-ft ²). No Slug Flow was Observed for Run No. 9R	19
9	Appearance of Oscilloscope Trace at Different Sweep Rates, Under Slug Flow Conditions (Probe on Centerline, $L_U = 8$ ft, $G = 0.52 \times 10^6$ lb/h-ft ² , Run No. 1, $\bar{X} = 0.041$, Run No. 2, $\bar{X} = 0.098$, Run No. 3, $\bar{X} = 0.142$). Evidence of Slug Flow Diminishes as Quality Increases	21
10	Film Thickness versus Quality ($G = 0.5 \times 10^6$ lb/h-ft ²)	23
11	Film Thickness versus Quality ($G = 1.0 \times 10^6$ lb/h-ft ²)	24
12	Film Thickness versus Quality ($G = 1.5 \times 10^6$ lb/h-ft ²)	25
13	Film Thickness versus Quality, Various Flows. Positions of Splitters Nos. 1, 2, and 3 Superposed	27
14	$P_W - P_C$ versus Sample Flow Rate, Nonisokinetic Conditions	28
15	Two-Phase Multiplier versus Quality, Martinelli-Nelson Multiplier Curve Superposed	32
A-1	Loop for Pump Test	34
A-2	Steady-State Pump Performance	35
A-3	NPSH Test No. 25, Valve Position-Full Open	36
A-4	Transient Pump Performance Test No. 41. Initial Conditions: Steam Blowdown through 1/2-Inch-Diameter Orifice, Water Level 176 Inches Above Pump Inlet, Blowdown at 5.96 Seconds	38
A-5	Transient Pump Performance Test No. 40. Initial Conditions: Steam Blowdown through 3/8-Inch-Diameter Orifice, Water Level 105 Inches Above Pump Inlet	39

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SUMMARY

A conductivity probe was used in the circular tube test section for flow regime observations, and for film thickness determination in the annular regime. Results show no evidence of slug flow right at the end of the heated length; instead, there is an extensive transition between the bubbly and annular regimes. Slug flow was observed at 8 feet past the end of the heated length, at the two flows 0.5×10^6 and 1.0×10^6 lb/h-ft², over a limited range of qualities, but the evidence of slug flow vanished when the flow was increased to 1.5×10^6 lb/h-ft². In the range of parameters for the circular tube tests, slug flow occurs only under adiabatic conditions, and then only at the lower flows.

A film thickness could be determined for qualities in excess of about 0.13. At $G = 0.5 \times 10^6$ lb/h-ft², the thickness for any particular quality changes very little with distance from the end of the heated length. At $G = 1 \times 10^6$ and 1.5×10^6 lb/h-ft², the film thickness is greater right at the end of the heated length than at 8 feet past, except when conditions are near CHF, in which case the film thickness is least right at the end of the heated length. At 8 feet past the end of the heated length and for qualities less than 0.18, the film thickness increases with increase in flow; for qualities greater than 0.22, the film thickness decreases with increase in flow. The trend in film thickness with flow rate right at the end of the heated length is essentially the same as at 8 feet past.

Samples of film flow obtained with Setup No. 1 under nonisokinetic conditions show that the sample flow rate is not very sensitive to $P_W - P_C$, the difference in static pressure between the wall and the centerline (measured at the same axial position as the leading edge of the splitter).

The two-phase multiplier determined from adiabatic two-phase pressure drop data is 25% to 35% below the Martinelli-Nelson value.

1. INTRODUCTION

This is the Eighteenth Quarterly Report on the work done under Contract AT(04-3)-189, Project Agreement No. 44, and covers the period from January 1 to March 31, 1970.

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.

The circular tube test section for the measurement of fully-developed and developing two-phase flow under Task C was described in the Sixteenth Quarterly Report.¹ The description and results for Setup No. 1 (isokinetic measurement of film flow rate) were given in the Seventeenth Quarterly Report.² The description and results for Setup No. 2 (measurement of film thickness) are given here. A table of nonisokinetic results for Setup No. 1, plus some pressure drop results, are also given.

Some special GE-funded tests were run, during the last quarter of 1969, to investigate the performance of a centrifugal pump under certain adverse conditions (suction head at or below minimum NPSH). The pump used for these tests is an item of AEC capital equipment assigned to P.A. 44. Although these tests are not part of the scope for P.A. 44, the results have been included here in the Appendix.

2. DESCRIPTION OF CIRCULAR TUBE TEST SECTION

The circular tube section shown in Figure 1 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. 2

Under conditions of annular flow, the thickness of the liquid film* at the exit end of the tube can be measured by a conductivity probe. The probe may also be useful for flow regime determination when the flow is not annular.

* The existence of a continuous liquid film is a generally accepted concept of the annular and annular-dispersed flow regimes which is often used in models of these 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 may be an oversimplification.

Figure 1. Circular Tube Test Section.

2.2 DESCRIPTION OF CONDUCTIVITY PROBE

The conductivity probe, as shown in Figure 2, consists of a 1/16-inch-diameter stainless steel conductor which is insulated from its surroundings by means of a Teflon tube that totally encases it, except for a small, sharp point on the inside end (projects into the channel), and a terminal on the other (outside) end. The Teflon tube, in turn, is housed inside a 1/8-inch-o.d. stainless steel tubular sheath which has a gland attached to its outside end. The gland provides a seal for the conductor and Teflon tube insulator. The inside end of the sheath was reduced in diameter to 3/32 inch to minimize flow disturbance. The 1/8-inch-o.d. portion of the sheath passes through a water-cooled O-ring gland in the probe fixture. A micrometer head, with its dial graduated in one ten-thousandths of an inch, is used to traverse the probe in or out, while the system pressure provides sufficient force (approximately 12 pounds) on the probe to maintain firm contact with the micrometer head. The threaded end of the probe fixture facilitates the attachment of the conductivity probe to the exit end of the circular tube test section.

2.3 PRINCIPLE OF OPERATION

The probe method has been developed and used by McManus;³ Hewitt, et al.;⁴ and Bergles, et al.⁵ The conductivity probe is inserted through the wall of the circular tube so that it can traverse normally to the opposite wall. When fully inserted, it must make electrical contact with the opposite wall; hence, that wall must be an electrical conductor. 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,³ the average thickness of the film is taken as the distance from the wall at which the probe loses contact with the liquid bridge 50% of the time.

2.4 CALIBRATION OF CONDUCTIVITY PROBE

An image-retaining oscilloscope (1 megohm pure resistive input impedance), connected in series with the conductivity probe and a battery as shown in Figure 3, was adjusted to yield an output signal of 6 volts dc when the probe was in contact with the wall, and a zero output voltage with open circuit.

After the test loop had been adjusted to provide single-phase flow at the test section exit with the water temperature at or near 545°F, the conductivity probe was traversed from the wall toward the center of the tube. Once the probe was out of contact with the wall, the output signal remained nearly constant at approximately 5 volts for all probe positions. The test loop conditions were then adjusted to provide two-phase, high-quality, annular flow at the exit end of the test section. The conductivity probe was traversed to the center of the tube, where the tip of the probe would be in the vapor phase. The output signal at this position was approximately zero.

The foregoing measurements give the upper and lower limits for the output signal where the probe "sees" only liquid phase and only vapor phase, respectively, and thus provide a guide in the determination of liquid film thickness.

2.5 OTHER QUANTITIES MEASURED IN SETUP NO. 2

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

- System pressure
- Total flow rate
- Inlet temperature
- Power to test section
- Exit temperature
- Conductivity probe conductance (versus time)
- Conductivity probe position

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 is then determined for mass rate, quality, and distance from the end of the heated length. The results may be correlated with the sample flow and pressure gradient measurements made with Setup No. 1.

Figure 2. Conductivity Probe.

Figure 3. Conductivity Probe Circuit.

3. TEST PROCEDURE

FILM THICKNESS DETERMINATION

When the predetermined steady-state test section conditions became established, the conductivity probe was traversed from the center of the tube toward the opposite wall, while observing the output signal on the image-retaining oscilloscope. The image was retained for several sweeps, then erased, the probe was moved a little farther, and the image again was retained for several sweeps. The oscilloscope beam intensity was adjusted to a low value so that when several traces were superposed, the resulting image was very faint, except where successive traces tended to lie on top of each other. Density of the image then became a measure of the time the probe was "seeing" all liquid or all vapor, or something in between. The probe was finally traversed to a position where the image density (see Figure 4) appeared to be equally distributed between the upper and lower limits of the output signal, as established in the probe calibration. This was then considered to be the position of the probe at which the probe is out of contact with the liquid bridge 50% of the time. Moving the probe in either direction from the above position results in an unequal distribution of image density on the oscilloscope screen, as shown in Figure 4.

The micrometer head reading was recorded for the foregoing probe position. The probe was then traversed toward the wall until contact with the wall was achieved, and the micrometer head reading was again recorded. The liquid film thickness was then taken as the difference between the two micrometer head readings for the two probe positions.

This procedure was repeated at least twice for every run. The second probe traverse would usually proceed from the wall toward the tube center, the third probe traverse from the tube center toward the wall, and so on. The average liquid film thickness as obtained from the three or more traverses was then recorded as the measured liquid film thickness.

$Y = 0.010$ (TOO CLOSE TO WALL)

$Y = 0.035$ (PROBE AT MEAN POSITION OF INTERFACE)

$Y = 0.100$ (TOO FAR FROM WALL)

Figure 4. Typical Oscilloscope Photos Used to Judge When the Probe Was "Seeing" a Continuous Liquid Film Bridge to the Wall 50% of the Time (Run No. 40.5).

4. RESULTS, SETUP NO. 2

Many observations were made with the conductivity probe, covering essentially the same range of conditions for which film flow rate data were obtained earlier in Setup No. 1.² In general, each observation was of a single oscilloscope trace, erased and repeated several times. Finally, one was selected which was judged characteristic for the particular flow conditions and distance of probe from the wall. The trace was recorded by means of a Polaroid oscilloscope camera. Some of the photos have been reproduced for this report, and are discussed in the following paragraphs.

Four different flow regimes (viz., the bubbly, slug, transition, and annular or annular/dispersed) were covered by the range of test conditions. The probe was located on the channel centerline for the slug flow runs, but was moved to the core/film interface for the annular flow runs. For each of a select number of the runs, a detailed traverse was made, and the oscilloscope trace was photographed at each position along the traverse. For many of the annular regime runs, however, no photographs were made; the only record kept was the measured film thickness.

The results, in terms of distance from end of heated length, pressure, flow rate, heat flux, quality, flow regime, and (in the case of annular flow) film thickness, are summarized in Table 1.

Figures 5, 6, and 7 are each a panel of photographs of oscilloscope traces* corresponding to different probe distances from the wall. For all three figures, the probe station is right at the end of the heated length ($L_U = 0$), the pressure is 1000 psia, the flow is 1.0×10^6 lb/h-ft², and the heat flux 0.55 to 0.57×10^6 Btu/h-ft². The qualities, however, are different for the three figures, being respectively -0.003, +0.050, and +0.147. The corresponding regimes are respectively bubbly, bubbly/transition, and annular. Figure 5 (bubbly regime) shows almost complete absence of bubbles in the region from wall to $y = 0.060$ inch, but fairly uniformly distributed bubbles inside of $y = 0.060$ inch; i.e., for $y > 0.060$ inch.

Figure 6 (bubbly/transition) also shows very few bubbles from wall to $y = 0.060$ inch, but shows rapidly increasing bubbles inside of this, to $y = 0.20$ inch. Inside of $y = 0.20$ inch, the regime appears to be entirely transition; i.e., neither the liquid nor the vapor phase appears to be continuous.

Figure 7 shows bubbles next to the wall, the interface at about $y = \delta = 0.09$ inch, and a continuous vapor phase in the core region. This is definitely the annular or annular/dispersed regime.

There was no evidence of slug flow right at the end of the heated length, regardless of quality, for any flow in the range $0.5 \times 10^6 \leq G \leq 1.5 \times 10^6$ lb/h-ft². There was no evidence of slug flow even 8 feet past the end of the heated length ($L_U = 8$) for $G = 1.5 \times 10^6$ lb/h-ft². However, for $G = 1.0 \times 10^6$ lb/h-ft², qualities 0.02 to 0.10 (Figure 8), and $G = 0.5 \times 10^6$ lb/h-ft², qualities 0.04 to 0.14 (Figure 9) slug flow was in evidence 8 feet past the end of the heated length. The slug flow vanished as the quality increased. Two of the runs ($G = 1 \times 10^6$ lb/h-ft², qualities 0.05 and 0.10) when repeated, showed bubbly/transition and transition rather than slug flow.

A film thickness could be determined both at the end of the heated length and 8 feet past the end, for all three flows and at qualities in excess of about 0.13. The results are plotted in Figures 10, 11, and 12, for $G = 0.5 \times 10^6$, 1.0×10^6 , and 1.5×10^6 lb/h-ft², respectively.

Referring to Figure 10 for $G = 0.5 \times 10^6$ lb/h-ft² and qualities in excess of 0.15, the film thickness is apparently independent of distance from the end of the heated length. At qualities near CHF, this is known not to be so (the film thickness right at the end of a uniformly heated circular tube goes to zero at CHF, whereas it will not generally be zero under adiabatic conditions except at qualities approaching 1.0).⁵ But it is evidently true for this particular test channel at this particular flow and pressure in the range of film thickness from 0.05 inch to 0.02 inch, qualities from 0.15 to 0.30. This is an unexpected result. No film flow data were obtained for this flow, but film flow data at higher flows² indicate that the mass flow rate in the film region increases with increasing distance from the end of the heated length. The fraction of vapor carried in the film region must therefore decrease with increasing distance from the end of the heated length, at least for a distance of 8 feet.

Referring to Figure 11, for $G = 1.0 \times 10^6$ lb/h-ft² and qualities 0.15 to 0.30, the film thickness is even greater right at the end of the heated length than at 8 feet past. This, again, is unexpected and leads to reinforcement of the conclusion—at least for the quality range from 0.15 to 0.30—that the fraction of vapor carried in the film must decrease with increasing distance.

* These particular traces include some 60-cycle and 1000-cycle "noise" superposed on the signal of interest. The Figure 5 trace for $y = 0.001$ inch, for example, consists entirely of this noise. The usefulness of the pictures is not significantly affected by its presence.

Table 1
FLOW REGIME AND FILM THICKNESS DETERMINATIONS

Run No.	L_u (ft)	P (psia)	$G/10^6$ (lb/h-ft ²)	$\phi/10^6$ (Btu/h-ft ²)	$\bar{X}$	Flow Regime*	δ (in.)
012	8	1005	1.027		0.297	A	0.010
013	↑	1007	1.025		0.393	↑	0.0035
011		1009	1.023		0.198	↓	0.0323
011.5		1005	1.025		0.240	↓	0.0172
010		1000	1.022		0.149	A	0.0522
007.25		1010	1.023		0.003	B	—
007.5		1000	1.022		0.023	S	
008		1009	1.017		0.049	S	
009		1005	1.023		0.104	S/A	
018		1013	1.536		0.310	A	0.0039
017		1010	1.538		0.200	↑	0.0232
017.5		1005	1.540		0.245		0.0103
018R		1015	1.538		0.293		0.0096
017.5R		1005	1.540		0.241		0.0246
017R		1003	1.538		0.199		0.0586
012R		1015	1.028		0.302		0.0173
013R		1000	1.023		0.404		0.005
011.5R		1000	1.030		0.238		0.0288
011R		995	1.022		0.206		0.043
012RA		1005	1.014		0.307		0.0118
011RA		1005	1.022		0.202		0.0407
018RA		1000	1.539		0.296		0.0091
017RA		995	1.532		0.203		0.0588
016		1000	1.531		0.153		0.1294
013RA		1005	1.027		0.397		0.0058
012RB	↓	1005	1.030		0.306		0.0133
012RC	8	1002	1.027		0.304		0.0136
039	0	1007	1.029	0.549	0.128		0.098
040	↑	1013	1.023	0.541	0.208		0.053
040.5		1013	1.031	0.546	0.232		0.035
040R		1019	1.027	0.559	0.181		0.1102
040RA		1033	1.026	0.533	0.180		0.1027
040.5R		1023	1.026	0.535	0.224		0.0864
033		1019	1.023	0.353	0.170		0.091
033R		1015	1.023	0.343	0.170		0.083
039R		1025	1.028	0.565	0.156		0.110
040RB		1019	1.020	0.556	0.191		0.0917
040.5R	↓	1015	1.026	0.567	0.267	↓	0.0598
041	0	1013	1.020	0.568	0.323	A	0.0089

- * 1 = Single phase with occasional bubbles
 B = Bubbly
 S = Slug
 T = Transition
 A = Annular or annular/dispersed

Table 1—(Continued)

Run No.	L_u (ft)	P (psia)	$G/10^6$ (lb/h-ft ²)	$\phi/10^6$ (Btu/h-ft ²)	$\bar{X}$	Flow Regime*	δ (in.)
036	0	1011	1.024	0.559	-0.003	B	
035		1005	1.023	0.568	-0.009	1	
037		1013	1.028	0.567	0.050	B/T	
038		1007	1.023	0.555	0.099	T/A	
044		1003	1.024	0.745	-0.007	B	
047		1005	1.026	0.750	0.147	A	0.1054
029		1000	1.026	0.351	0.006	B	
033RA		1005	1.020	0.345	0.179	A	0.073
032		1000	1.019	0.345	0.138		0.0883
060		1021	1.031	0.564	0.358		0.0015
059		1015	1.025	0.563	0.306		0.0064
056		1000	1.024	0.567	0.157		
040.5RB		1015	1.025	0.571	0.275		0.0112
040.5RC		1000	1.026	0.523	0.228		
059R		1003	1.026	0.559	0.305	A	0.0054
020		1000	0.524	0.347	-0.015	1	
023		1003	0.514	0.350	0.129	T/A	0.060
024		1005	0.515	0.350	0.190	A	0.0385
024.5		1010	0.515	0.346	0.219		0.031
025		1005	0.511	0.347	0.290		0.020
033RB		1015	1.022	0.352	0.175		0.0685
040.5RD		1015	1.026	0.565	0.269		0.019
041R		1017	1.026	0.559	0.299		0.0044
039RA		1001	1.026	0.564	0.165		0.0743
040RC		1015	1.024	0.565	0.201		0.0612
040.5RE		1018	1.025	0.570	0.270		0.019
059RA		1027	1.026	0.573	0.321		0.0061
033RC	0	1000	1.020	0.347	0.171		0.0653
011RC	8	1011	1.022		0.191		0.0329
011.5RA		1013	1.028		0.249		0.0171
012RC		1015	1.025		0.291		0.0085
013RB		1017	1.032		0.393	A	0.0021
008R		1007	1.021		0.048	B/T	
009R		1009	1.018		0.099	B/T	
010R		1003	1.023		0.147	A	0.0676
014		1011	1.544		0.044	T	
015		1009	1.546		0.094	T	
016R		1002	1.537		0.149	A	0.0944
017RB		1000	1.542		0.203		0.0383
017.5RA		1025	1.546		0.243		0.009
018RB	8	1015	1.550		0.293	A	0.0027

* 1 = Single phase with occasional bubbles

B = Bubbly

S = Slug

T = Transition

A = Annular or annular/dispersed

Table 1—(Continued)

Run No.	L_u (ft)	P (psia)	$G/10^6$ (lb/h-ft ²)	$\phi/10^6$ (Btu/h-ft ²)	$\bar{X}$	Flow Regime*	δ (in.)
001	8 ↑	1013	0.521		0.041	S	
002		1003	0.520		0.098	S	
003		1013	0.518		0.142	S/A	0.0711
004		1009	0.518		0.196	A	0.0396
004.5		1009	0.530		0.228	↑	0.0301
005		1011	0.525		0.286		0.0232
006	↓	1015	0.515		0.392		0.0108
007		1013	0.523		0.572		0.0028
003R		1001	0.527		0.142		0.0607
042		1015	1.012	0.598	0.403		CHF
061		1015	1.540	0.605	0.262		CHF
042a	↑	1000	1.030	0.608	0.183	↓	0.0712
042b		1005	1.025	0.607	0.240		0.0228
042c		997	1.023	0.617	0.302		0.0037
042d		1015	1.022	0.613	0.332		0.0018
042e		1000	1.020	0.611	0.359		0.0010
042f		1003	1.018	0.611	0.369		0.0010
042g		1005	1.017	0.612	0.371		0.0008
042h		1013	1.021	0.614	0.378		0.0010
61A		1013	1.542	0.618	0.143		0.1204
61B		1009	1.537	0.621	0.198		0.0677
61C	↓	1015	1.538	0.620	0.219	↓	0.0667
61D		1005	1.536	0.620	0.240		0.0387
61E		1000	1.538	0.621	0.248		0.0284
61F		1013	1.544	0.617	0.246		0.0138
61G		1003	1.532	0.626	0.268		0.0112
60R		1015	1.536	0.565	0.192	A	0.0814

- * 1 = Single phase with occasional bubbles
 B = Bubbly
 S = Slug
 T = Transition
 A = Annular or annular/dispersed

Y = 0.001 INCH

Y = 0.020 INCH

Y = 0.060 INCH

Y = 0.090 INCH

Y = 0.003 INCH

Y = 0.030 INCH

Y = 0.120 INCH

Y = 0.180 INCH

Y = 0.010 INCH

Y = 0.045 INCH

Y = 0.240 INCH

Y = 0.341 INCH (CENTERLINE)

Figure 5. Bubbly Region 0.06 Inch from Wall to Centerline Near Zero Quality (Run No. 36, $L_U = 0$, $G = 1.02 \times 10^6$ lb/h-ft², $\phi = 0.56 \times 10^6$ Btu/h-ft², $\bar{X} = 0.003$).

Y = 0.003 INCH

Y = 0.030 INCH

Y = 0.090 INCH

Y = 0.270 INCH

Y = 0.010 INCH

Y = 0.045 INCH

Y = 0.150 INCH

Y = 0.341 INCH (CENTERLINE)

Y = 0.020 INCH

Y = 0.060 INCH

Y = 0.210 INCH

Figure 6. Bubbly Region 0.06 Inch from Wall to 0.20 Inch from Wall, Transition Region 0.20 Inch from Wall to Centerline (Run No. 37, $L_U = 0$, $G = 1.03 \times 10^6$ lb/h-ft², $\phi = 0.57 \times 10^6$ Btu/h-ft², $\bar{X} = 0.050$).

$Y = 0.003$ INCH $Y = 0.030$ INCH $Y = 0.060$ INCH $Y = 0.210$ INCH $Y = 0.010$ INCH $Y = 0.045$ INCH $Y = 0.090$ INCH $Y = 0.341$ INCH (CENTER LINE) $Y = 0.020$ INCH $Y = 0.150$ INCH

Figure 7. Annular/Dispersed Flow (Run No. 56, $L_U = 0$, $G = 1.02 \times 10^6$ lb/h-ft², $\phi = 0.57 \times 10^6$ Btu/h-ft², $\bar{X} = 0.157$).

RUN NO. 7.5, $\bar{X} = 0.023$
20 msec SWEEP

RUN NO. 8, $\bar{X} = 0.049$
20 msec SWEEP

RUN NO. 9, $\bar{X} = 0.104$
20 msec SWEEP

RUN NO. 9R, $\bar{X} = 0.099$
5 msec SWEEP

Figure 8. Evidence of Slug Flow Diminishes as Quality Increases (Probe On Centerline, $L_U = 8$ ft, $G = 1.02 \times 10^6$ lb/h-ft²). No Slug Flow Was Observed for Run No. 9R.

$\bar{X} = 0.041$, 5 msec SWEEP

$\bar{X} = 0.041$, 10 msec SWEEP

$\bar{X} = 0.041$, 50 msec SWEEP

$\bar{X} = 0.098$

$\bar{X} = 0.098$

$\bar{X} = 0.142$
5 msec SWEEP

$\bar{X} = 0.142$
50 msec SWEEP

Figure 9. Appearance of Oscilloscope Trace at Different Sweep Rates, Under Slug Flow Conditions (Probe on Centerline, $L_U = 8$ ft, $G = 0.52 \times 10^6$ lb/h-ft², Run No. 1, $\bar{X} = 0.041$, Run No. 2, $\bar{X} = 0.098$, Run No. 3, $\bar{X} = 0.142$). Evidence of Slug Flow Diminishes as Quality Increases.

Figure 10. Film Thickness versus Quality ($G = 0.5 \times 10^6$ lb/h-ft²).

Figure 11. Film Thickness versus Quality ($G = 1.0 \times 10^6 \text{ lb/h-ft}^2$).

Figure 12. Film Thickness versus Quality ($G = 1.5 \times 10^6 \text{ lb/h-ft}^2$).

Referring again to Figure 11, it will be noted that for qualities in excess of 0.30, on the other hand, the film thickness is less at the end of the heated length than it is 8 feet past. In this case, the film at the end of the heated length is near a CHF condition.* As already noted, the film under heat transfer conditions goes to zero at CHF, whereas the adiabatic film does not. No conclusions can be drawn about changes in the relative amount of vapor carried in the film with increasing distance from the end of the heated length when conditions are near CHF. However, it is probable that when the film is this thin (in the order of 0.005 inch or less), very little vapor is carried.

Referring to Figure 12, for $G = 1.5 \times 10^6$ lb/h-ft² and qualities 0.15 to 0.25, the film thickness is again greater at the end of the heated length than at 8 feet past. The same conclusion can be drawn for the two lower flows, concerning decrease in fraction of vapor carried in the film with increasing distance. It will be noted that CHF occurred at a lower quality than would be predicted from an extrapolation of the smooth curve through the data for $L_U = 0$. Bergles, et al.,⁶ observed a similar behavior at higher flows for some of their test runs. Disruption of the film tends to occur abruptly at higher flows as CHF is approached.

All the best-fit curves through the data of Figures 10, 11, and 12 have been superposed on Figure 13, to facilitate comparison. Referring to Figure 13, and considering the curves for $L_U = 8$, the film thickness at qualities less than 0.18 *increases* with increasing channel flow rate. At qualities greater than 0.22, the trend reverses, and the film thickness *decreases* with increasing channel flow rate. Considering the curves for $L_U = 0$, the trend in film thickness with channel flows rate is essentially the same as for $L_U = 8$, but the reversal in trend occurs at slightly higher qualities.

The positions of the splitters used for taking off film flow samples isokinetically in Setup No. 1 are shown in Figure 13. If the film thickness is less than the splitter distance, the sample must include core flow as well as film flow, and the sample quality must increase. Figures 16 and 18 of the Seventeenth Quarterly Report² show that the sample quality increases rapidly when the measured film thickness becomes less than the distance from wall to splitter. It is evident from these considerations that the conductivity probe is determining the film thickness correctly.

A direct comparison with most of the results obtained at Dynatech by Bergles, et al.,⁶ cannot be made, because their data were obtained under different conditions; e.g., different channel diameter, generally different flow rates, heat flux not constant. Nevertheless, certain Dynatech data obtained under adiabatic conditions have been superposed on Figure 13, for a channel diameter of 0.40 inch, heated length 58 inches, pressure 1000 psia, main velocity 0.8×10^6 lb/h-ft². The Dynatech data are qualitatively in very good agreement with the results obtained on this program, being parallel to, but about 50% higher than, the Figure 13 curve for $G = 0.5 \times 10^6$ lb/h-ft². An effort is currently under way to compare our results with the findings of other workers.

5. NONISOKINETIC RESULTS, SETUP NO. 1

A few runs were made with Setup No. 1, during which film samples were drawn off under nonisokinetic conditions. When the sampling is done isokinetically, the sample flow rate $\dot{W}_S$ is adjusted so that the static pressure P_W on the channel wall (same axial position as leading edge of splitter) is just equal to the static pressure P_C on the channel centerline. When the sampling is done nonisokinetically, P_W is different from P_C . Results for Splitters Nos. 1 and 3 are listed in Table 2, and plotted as $P_W - P_C = \Delta P_{WC}$ versus $\dot{W}_S$ in Figure 14. These results show that the sample rate is not very sensitive to ΔP_{WC} . For example, ΔP_{WC} can be set to ± 0.002 psi. The corresponding variation in $\dot{W}_S$ is in the order of 1% or less. This is smaller than the error limits in the measurement of $\dot{W}_S$.

6. PRESSURE DROP RESULTS

Single-phase pressure drop results have already been presented in the Seventeenth Quarterly Report. Pressure drop was also measured under two-phase conditions, both adiabatic and with heat addition. The adiabatic data are listed in Table 3, the data with heat addition in Table 4.

* If the curve of Figure 11 for $L_U = 0$ were extrapolated to zero film thickness, it would intersect the $\bar{X}$ axis at almost the exact quality at which CHF was observed; i.e., at which the film thickness did in fact go to zero.

Figure 13. Film Thickness versus Quality, Various Flows. Positions of Splitters Nos. 1, 2, and 3 Superposed.

Figure 14. $P_w - P_c$ versus Sample Flow Rate, Nonisokinetic Conditions.

Table 2

NONISOKINETIC SAMPLE FLOW

Single Phase								
Run No.	Splitter No.	L_u (ft)	L_H (ft)	$\dot{W}$ (lb/sec)	W_S (lb/sec)	W_S/W	N_R	$P_W - P_C$ (psi)
N-1	3	4	4	0.714	0.1138	0.1593	32,731	-0.060
16*	3	4	4	0.714	0.0903	0.1265	32,731	0
N-2	3	4	4	0.714	0.0475	0.0665	32,731	+0.060
N-3	3	4	4	1.070	0.1556	0.1454	48,114	-0.060
17*	3	4	4	1.070	0.1352	0.1264	48,114	0
N-4	3	4	4	1.070	0.1208	0.1129	48,114	+0.060
N-5	3	4	4	0.722	0.1205	0.1671	233,018	-0.060
18*	3	4	4	0.722	0.1034	0.1433	233,018	0
N-6	3	4	4	0.722	0.0768	0.1065	233,018	+0.060
N-7	3	4	4	1.079	0.1684	0.1561	340,133	-0.060
19*	3	4	4	1.079	0.1536	0.1424	340,133	0
N-8	3	4	4	1.079	0.1391	0.1289	340,133	+0.060

Two Phase										
Run No.	Splitter No.	Δ/D	L_u (ft)	$G/10^6$ (lb/h-ft ²)	$\phi/10^6$ (Btu/h-ft ²)	$\bar{X}$	W_S (lb/sec)	W_S/W	X_S	$P_W - P_C$ (psi)
N-9	1	0.0214	8	1.026	0.313	0.200	0.0799	0.1112	0.0079	-0.0128
22**	1	0.0214	8	1.026	0.313	0.200	0.0791	0.1101	0.0097	0
N-10	1	0.0214	8	1.026	0.313	0.200	0.0727	0.1012	0.0256	+0.048
N-11	1	0.0214	8	1.024	0.253	0.099	0.0716	0.0998	-0.0122	-0.0468
23**	1	0.0214	8	1.024	0.253	0.099	0.0635	0.0885	0.0116	0
N-12	1	0.0214	8	1.024	0.253	0.099	0.0616	0.0859	0.0180	+0.042

* These runs are isokinetic and are also listed in Table 2 of Ref. 2.

** These runs are isokinetic and are also listed in Table 3 of Ref. 2.

Table 3

TWO-PHASE ADIABATIC PRESSURE DROP

Run No.	L_u (ft)	P (psia)	$G/10^6$ (lb/h-ft ²)	$\bar{X}$	$\Delta P_{TPF}/\Delta Z$ (lb/ft ³)	$\Delta P_{TPF}/\Delta P_F$
$\Delta P-6$	8	1002	1.501	0.0581	41.77	2.883
$\Delta P-7$	8	997	1.507	0.1071	58.62	4.017
$\Delta P-8$	8	1023	1.524	0.1886	78.60	5.281
$\Delta P-9$	8	995	1.021	0.2487	50.02	6.777
$\Delta P-10$	8	989	1.018	0.1985	43.37	5.906
$\Delta P-11$	8	1011	1.015	0.1000	28.86	3.951

Table 4

TWO-PHASE PRESSURE DROP WITH HEAT ADDITION

Run No.	L _H (ft)	P (psia)	G/10 ⁶ (lb/h-ft ²)	φ10 ⁶ (Btu/h-ft ²)	Δh _s (Btu/lb)	$\bar{X}_e$	Z - Z _(REF) (in.)						
							12-1/8	24-1/4	36-3/8	48-1/2	60-5/8	72-3/4	84-7/8
ΔP-12	8	999	1.529	0.550	169.7	0.0472	64.50	133.3	205.8	—	357.2	452.2	561.4
ΔP-13	8	993	1.529	0.550	134.1	0.1018	76.38	142.8	216.2	—	394.7	508.5	629.4
ΔP-14	8	1009	1.514	0.554	64.3	0.2156	83.42	170.8	277.9	—	533.4	696.1	—
ΔP-15	6	1005	1.015	0.557	99.7	0.1990	61.58	134.5	206.0	—	402.9	507.7	535.2
ΔP-16	6	995	1.012	0.565	157.2	0.1093	61.81	123.2	191.6	—	337.0	433.8	465.6
ΔP-17	6	1002	1.016	0.561	194.8	0.0545	60.85	122.1	183.9	—	324.8	404.2	434.4
ΔP-18	6	1005	1.008	0.565	228.0	0.0088	60.11	122.1	184.4	—	309.2	395.7	424.8
ΔP-19	6	1010	1.012	0.565	259.1	-0.0406	61.50	123.6	185.9	—	310.7	385.9	425.5
ΔP-20	6	1000	1.513	0.559	41.0	0.1742	96.80	208.8	324.0	—	622.8	—	—

The pressure drop listed in Table 3 is the measured drop corrected for hydrostatic head, using the Martinelli-Nelson void correlation.⁷ The ratio of two-phase to single-phase pressure loss is also listed in Table 3, and compared with the Martinelli-Nelson multiplier in Figure 15. The measured ratio is 25 to 35% below the Martinelli-Nelson value. This is consistent with the two-phase adiabatic pressure drop results reported by Janssen and Kervinen⁸ for round pipes and rectangular channels.

The pressure drop listed in Table 4 is the total pressure drop; i.e., it includes friction, hydrostatic head, and acceleration.

Further analysis of the two-phase pressure drop data will be reported at a later date.

Figure 15. Two-Phase Multiplier versus Quality, Martinelli-Nelson Multiplier Curve Superposed.

APPENDIX. RECIRCULATION PUMP PERFORMANCE TESTS

(G. L. Sozzi)

ABSTRACT

Results from an exploratory test program to investigate the performance characteristics of a centrifugal pump under adverse steady-state operation and during a vessel blowdown transient are presented. The pump continues to deliver flow even though the available NPSH is below the minimum. It also delivers flow during a blowdown, but for some tests, depending upon the depressurization rate, it becomes vapor bound due to flashing within the pump housing.

A.1 INTRODUCTION

A test program was initiated to investigate pump performance characteristics under saturated liquid and two-phase flow conditions. The majority of information now available on pumping machinery is for steady-flow, single-phase operation, whereas these tests have investigated the effect on pumping capability when operating in the two-phase flow region. Currently, pump designers must rely on manufacturers' specifications regarding minimum net positive suction head (NPSH) for pump application. Design basis dictates that the pumping capacity deteriorates rapidly due to cavitation when the available NPSH is below the minimum. Steady-state pump performance tests that are reported herein confirm that the pump performance deteriorates appreciably when the minimum NPSH is approached; however, a sudden or rapid drop-off in pumping capabilities due to low suction head was not experienced. On the other hand, during transient testing to simulate a vessel blowdown, sudden flow stoppage was experienced. This sudden deterioration in performance is believed to be a result of vapor binding in the pump.

A summary of the results from this short-term exploratory testing effort is included herein.

A.2 TEST FACILITY

A test loop was designed and installed in the small blowdown test stand located at General Electric Company's main site in San Jose, California. The test loop, which is shown in Figure A-1, consisted of a 40-hp-motor-driven centrifugal pump which takes suction from the bottom of a blowdown vessel and discharges the fluid back into the vessel at the midplane. Instrumentation was included on the loop to measure pump head and flow rate.

A.3 RESULTS

Steady-state pump performance data were obtained in tests under normal and adverse conditions. The data were summarized in the classical manner by comparing total pump head and flow. The test results indicate that the actual pump characteristic curve, shown in Figure A-2, is from 2.5 to 10.0% below the characteristic curve supplied by the pump manufacturer. The pump performance, however, does not appear to be seriously affected when pumping saturated water since several of the tests summarized in Figure A-2 (namely, Tests Nos. 15, 18, 20, 21, and 22) were conducted with saturated fluid. The maximum flow attainable with the pump loop was approximately 280 gpm, limited primarily by available facility power and the test loop configuration.

Some tests were conducted to determine the minimum net positive suction head (NPSH) for the pump by incrementally lowering the water level in the vessel. These steady-state test results show the expected pumping deterioration due to incipient pump cavitation when the vessel water level nears that corresponding to the minimum NPSH specified by the manufacturer. Shown in Figure A-3 are the results of a typical NPSH test. Time-averaged data is shown, whereas the actual pump characteristics oscillate with increasing amplitudes as the water level decreases. This results from the formation and sudden collapse of the vapor cavities near the pump impeller which affect the pump performance. Complete suction head is lost when the water level in the vessel reaches the level of the pump suction line, which is located around 3-1/2 feet above the pump inlet line. This is depicted by the sudden dropoff in performance that occurs at this level, shown in Figure A-3.

Transient tests were conducted by blowing the vessel down from the top through various-sized flow limiting orifices; these varied the depressurization rate. Both continuous flow and sudden pump flow stoppage were experienced in these transient tests. This sudden drop in flow appears to be a function of the depressurization rate. Several tests were conducted with a 1/2-inch-diameter flow-limiting orifice mounted in the 2-inch blowdown line. The initial water level in the vessel was

Figure A-1. Loop for Pump Test.

Figure A-2. Steady-State Pump Performance.

Figure A-3. NPSH Test No. 25, Valve Position-Full Open.

varied for these tests, and in each case a sudden flow stoppage was realized. Shown in Figure A-4 are the pump performance responses for a typical test. It was customary for these tests to terminate the blowdown by manually closing the valve in the blowdown line when the system pressure reached 100 psig. For each test, although it is not shown on the figures, the pump reestablished flow at a positive head shortly after the tests were terminated.

Several tests were also conducted with a 3/8-inch diameter limiting blowdown orifice. The initial water level of each of these tests was also varied; however, in each case the pump continued to deliver recirculation flow, but at a degraded rate. Shown in Figure A-5 are the results for a typical 3/8-inch-orifice blowdown. Comparing the two sized decompression rates demonstrates that the flow stoppage is a consequence of the transient behavior of the system. More specifically, the higher local flashing rates associated with faster depressurization rates within the system cause the pump to become vapor bound. In addition, since the pump adds net circulation to the system, it is possible that due to the increased sloshing of the liquid surface at higher decompression rates, more steam from above the surface is entrained, as a result of a vortex action. This, coupled with the flashing from two-phase momentum pressure drop in the pump suction line, enhances the formation of vapor. The binding is thus a result of a vapor pocket's being formed at the pump impeller. The pressure builds up as the vapor is formed more rapidly than it can escape from the pump housing. Consequently, the pump loses its suction head and ceases to pump. Conversely, when the blowdown is terminated and the flashing stops, the vapor pocket collapses under the influence of the positive elevation head of the fluid in the vessel and the pump is able to regain suction prime.

After the test program was completed, the pump was disassembled and examined for any evidence of permanent pump damage. No damage was evident.

Figure A-4. Transient Pump Performance Test No. 41. Initial Conditions: Steam Blowdown through 1/2-Inch-Diameter Orifice, Water Level 176 Inches Above Pump Inlet, Blowdown at 5.96 Seconds.

Figure A-5. Transient Pump Performance Test No. 40. Initial Conditions: Steam Blowdown through 3/8-Inch-Diameter Orifice, Water Level 105 Inches Above Pump Inlet.

NOMENCLATURE

D	=	Inside diameter of circular tube channel, in.
G	=	Mass velocity, lb/h-ft ²
Δh_S	=	Subcooling, Btu/lb
L_H	=	Heated length, ft
L_U	=	Unheated length (i.e., distance between exit end of heated length and exit end of channel), ft
N_R	=	Reynolds number
P	=	Pressure, psf or psi
ΔP	=	Pressure difference, psf or psi
$\dot{W}$	=	Total flow rate, lb/sec
$\dot{W}_S$	=	Sample flow rate, lb/sec
$\bar{X}$	=	Average flow quality at any given channel cross section
y	=	Distance from wall, in.
z	=	Distance along channel (positive in direction of flow), in. or ft
δ	=	Film thickness, in.
Δ	=	Distance from wall to splitter, in.
ϕ	=	Heat flux, Btu/h-ft ²

Subscripts

C	=	Centerline
e	=	Exit end of test channel
F	=	Friction (single phase)
TPF	=	Two-phase friction
W	=	Wall

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