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**TWO-PHASE FLOW
AND HEAT TRANSFER
IN MULTIROD GEOMETRIES
FIFTEENTH
QUARTERLY PROGRESS REPORT
APRIL 1 - JUNE 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-10067
AEC Research and
Development Report
August 1969

TWO-PHASE FLOW AND HEAT TRANSFER IN MULTIROD GEOMETRIES

Fifteenth Quarterly Progress Report
April 1-June 30, 1969

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SUMMARY

Task C

Subchannel sampling tests were continued in the "side" and "center" subchannels. Results of measurements of the mass velocity and enthalpy for these subchannels and the overall

trends are reported. Pressure drop results for the nine-rod assembly are also given.

1. INTRODUCTION

This is the fifteenth quarterly report on the work done under Contract AT(04-3)-189, Project Agreement No. 44, and covers the period from April 1 to June 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 are to 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 "Final 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. Also measure flow and enthalpy in representative subchannels of the nine-rod channel.
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.

During this quarter, the subchannel sampling tests were continued. The side and center subchannels were sampled with both single- and two-phase conditions at exit, and with uniform heat flux on the nine heater rods. Pressure drop measurements were also made, and the data were reduced to give values of the single-phase friction factor and two-phase friction multiplier (ϕ_{LO}^2).

2. TESTS IN THE SIDE SUBCHANNEL

The side subchannel is formed by the channel wall and two rods, as shown in Figure 1. The isokinetic condition was set, using the pressure taps W1 and W2. The test procedure and data reduction were the same as described in the Fourteenth Quarterly Report for the corner subchannel.

2.1 THE ISOKINETIC SETTING

Preliminary tests were performed to determine the isokinetic setting, following a procedure similar to that for the corner subchannel. The pressure difference between the pressure taps W1 and W2 was measured for different conditions of single-phase and two-phase flow, with the sample tube removed. This was done with the splitters in place but with the top of the box formed by the splitters being open so flow could pass through with little resistance. It is evident that the presence of the splitters had little effect on the quantity being measured; it was noted that the difference was always small, and that the pressure at W2 was

Figure 1. Test Channel Geometry Showing Side Subchannel

consistently slightly greater than at W1. This difference is an error which is presumably caused by impacting on the pressure taps, small differences in the height of lines, etc.

The pressure difference was correlated against the average dynamic head at the exit, as shown in Figure 2. For two-phase exit conditions, the dynamic head was computed as $(\bar{G}^2/2g_c)(v_f + xv_{fg})$. The curve of Figure 2 was subsequently used as a correction for making isokinetic settings. It is shown in Figure 2 that the correction was rather small, varying between 1% and 1-1/2% of the dynamic head.

2.2 TEST RESULTS

The nominal test conditions for the side subchannel are shown in Table 1. An attempt was made to maintain the test conditions identical to those for the corner subchannel as far as possible. Generally, small discrepancies existed in the values of the average flow rate and the average exit quality. To compare the corner, side, and center subchannels on an identical basis, the following corrections were made to the data:

$$G_{\text{subchannel}} \equiv G_{\text{subchannel (experiment)}} \times \frac{\bar{G}_{\text{nominal}}}{\bar{G}_{\text{experimental}}}$$

$$x_{\text{subchannel}} \equiv x_{\text{subchannel (experiment)}} + \bar{x}_e \text{ nominal} - \bar{x}_e \text{ experimental}$$

Figure 2. Calibration for Isokinetic Setting for Side Subchannel

The test results for the side subchannel as corrected, using this procedure, are shown in Table 2. The subchannel mass flux and exit quality are based on isokinetic conditions, set with the calibration in Figure 2.

Nonisokinetic data were also taken for the side subchannel for some of the test points. These are shown in Figures 3 and 4, where the differential pressure W1-W2 is plotted against the nondimensionalized subchannel flow rate and enthalpy. The higher slope for Curve 2G1 in Figure 3 is caused by the higher mass velocity ($G = 1 \times 10^6$ lb/ft²-h). A comparison between Figures 3 and 4 shows that as the amount of flow in the subchannel is increased, the subchannel enthalpy also generally increases, indicating that the enthalpy of flow diversion is higher than the subchannel enthalpy.

Figures 5 and 6 represent the variation in isokinetic flow rate and enthalpy of the subchannel as a function of the average channel exit quality. Error bands are not shown on the mass flux to avoid confusion. The error was estimated to be of the order of 1% of the channel flow. The trends show that the side subchannel flow rate and enthalpy are very close to the average conditions. An examination of Table 2 reveals that generally the subchannel flow and enthalpy are slightly on the low side, compared with the mean flow rate and enthalpy.

Table 1
NOMINAL TEST CONDITIONS

P = 1000 psia

Test Point	$\bar{G}/10^6$ (lb/ft ² ·h)	Power (kW)	Heat Flux (Btu/ft ² ·h)	Subcooling (Btu/lb)	$\bar{x}_e$
1B	0.480	0	0	504.6	-
1C	0.990	0	0	504.6	-
1D	1.510	0	0	504.6	-
1E	1.97	0	0	504.6	-
2B2	0.530	532	225,000	149.9	0.029
2B3	0.535	532	225,000	108.7	0.090
2B4	0.535	532	225,000	52.8	0.176
2C1	1.060	532	225,000	57.2	0.042
2C2	1.068	532	225,000	35.1	0.075
2D1	0.540	1064	450,000	259.2	0.110
2D3	0.540	1064	450,000	124.4	0.318
2E1	1.080	1064	450,000	142.9	0.035
2E2	1.080	1064	450,000	96.7	0.106
2E3	1.060	1064	450,000	29.1	0.215
2G1	1.070	1596	675,000	225.9	0.038
2G2	1.080	1596	675,000	189.8	0.090
2G3	1.070	1596	675,000	146.7	0.160

Table 2

CORRECTED TEST RESULTS FOR SIDE SUBCHANNEL

Test Point	$\bar{G}/10^6$ (lb/h-ft ²)	$\bar{x}$	$\bar{G}_{ch}/10^6$ (lb/h-ft ²)	x_{ch}	$\frac{G_{ch} - \bar{G}}{\bar{G}}$	$\frac{H_{ch} - \bar{H}}{\bar{H}}$
1B	0.480	-	0.462	-	- 0.037	-
1C	0.990	-	0.939	-	- 0.0515	-
1D	1.510	-	1.441	-	- 0.0458	-
1E	1.97	-	1.91	-	- 0.0304	-
2B2	0.530	0.029	0.521	0.015	- 0.017	- 0.0144
2B3	0.535	0.090	0.530	0.076	- 0.0093	- 0.0175
2B4	0.535	0.176	0.517	0.180	- 0.0336	0.0039
2C1	1.060	0.042	1.066	0.018	+ 0.0054	- 0.0273
2C2	1.068	0.075	1.028	0.075	- 0.0374	0
2D1	0.540	0.110	0.560	0.105	+ 0.037	- 0.0053
2D3	0.540	0.318	0.532	0.330	- 0.015	0.0103
2E1	1.080	0.035	1.102	0.026	+ 0.020	- 0.0103
2E2	1.080	0.106	1.078	0.097	- 0.002	- 0.0095
2E3	1.060	0.215	1.081	0.185	+ 0.0197	- 0.0286
2G1	1.070	0.038	0.968	0.044	- 0.095	+ 0.0069
2G2	1.080	0.090	1.111	0.068	+ 0.0287	- 0.0238
2G3	1.070	0.160	1.132	0.127	+ 0.0551	- 0.0332

Figure 3. Non-Isokinetic Data—Variation of Differential Pressure with Subchannel Flow

Figure 4. Non-Isokinetic Data—Variation of Differential Pressure versus Subchannel Enthalpy

Figure 5. Subchannel Flow and Enthalpy Variation versus Average Quality

Figure 6. Subchannel Flow and Enthalpy Variation versus Average Quality

3. CENTER SUBCHANNEL TESTS

The center subchannel is formed by four heater rods and constitutes the third of three different kinds of subchannels in a uniformly heated nine-rod assembly. To sample the center subchannel, a different procedure had to be used to measure the pressure differential between the inside and outside of the subchannel. Three different schemes were tried, and the one shown in Figure 7 was adopted as being the best. The decision was based on comparison of single-phase results with those predicted by calculation and continuity. This method used a horizontal pressure tap through one of the rods, together with a reference tap CC2 at the same elevation. In the first scheme tried, a pressure tap through the splitter plate was employed, but was found to cause appreciable flow blockage in the adjoining side subchannel. A third method with two vertical taps in rods 1 and 2 was also found to be unsatisfactory due to erratic behavior during diabatic runs.

Table 3 shows the isokinetic sampling results. The center subchannel mass flux was generally higher than the average mass flux, and the quality was also higher than average.

Figure 7. Test Channel Geometry Showing Center Subchannel and Locations of Pressure Taps

Nonisokinetic data were also taken, some of which are shown plotted in Figures 8 and 9. It is shown in Figure 9 that as the subchannel mass flux is increased, its enthalpy increases slightly. The effect was generally smaller than in the corner and side subchannels because the center subchannel is bounded on two sides by similar center subchannels.

Shown in Figures 10, 11, and 12, is the variation in the center subchannel isokinetic mass flux and enthalpy versus average channel quality. It can be seen that most points lie above the zero of the ordinate, indicating higher than average conditions.

Table 3
CENTER SUBCHANNEL RESULTS

Test Point	$\bar{G}/10^6$ (lb/h-ft ²)	$\bar{x}$	$G_{ch}/10^6$ (lb/h-ft ²)	x_{ch}	$\frac{G_{ch} - \bar{G}}{\bar{G}}$	$\frac{H_{ch} - \bar{H}}{\bar{H}}$
1B	0.480	-	0.526	-	0.096	-
1C	0.990	-	1.150	-	0.162	-
1D	1.510	-	1.690	-	0.119	-
1E	1.97	-	2.190	-	0.119	-
2B2	0.530	0.029	0.540	0.030	0.0188	0.0011
2B3	0.535	0.090	0.521	0.104	-0.0265	0.0151
2B4	0.535	0.176	0.560	0.220	0.0467	0.0435
2C1	1.060	0.042	1.077	0.059	0.0161	0.0195
2C2	1.068	0.075	1.144	0.100	0.0712	0.0275
2D1	0.540	0.110	0.556	0.117	0.0295	0.0074
2D3	0.540	0.318	0.563	0.364	0.0425	0.0399
2E1	1.080	0.035	1.162	0.051	0.0761	0.0184
2E2	1.080	0.106	1.180	0.105	0.0925	0.0001
2E3	1.060	0.215	1.126	0.249	0.0624	0.0324
2G1	1.070	0.038	1.142	0.043	0.0671	0.0057
2G2	1.080	0.090	1.130	0.110	0.0464	0.0216
2G3	1.070	0.160	1.160	0.176	0.0838	0.0161

Figure 8. Non-Isokinetic Data—Variation of Differential Pressure with Subchannel Flow

Figure 9. Non-Isokinetic Data—Variation of Subchannel Enthalpy with Subchannel Flow

Figure 10. Subchannel Flow and Enthalpy versus Average Quality

Figure 11. Subchannel Flow and Enthalpy versus Average Quality

Figure 12. Subchannel Flow and Enthalpy versus Average Quality

4. CONCLUSIONS

An overall comparison of the subchannel sampling results for uniformly heated rods reveals the following:

- a. Generally, the corner subchannel is lower, the side subchannel slightly lower, and center subchannel higher in mass flux than the bundle average mass flux (Figure 13).
- b. For two-phase exit conditions, the foregoing statement is also true for the subchannel enthalpies with respect to the average enthalpy (Figure 14).
- c. The enthalpy of the flow diversion which occurs in the presence of a nonisokinetic forced split was calculated to be higher than the enthalpy of the donor subchannel.

Figure 13. Comparison of Subchannel Flows for the Three Subchannels

Figure 14. Comparison of Subchannel Enthalpies for the Three Subchannels

5. PRESSURE DROP RESULTS

5.1 DATA REDUCTION PROCEDURE

The data, as obtained from the Pace ΔP cells, were corrected for the density head in the pressure tap lines to get the total pressure drop for 1-foot lengths along the test section, and also for the total 6-foot heated length. Some of the total pressure drop data for 6 feet are shown in Table 4.

Friction pressure drop was extracted from the total pressure drop by subtracting the drag due to spacer pins and the pressure drop due to acceleration and density heads.

Spacer pins were mounted on the heater rods to maintain the correct rod-rod and rod-wall spacing, as shown in Figure 7. These are 1/8-inch-diameter pins with rounded ends, lo-

Table 4
NINE-ROD SUBCHANNEL PRESSURE DROP DATA

P = 1000 psia

Run No.	$G \cdot 10^{-6}$ (lb-h-ft ²)	x_{exit} (%)	H_{in} (Btu/lb)	$q'' \cdot 10^{-3}$ (Btu/lb-ft ²)	ΔP_{TOT} (6 ft) (psi)
2A2-1	0.263	9.8	290	229	2.12
2A2-2	0.281	6.9	293	229	2.18
2A3-1	0.235	44.4	463	229	1.63
2A3-3	0.242	41.6	460	227	1.63
2B2-1	0.525	3.3	417	224	2.31
2B4-1	0.536	21.4	514	227	2.39
2B4-2	0.537	19.7	517	219	2.46
2D1-1	0.525	11.6	302	456	2.47
2D3-4	0.535	32.9	436	461	2.83
2D3-5	0.532	32.7	436	458	2.82
2C1-1	1.046	5.4	503	225	3.17
2C2-1	1.053	11.0	533	225	3.72
2C2-2	1.053	9.4	527	222	3.77
2C2-4	1.057	8.5	520	229	3.74
2C2-7	1.068	9.1	524	227	3.84
2C2-8	1.071	10.1	530	227	3.86
2E1-1	1.053	4.2	422	451	3.37
2E3-1	1.048	22.9	528	451	5.64
2E3-2	1.050	23.9	532	452	5.53
2G1-1	1.070	3.4	346	666	3.59
2G1-3	1.060	4.1	348	667	3.57
2G3-1	1.067	16.0	419	674	3.90
2G3-2	1.073	15.5	420	670	4.35
2I2-1	1.067	10.4	342	797	4.19
2I2-3	1.062	10.1	340	792	4.06
2F2-1	2.119	10.4	531	456	9.80
2F1-3	2.097	5.0	501	453	7.30
2H1-1	2.135	0.6	462	552	6.88
2H1-3	2.118	3.2	459	660	6.56
2H1-4	2.192	3.1	461	662	6.77
2H2-1	2.114	7.3	498	550	9.75

cated axially in five rows in the heated length, 1 foot apart, and 2 inches downstream from successive pressure tap locations. The pressure drop due to the drag of the spacer pins was calculated as*

$$\frac{\Delta p_d}{\rho V^2 / 2g_c} = \frac{C_d (A_o/A_u) K^3 (1 - 2y/D)^{3.7}}{[1 - A_o/A_u]^3}$$

where

- C_d = drag coefficient,
 A_o = area of the obstructing pin,
 A_u = unobstructed upstream area,
 y = eccentricity, and
 K = maximum upstream velocity/average upstream velocity.

For two-phase flow, a homogeneous multiplier $\left(1 + \frac{v_{fg}}{v_f} \times \bar{x}\right)$ was used.

The void fraction used in the calculation of the other components of pressure drop was calculated from the quality using a Zuber-Findlay type of correlation* with $Co = 1.1$.

5.2 SINGLE-PHASE DATA

Single-phase data were obtained at room temperature, and also at higher temperatures with the aid of an afterheater. These data were used to generate a friction factor as a function of the average Reynolds number. The data are shown in Figure 15. The friction factor for the nine-rod array was found to be higher than that of a smooth tube of the same hydraulic diameter as the nine-rod bundle.

5.3 TWO-PHASE DATA

The two-phase friction pressure drop was plotted against boiling length. From the slope of this curve (dp/dz), the two-phase multiplier (Martinelli parameter ϕ_{LO}^2) was calculated, based on the measured single-phase friction factor. Figures 16 and 17 illustrate the behavior of the multiplier versus average quality in the channel, as well as the Martinelli-Nelson curve, for two mass velocities. The Martinelli-Nelson curve appears to correlate the two-phase friction pressure drop well.

* Idelchik, I. E., "Handbook of Hydraulic Resistance Coefficients of Local Resistance and of Friction," AEC TR-6630, 1960 (p. 379ff).

* Levy, S., "Forced Convection Subcooled Boiling—Prediction of Vapor Volumetric Fraction," GEAP-5157, April 1966.

Figure 15. Single-Phase Friction Factor for Nine-Rod Bundle

Figure 16. Two-Phase Friction Multiplier versus Average Flow Quality

Figure 17. Two-Phase Friction Multiplier versus Average Flow Quality

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