Printed in U.S.A.

79-HT-113

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Contributed by the Heat Transfer Division of The American Society of Mechanical Engineers for presentation at the Joint ASME/AIChE 18th National Heat Transfer Conference, San Diego, Calif., August 6-8, 1979. Manuscript received at ASME Headquarters June 6, 1979.

Copies will be available until May 1, 1980.

THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS, UNITED ENGINEERING CENTER, 345 EAST 47th STREET, NEW YORK, N.Y. 10017

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ABSTRACT

Experiments were conducted on heat transfer from internally heated $ZnSO_4$-H_2O pools to curved surfaces. These experiments extended existing data for nonboiling pools to higher Rayleigh numbers. The data for convective downward heat transfer from nonboiling pools to a curved surface were reasonably close to the Mayinger correlation extrapolated to higher Rayleigh numbers and lower ratios of pool depth to radius of curvature. Sideward heat transfer to a surface could be described by

$$Nu = 0.7\ Ra^{0.2}\quad .$$

Insulating the upper pool surface from the atmosphere had no effect on either sideward or downward heat transfer.

An investigation was also made on effects of curvature on heat transfer from boiling pools. Nusselt numbers for sideward heat transfer were proportional to a boiling Reynolds number based on superficial vapor velocity to the 0.275 power and quite close to the correlation for a pool with flat vertical walls. Downward boiling heat transfer to a curved surface appears to be independent of the Reynolds number.

NOMENCLATURE

C_p	specific heat
g	gravitational constant
k	thermal conductivity
L	pool depth
Nu	Nusselt number, $QL/k(T_p-T_s)$
'	Modified Nusselt number, $Q/[kq(T_p-T_s)]^{1/2}$
	volumetric heat generation rate
Q	heat flux
R	radius of curvature
Ra	Rayleigh number, $g\beta qL\ /\alpha\nu k$
Re	Boiling Reynolds number, LV_o/ν
T	temperature
V_o	superficial vapor velocity

Greek symbols

α	thermal diffusivity, $k/\rho C_p$
β	volumetric expansion coefficient
ν	kinematic viscosity
ρ	density

Subscripts

1,2,3,4,5,6	identification of section in round-bottom apparatus
B	boiling
c	conduction
D	downward
p	pool center
s	surface
S	sideward

INTRODUCTION

This investigation on heat transfer to curved surfaces from an internally heated pool has particular application to nuclear reactor safety analysis. Knowledge of the possible magnitudes of the heat fluxes at the boundaries of a fuel pool is necessary to bound the extent of melting attack on containment structures and the rate at which heat must be removed to prevent meltthrough and to stabilize the pool. This work also has application to chemical engineering and absorption of solar radiation in liquid pools.

Experiments were conducted in which heat transfer to curved surfaces was measured for both boiling and nonboiling liquid pools. These experiments extend the data for nonboiling pools to higher Rayleigh numbers and provide information on effects of curvature for boiling pools.

A variety of geometries have been studied for nonboiling pools generating heat internally at lower Rayleigh numbers. Kulacki and Goldstein (1) and Kulacki and Emara (2) correlated upward and downward heat transfer for rectangular geometries. Jahn and Reineke (3) theoretically and experimentally investigated free convection in rectangular and semicircular cavities. Mayinger et al. (4) reported results for a semicircular geometry and a right circular cylinder. Watson (5) and Martin (6) analyzed free convection in a vertical cylinder. Min and Kulacki (7) measured thermal convection in a fluid layer bounded from below by a segment of a sphere.

Initial work on internally heated boiling liquids was reported by Stein et al. (8). Suo-Anttila et al. (9) developed a model for downward heat transfer from an internally heated boiling pool of infinite width based on bubble induced fluid circulation. Gabor et al. (10) measured and correlated sideward and downward heat transfer for rectangular pools with various aspect ratios. Gustavson et al. (11) examined local values and correlated the results in terms of combined free and forced convection contributions. Greene et al. (12) reexamined the data of Gustavson et al. in order to simplify the correlation of local heat transfer.

The results of this investigation will be discussed as follows:

I. Experimental Description

II. Experiments with Round-Bottom Apparatus
    A. Nonboiling Pools
        1. Total Downward Heat Transfer
        2. Local Downward Heat Transfer
    B. Boiling Pool

III. Experiments with Curved-Electrode Apparatus
    A. Nonboiling Pool
    B. Boiling Pool

IV. Conclusions

I. EXPERIMENTAL DESCRIPTION

Two types of apparatus were used to measure heat transfer to curved surfaces in the downward and sideward directions. The apparatus for measuring downward heat transfer to a curved surface had a base consisting of 6 curved copper sections 0.376 m long by 0.113 m wide (see Fig. 1). Each curved section was water cooled and was electrically insulated with 0.076-mm thick teflon film. The base of the apparatus was an arc with a radius of 0.45 m and a subtended angle of 90 deg. For a pool of depth such that four of the six heat-transfer sections were covered, the subtended angle was 60 deg. The electrodes were two copper plates attached to opposite ends of the base cooling sections. The electrodes were also water-cooled to prevent nucleation on their surface during experiments with boiling pools. The pool depths were 55 mm where four sections were covered and 113 mm when six sections were covered.

The apparatus for measuring sideward heat transfer to a curved surface is shown in Fig. 2. In this pool container each electrode was concavely curved to form a semicircle with a radius of curvature of 76 mm. The flat base plate of the apparatus was electrically insulated with 0.076-mm-thick Teflon film. The electrodes were curved copper plates attached to opposite ends at the base plate. The right electrode as shown in Fig. 2 was split into two sections in order to determine relative rates of heat transfer to the section near the top of the pool and to the section near the bottom of the pool. The front and back sides were each constructed from two 12.7-mm thick Lucite plates to minimize heat losses.

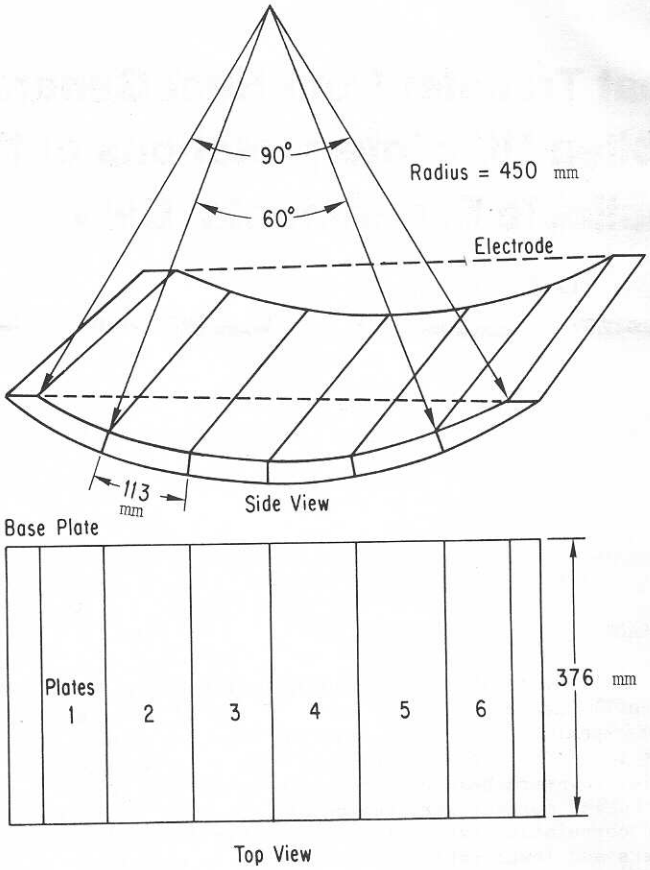

Fig.1 Apparatus for Downward Heat Flux Experiments

The temperatures of the base cooling plates, electrodes, and cooling water inlets and outlets were measured by Chromel-Alumel thermocouples. The thermocouples were mounted in holes drilled halfway into each heat-transfer plate. Seven thermocouples were mounted in each heat-transfer plate (plate thickness of 6.35 mm) of the round-bottomed apparatus. Six thermocouples were mounted in the right electrode (plate thickness of 4.76 mm) and six in the base plate of the apparatus with the curved electrodes. Three thermocouples were mounted in the upper half and three in the lower half of the split electrode. The temperatures from the round-bottom apparatus were recorded by a Doric Scientific Digitrend 210 data logger with 100 channels and 0.25 C precision. The temperatures of the curved-electrode apparatus were read from a Doric Trendicator type 400A with 0.1 C precision. Flow rates of cooling water were measured with either a stopwatch and graduate for low flow rates or a brooks rotameter, Type 1307-08F1B1E, for higher flow rates (0.76 to 7.57 ℓ/m). Heat fluxes to the surfaces were determined from the changes in cooling water temperature. In these experiments, the inlet temperatures and flow rates of the cooling water were adjusted so that the base plates all had the same surface temperature. In

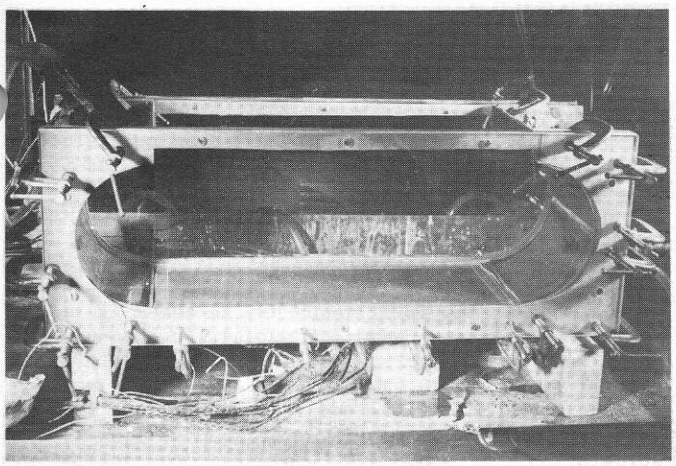

Fig.2 Apparatus for Measuring Sideward Heat Transfer from an Internally Heated Pool to Curved Surfaces

the nonboiling experiments pool temperatures were measured by a movable thermocouple within the pool. This thermocouple was not used in the boiling experiments because it was a nucleation site.

Pools of $ZnSO_4$-H_2O electrolyte were Joule heated in these experiments. Experiments under nonboiling conditions were performed with 1. the top of the pool open to the atmosphere and 2. the top of the pool insulated with a floating layer of foam rubber.

II. EXPERIMENTS WITH ROUND-BOTTOM APPARATUS

A. Nonboiling Pools

1. Total Downward Heat Transfer

The Nusselt numbers for total downward heat transfer to four sections under nonboiling conditions are plotted in Fig. 3. For each experiment, pool properties were calculated for an average temperature between the pool and the plate temperatures.

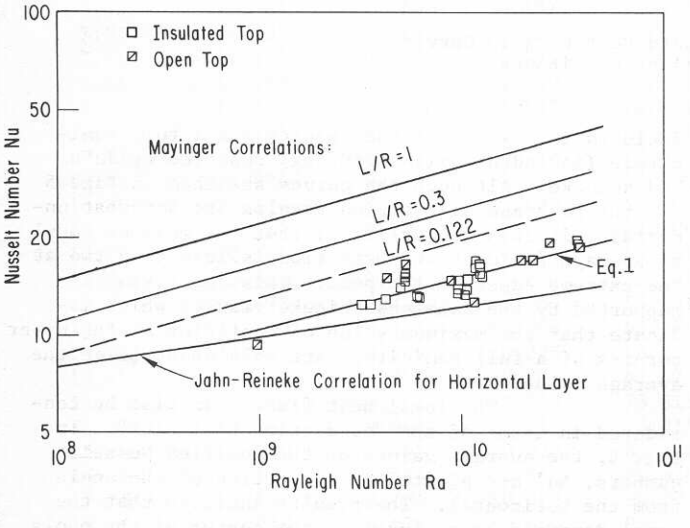

Fig.3 Experimental Results for Total Downward Heat Transfer to a Curved Surface having an Included Angle of 60 deg under Nonboiling Conditions

The experimental Nusselt numbers were largely independent of whether the top of pool was insulated or open. The experimental points were fitted by the method of least squares and the following correlation was obtained:

$$Nu = 0.38\ Ra^{0.16} \pm 7.5\% \qquad (1)$$

$$\text{for} \quad 1 \times 10^9 < Ra < 4 \times 10^{10}.$$

The experimental results in Fig. 3 are compared with the correlation of Mayinger (4) for circular segments and with the Jahn-Reineke (3) correlation for horizontal layers. The Mayinger correlation is:

$$Nu = 0.54\ Ra^{0.18}\ (L/R)^{0.26} \qquad (2)$$

$$\text{for} \quad 0.3 < (L/R) < 1.0 \text{ and } 10^7 < Ra < 5 \times 10^{10}.$$

where R = the radius of curvature of the segment. The Rayleigh number range of the Mayinger correlation includes that of the present study; however, the ratio of pool depth to radius of curvature in the four-section experiments (L/R = 0.122) is well below the lower limit of the correlation. The Mayinger correlation for L/R = 0.122 is shown as a dashed line in Fig. 3. The experimental data are found to fall below the extrapolated Mayinger correlation but above the well-established Jahn-Reineke correlation for downward heat transfer in a horizontal layer:

$$Nu = 1.389\ Ra^{0.095} \qquad (3)$$

$$\text{for} \quad 4 \times 10^4 < Ra < 5 \times 10^{10}.$$

It is concluded that the downward heat transfer is increased relative to that for a horizontal surface but that the increase is much less than that for a full semicircle represented by the Mayinger correlation, equation (2), with L/R = 1.

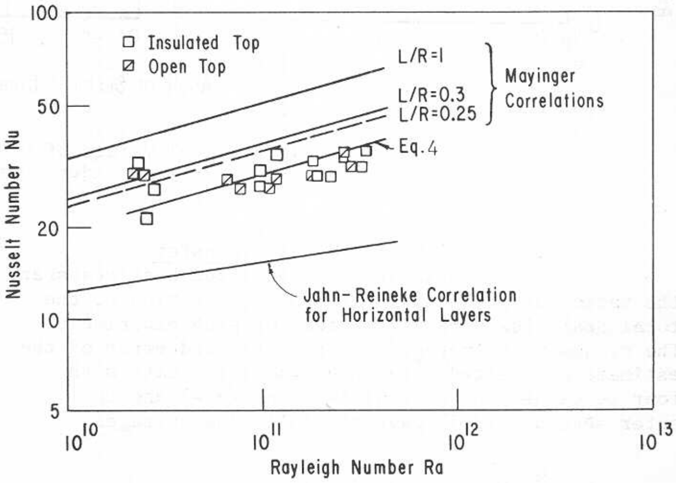

Fig.4 Experimental Results for Total Downward Heat Transfer to a Curved Surface having an Included Angle of 90 deg under Nonboiling Conditions

The nonboiling experiments which used all six of the curved sections are plotted in Fig. 4. Again, the experimental Nusselt numbers did not depend significantly upon whether the top of the pool was insulated or open. The experimental points were reasonably close to the extrapolated Mayinger correlation for the appropriate ratio of $L/R = 0.25$. Accordingly, the data were tentatively correlated using the exponent of the correlation of 0.18. The coefficient of the Rayleigh number term was found by least squares and the following correlation obtained:

$$Nu = 0.31\ Ra^{0.18} \pm 15\% \qquad \text{for} \quad 2 \times 10^{10} < Ra < 4 \times 10^{11}. \tag{4}$$

Equation (4) yields Nusselt numbers about 18% lower than that of equation (2) with $L/R = 0.25$.

$$\frac{Q_{2-5}}{Q_{TOTAL}} = 1.14 \pm 12\% \ , \qquad \frac{Q_{1-6}}{Q_{TOTAL}} = 1.51 \pm 15\% \ . \tag{6}$$

The ratios for the nonboiling cases are plotted in Fig. 5 as a function of the average angle from the horizontal of the center of the heat transfer section.

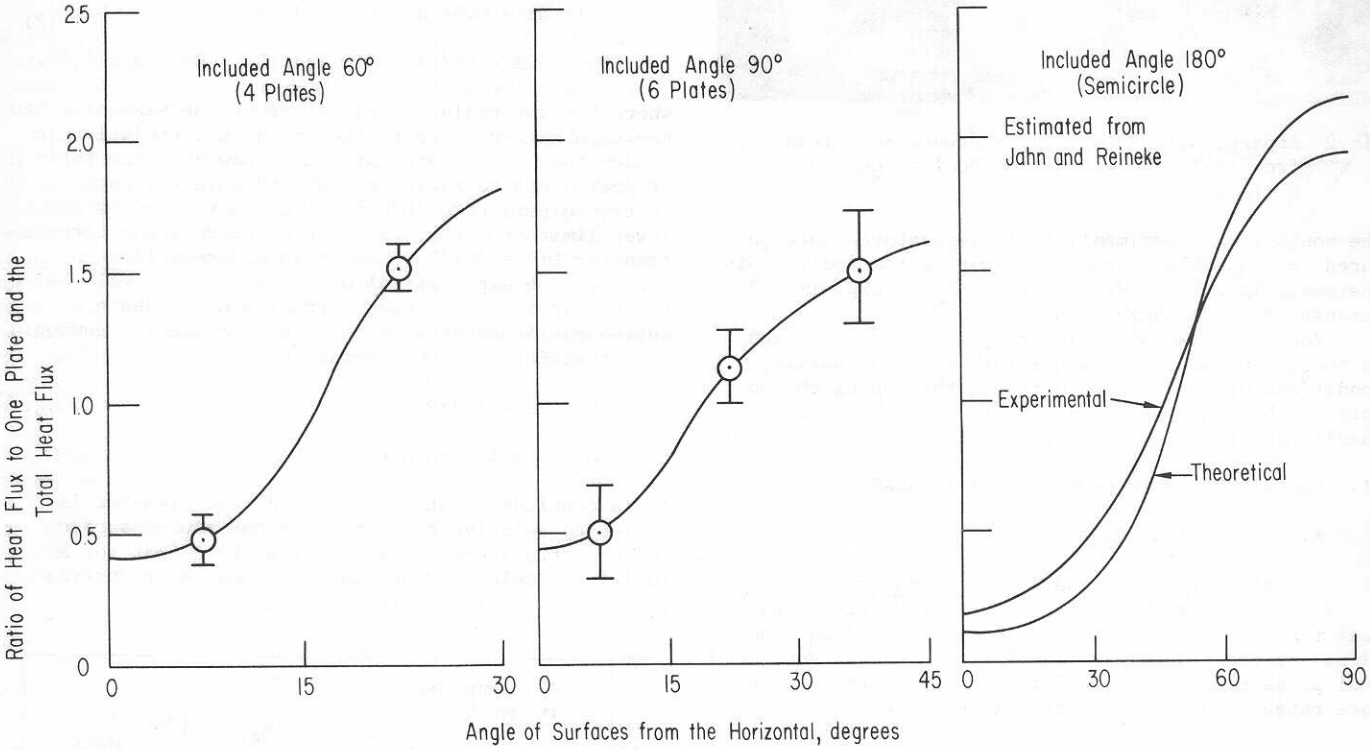

Fig.5 Local Values of Downward Heat Flux to Curved Surfaces under Nonboiling Conditions

2. Local Downward Heat Transfer

To evaluate the localized heat transfer, the ratios of the heat fluxes to each section to the total heat flux were calculated for each experiment. The values were averaged and the standard error of the estimate calculated. For the nonboiling data with four sections, the central sections (3-4) and the outer sections (2-5) gave the following averages:

$$\frac{Q_{3-4}}{Q_{TOTAL}} = 0.48 \pm 19\% \ , \quad \text{and} \quad \frac{Q_{2-5}}{Q_{TOTAL}} = 1.52 \pm 6\% \ . \tag{5}$$

For the nonboiling data with all six sections covered, the average ratios were calculated as follows:

$$\frac{Q_{3-4}}{Q_{TOTAL}} = 0.51 \pm 35\% \ ,$$

Included in Fig. 5 are the results for a full semicircle (included angle = 180 deg) reported by Jahn and Reineke. Although the curves sketched in Fig. 5 for the four and six section results are somewhat uncertain, it does appear likely that the maximum local to average ratio of the heat flux is less than two at the extreme edges of the pool. This conclusion is supported by the Jahn and Reineke results which indicate that the maximum value of heat flux at the upper corners of a full semicircle are only about twice the average value.

The local heat fluxes can also be considered in terms of the "conduction heat flux". In Fig. 6, the average values of the modified Nusselt numbers, Nu' are plotted as a function of the angle from the horizontal. The results indicate that the local downward heat fluxes at the center of the pools are approximately equal to the conduction value of Nu' = 1.414. At the extreme edges of the pool, the local values of heat flux are three to four times the conduction value.

B. Boiling Pool

The boiling experiments used four sections and are listed in Table 1. The table presents the total pool power, the heat fluxes to the individual sections, the average total heat flux, the upward or vaporization heat flux, the surface and pool temperatures and the heat balance error.

The data for the total downward heat transfer under boiling conditions which were obtained with the four section configuration are plotted in Fig. 7. These data are plotted in terms of the Nusselt number versus the boiling Reynolds number. The Reynolds number is based on the superficial velocity of the vapor on the assumption that the agitation caused by the rising vapor bubbles predominates over natural convection caused by liquid density differences. The bubbles nucleate within the interior of an internally heated pool and not on a wall which is the usual case in boiling heat transfer. Therefore, the correlation must be made in terms of the mechanisms involved in boiling in internally heated pools (10). The Nusselt numbers did not vary much with the Reynolds number over the range studied so that the tentative correlation is as follows:

$$Nu = 35 \pm 12\% \quad . \qquad (7)$$

The total downward heat transfer can also be correlated in terms of the modified Nusselt number as follows:

$$Nu' = 2.07 \pm 17\% \quad . \qquad (8)$$

Downward heat transfer from internally heated fluids can also be characterized in terms of a conduction heat flux for which

$$Nu'_c = 2^{1/2} \quad . \qquad (9)$$

On this basis, the total heat fluxes under boiling conditions are on the average, 1.5 times the conduction heat flux.

The data for boiling pools indicate that the variation of local heat flux with angle is very much less than that for nonboiling pools. This probably results from a destruction of the convection patterns within the pool by bubble agitation.

III. EXPERIMENTS WITH CURVED-ELECTRODE APPARATUS

A. Nonboiling Pool

Experiments were conducted with pool temperatures above and below the boiling point. The surfaces of both electrodes and the base plate were maintained at the same temperature. The first set of runs (37 runs) was carried out with the upper pool surface open

Table 1 Experimental Heat Transfer Data from an Internally-heated Water Pool to a Curved Lower Surface: Boiling with 4 Sections

Power kW	Heat Flux, kW/m^2				Surface Temp. °C	Heat Balance Error, %	Nu_{TOTAL}	Re x 10^4
	Q_{2-5}	Q_{3-4}	Q_{TOTAL}	Q_{VAP}				
6.46	10.019	7.234	8.626	25.858	74.1	4.8	27.8	0.361
6.47	10.836	7.755	9.295	25.858	73.9	1.9	29.7	0.361
6.58	10.038	6.193	8.116	26.611	75.4	-1.6	27.5	0.374
6.60	10.858	7.169	9.014	26.611	77.0	-3.8	32.6	0.377
6.70	10.150	6.685	8.418	26.611	76.5	-0.8	29.8	0.376
6.63	10.254	7.543	8.899	25.858	75.1	3.8	29.8	0.363
7.33	12.837	8.711	10.774	31.632	76.7	-8.7	38.5	0.448
7.49	10.888	7.487	9.187	31.632	73.6	-2.4	29.0	0.440
7.55	11.555	8.269	9.912	31.632	75.6	-3.7	33.9	0.445
7.88	11.376	8.765	10.071	26.611	76.2	11.6	35.3	0.376
7.88	11.469	8.351	9.910	26.611	76.1	10.6	34.5	0.376
7.88	11.623	8.050	9.837	26.611	75.3	10.8	33.1	0.374
9.81	11.963	8.489	10.226	26.611	77.8	27.2	38.3	0.379
9.81	11.809	8.487	10.148	26.611	77.6	27.5	37.6	0.379
10.38	11.824	9.129	10.477	47.700	76.9	-2.1	37.7	0.676
10.38	12.234	8.764	10.499	47.700	75.9	-2.9	36.3	0.672
10.38	12.453	9.104	10.779	47.700	76.2	-3.5	37.7	0.673
12.02	12.705	8.983	10.844	55.231	77.7	0.1	40.5	0.786
12.02	12.528	8.461	10.494	55.231	77.2	0.8	38.3	0.784
12.02	12.678	8.730	10.704	55.231	77.3	0.1	39.2	0.785
13.53	11.790	8.946	10.368	65.273	75.8	-1.1	35.7	0.919
13.53	11.302	9.149	10.225	65.273	74.3	-0.8	33.1	0.912
13.73	11.908	8.854	10.381	65.273	76.3	0.1	36.5	0.922
14.70	12.362	9.101	10.732	75.315	76.8	-5.9	38.6	1.07
14.90	11.973	9.061	10.517	75.315	76.9	-4.1	37.8	1.07
15.66	13.030	8.841	10.936	80.838	78.0	-5.2	41.3	1.15
15.66	12.835	8.844	10.840	80.838	77.8	-5.2	40.5	1.15
17.25	12.759	9.024	10.892	90.378	75.6	-3.5	37.2	1.27
19.20	12.248	9.072	10.660	90.378	76.4	5.8	37.6	1.28
20.16	12.322	9.707	11.014	90.378	76.2	10.1	38.6	1.28
21.42	12.314	8.183	10.249	110.462	76.7	-0.5	36.7	1.56
21.42	12.508	9.269	10.888	110.462	77.0	-0.9	39.5	1.57
21.92	12.854	8.983	10.919	124.772	76.6	-9.6	38.8	1.77
21.92	12.650	8.659	10.654	124.772	76.3	-9.0	37.5	1.76
21.92	12.849	6.017	9.433	124.772	73.8	-8.3	30.0	1.74

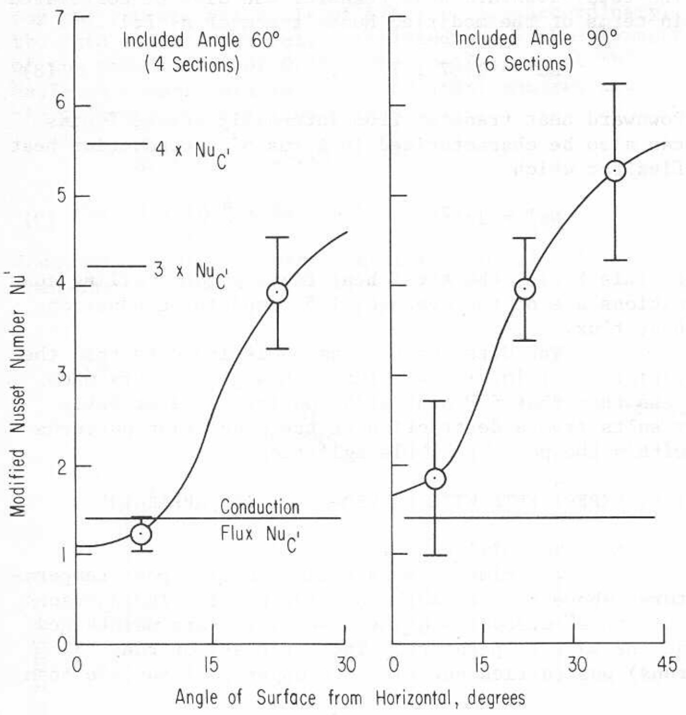

Fig.6 Modified Nusselt Numbers for Downward Heat Transfer to Curved Surfaces under Nonboiling Conditions

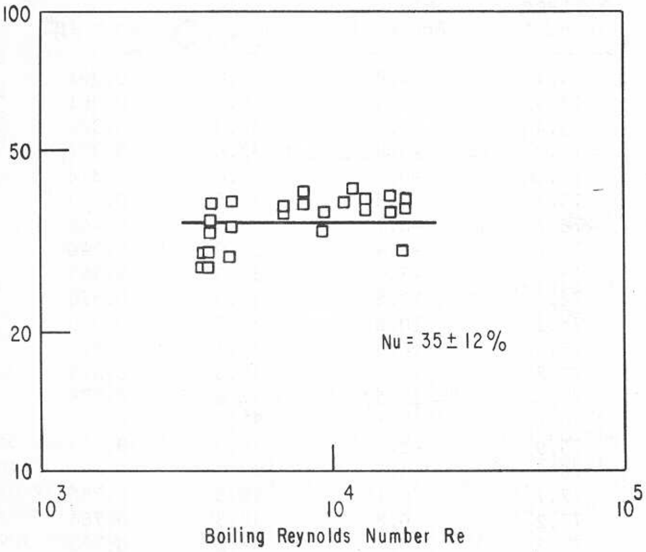

Fig.7 Average Downward Heat Transfer to a Curved Surface having an Included Angle of 60 deg under Boiling Conditions

to the atmosphere. In the next series of runs (29 runs) the upper pool surface was covered with insulating foam rubber. In the experiments with the insulated top, the upward heat flux because of surface evaporation was eliminated.

The data were correlated in terms of Nusselt number versus Rayleigh number (see Fig. 8). The data for the "open-top" and the "insulated-top" experiments were in close agreement. Within the range of experimental error, there did not appear to be any effect of covering the top surface on the heat transfer to the electrodes. Therefore, the data from both sets of experiments are plotted on Fig. 8 and were combined for a least square analysis.

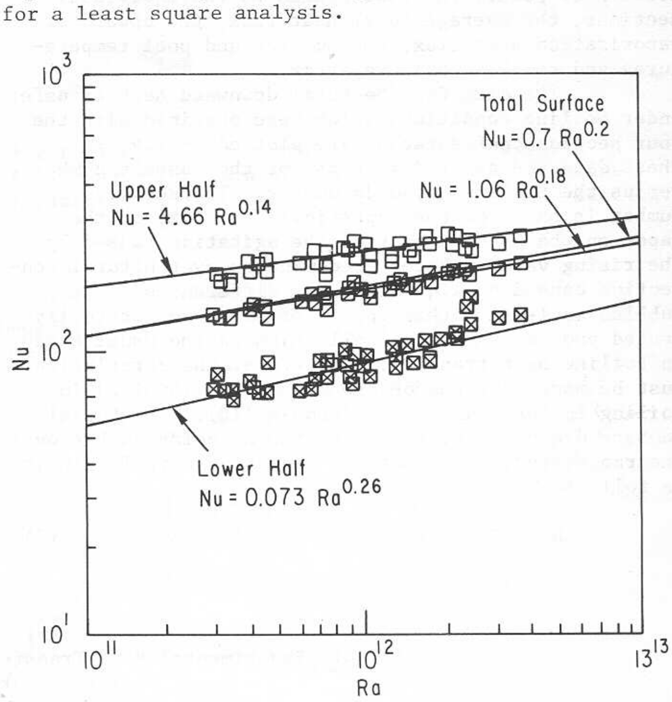

Fig. 8 Heat Transfer to a Semicircular Curved Surface from an Internally Heated Pool

The heat flux to the upper half of the curved split electrode was correlated by:

$$Nu = 4.66\ Ra^{0.14} \quad . \tag{10}$$

The heat flux to the lower half of the split electrode was less than to the upper half and was correlated by:

$$Nu = 0.073\ Ra^{0.26} \quad . \tag{11}$$

The average of the heat flux to the continuous left electrode and the total heat flux to both sections of the right electrode was correlated by:

$$Nu = 1.06\ Ra^{0.18} \quad . \tag{12}$$

Also shown on Fig. 8 is the curve:

$$Nu = 0.7\ Ra^{0.2} \quad . \tag{13}$$

This curve appears to correlate the data for heat transfer over the entire electrode surface quite well within the range of the data with little difference from the correlation obtained by least square analysis. The correlation has the advantage that it is independent of pool depth since the pool depth term, L, appears to the first power on both sides of the equation.

The heat flux downward to the flat base plate was less than that predicted by conduction using the difference in temperature between the center of the pool and the surface of the base plate even though convective liquid flow was visually evident. The cooled liquid flowing down from the electrode surfaces and then across the base plate effectively reduced the temperature driving force at the base plate surface resulting in a lowered downward heat flux.

B. Boiling Pool

The data for these boiling experiments are listed in Table 2. The data for sidewards heat transfer are plotted on Fig. 9 in terms of Nusselt number versus Reynolds number based on the superficial vapor velocity, V_o. The data of Gabor et al. for vertical flat walls in a rectangular geometry with various aspect ratios were correlated in these terms by:

$$Nu = 3.096\ Re^{1/2} \quad . \tag{14}$$

Table 2 Experimental Heat Transfer Data from an Internally-heated $ZnSO_4$-H_2O Pool to Curved Side Electrodes (Right Electrode Split into Two Equal Sections)

Power	Heat Flux, kW/m²								
kW	Q_{VAP}	$Q_{LOWER\ RIGHT}$	$Q_{UPPER\ RIGHT}$	Q_{LEFT}	Q_{DOWN}	Wall Temp., °C	Heat Balance Error, %	Nu_{TOTAL} *	Re x 10^4
6.14	22.68	44.64	82.75	68.19	4.15	40.1	3	276	0.560
6.24	24.07	44.25	84.39	70.36	4.89	39.7	5	280	0.593
10.13	63.33	51.19	104.35	81.25	14.52	43.8	2	353	1.60
10.17	63.61	50.71	106.49	80.70	13.93	43.1	2	350	1.60
13.97	109.59	53.69	105.96	86.81	29.76	49.2	3	408	2.88
13.97	108.41	52.95	108.88	85.33	30.01	49.9	2	412	2.86
15.99	131.30	59.42	112.40	90.82	33.93	51.7	2	453	3.50
15.90	136.16	57.42	114.85	86.87	31.96	50.1	3	430	3.60
19.31	171.12	59.66	113.36	93.99	39.56	56.2	0	508	4.70
19.04	172.71	59.06	114.55	95.13	38.73	55.7	2	507	4.73

* Total refers to total electrode surface

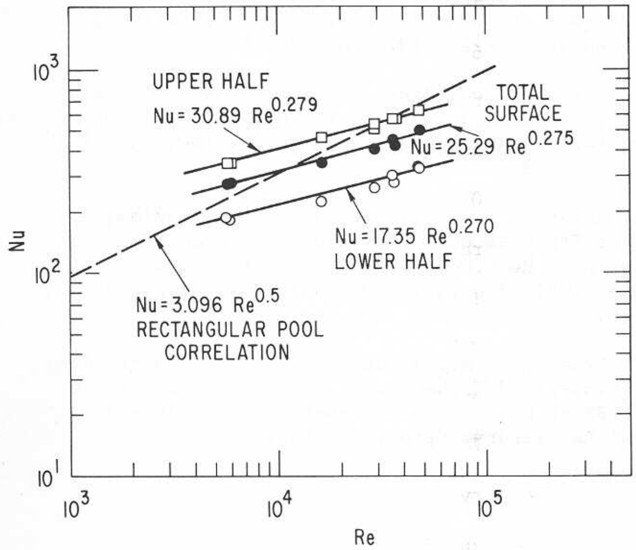

Fig.9 Sideward Heat Transfer to a Curved Surface from an Internally Heated Boiling Pool

Equation (14) is plotted on Fig. 9 and is not out of line with the data for the average of the total heat transfer to the curved electrodes. The Nusselt numbers for heat transfer to the upper and lower sections of the split electrode are also given on Fig. 9. The heat flux to the upper section was about twice that to the lower section.

A least squares fit of the data gives the following correlations:

For heat transfer to the entire electrode surface,

$$Nu = 25.29\ Re^{0.275} \quad . \tag{15}$$

For heat transfer to the upper half of the split right electrode,

$$Nu = 30.89\ Re^{0.279} \quad . \tag{16}$$

For heat transfer to the lower half of the split right electrode,

$$Nu = 17.35\ Re^{0.270} \quad . \tag{17}$$

The pattern of liquid flow along the base of the pool is not a simple one-directional flow as along the electrode wall. Along the electrode wall, the liquid flows in a downward direction. The liquid cooled at the electrodes flows down onto both ends of the base plate. At low rates of boiling, a wave of cold liquid can be seen washing back and forth across the base. At higher boiling rates, with a thicker bubbly layer, turbulence from the bubbly layer destroys this wave motion.

This effect of change in flow pattern at the base of the pool is shown in Fig. 10 in which the ratio of horizontal to downward heat flux, Q_S/Q_D, is plotted against the boiling flux, Q_B. At the lower boiling rates, the Q_S/Q_D ratio declines rapidly from about 16 to 3 as Q_B increases. As Q_B increases above 100 kW/m², the ratio declines less rapidly from about 2.8 to 2.3. This same behavior occurred with a pool of rectangular geometry and flat vertical walls (10). However, at the higher boiling rates with the rectangular pool Q_S/Q_D leveled out fairly consistently at 3.8. This high Q_S/Q_D ratio for the rectangular pool compared to the pool with curved electrodes indicates higher downward heat transfer for the curved electrode pool. This is obviously a geometry effect in that the cooled downward liquid along the curved electrode flowed more smoothly onto the surface at the base. With the straight vertical electrodes, the cooled liquid flowed directly normal to the base and after reaching the base of the electrode would flow into the lower liquid level at approximately a 45 deg angle from the bottom corner of the pool. Evidently the flow coming off the curved electrode was at a higher velocity as it moved into the liquid level near the base.

CONCLUSIONS

The experimental data for convective downward heat transfer to a curved surface were reasonably close to the Mayinger correlation when extrapolated to higher Rayleigh numbers and lower L/R ratios. Sideward heat transfer from a nonboiling pool can be described by

$$\mathrm{Nu} = 0.7\ \mathrm{Ra}^{0.2} \quad . \qquad (13)$$

Within the range of experimental error, there did not appear to be any effect of insulating the top surface on either sideward or downward heat transfer.

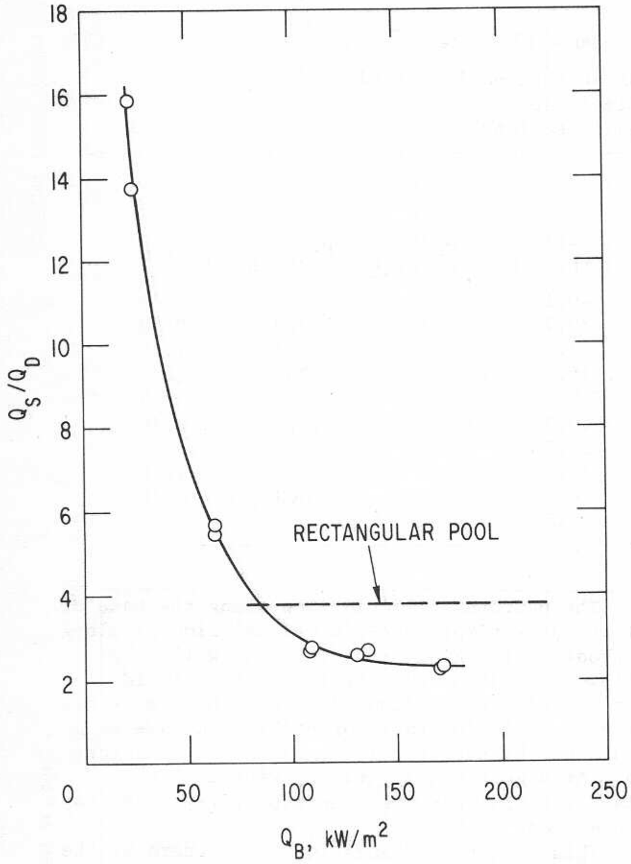

Fig.10 Ratio of Sideward to Downward Heat Fluxes for Boiling Pool with Curved Electrodes

ACKNOWLEDGEMENT

The contribution to this paper by Marilyn Goldman in typing the manuscript is appreciated.

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