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LOCAL BOILING PRESSURE DROP

by

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Reactor Engineering Division

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NOMENCLATURE

<u>Symbol</u>	<u>Definition</u>	<u>Units</u>
a	Parameter related to heat flux (q'') by the equation $a = 4.6 \times 10^{-6} q'' + 1.2$	none
A_s	Heat transfer surface	sq ft
A_f	Cross-sectional area of flow	sq ft
C	Orifice coefficient	none
c_p	Specific heat of water	Btu/(lb)(F)
cosh	Hyperbolic cosine	none
D	Inside tube diameter	ft
d	Inside tube diameter	in.
f	Friction factor as defined by Fanning Equation	none
G	Mass velocity of fluid through tube	lb/(sec)(sq ft)
G'	Mass velocity of fluid through tube	lb/(hr)(sq ft)
h	Heat transfer coefficient	Btu/(hr)(sq ft)(F)
k	Thermal conductivity of water	Btu/(hr)(ft)(F)
l	Distance of pressure tap (N_n) downstream from the reference pressure tap (N_0)	ft
L	Distance from the point where local boiling starts to any point in question (along the length of local boiling), up to the point where net boiling starts ($\Delta t_{sub} = 0$)	ft
L_T	Distance from the point where local boiling starts to the point along the tube where net boiling starts ($\Delta t_{sub} = 0$)	ft
N_0	Refers to the reference pressure tap	none
N_n	Refers to any pressure tap down stream from (N_0)	none
N_{Re}	Reynolds number DG'/μ	none
P	Absolute pressure	psia
$\Delta P_{L.B.}$	Local boiling pressure drop	in. of H_2O
ΔP_0	Isothermal liquid pressure drop	in. of H_2O

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NOMENCLATURE (Cont'd)

<u>Symbol</u>	<u>Definition</u>	<u>Units</u>
$\left(\frac{dp}{dL}\right)_0$	Isothermal liquid pressure gradient at average bulk water temperature	in. of H ₂ O/ft
$\left(\frac{dp}{dL}\right)_L$	Local boiling pressure gradient	in. of H ₂ O/ft
q	Rate of heat transfer	Btu/hr
q"	Density of heat flux = q/A_s	Btu/(hr)(sq ft)
R	Ratio of local boiling pressure gradient to the isothermal liquid pressure gradient $(dp/dL)_L/(dp/dL)_0$	none
sinh	Hyperbolic sine	none
t	Bulk water temperature (t_0 = water temperature at point where local boiling starts, t_L = water temperature at any point L)	F
t_{wall}	Inside heater wall temperature	F
t_{sat}	Saturation temperature of water from steam tables	F
Δt_{sat}	Temperature difference between inside heater wall temperature and saturation temperature ($t_{wall} - t_{sat}$)	F
$(\Delta t_{sub})_0$	Subcooling at point where local boiling starts = $(t_{sat} - t_0)$	F
$(\Delta t_{sub})_L$	Subcooling at any point = $(t_{sat} - t_L)$	F
V	Variables group = $\frac{4 q'' L}{G' c_p D (\Delta t_{sub})_0} = \frac{L}{L_T} = zL$	none
W	Water flow rate through test section	lb/hr
μ	Viscosity of water	lb/(hr)(ft)

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7 LOCAL BOILING PRESSURE DROP

by

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ABSTRACT

Local boiling pressure drop data for forced circulation of distilled water in a uniformly heated, horizontal, Type 347 stainless steel tube (3/8 in. ID x 1/2 in. OD x 6 ft long) is correlated within $\pm 20\%$ over the following range of variables: heat fluxes from 130,000 to 304,000 Btu/(hr)(sq ft); mass velocities from 343 to 652 lb/(sec)(sq ft) (corresponding to inlet water velocities of 7 to 10.6 fps); and pressures from 45 to 100 psia.

Graphical comparison of local boiling pressure drop to isothermal pressure drop shows a maximum ratio of approximately 2.6.

I. INTRODUCTION

Local boiling is a form of nucleate boiling which occurs when a subcooled liquid (at a temperature below saturation) is brought into contact with a metal surface hot enough to cause boiling at the interface. The vapor bubbles condense in the subcooled liquid, and no net generation of vapor is realized. Local boiling may occur in certain flow systems such as water-tube boilers or water-cooled nuclear reactors, where water enters the system in a subcooled state.

Figure 1 shows the general shape of the characteristic pressure drop flow curve of water flowing under forced circulation in a uniformly heated channel. The pressure drop in the non-boiling region can be predicted by the Fanning Friction Equation. The Martinelli-Nelson⁽¹⁾ method is recommended for the calculation of pressure drop in the net boiling or two-phase flow region.

The shape of this type of curve has been experimentally verified;⁽²⁾ however, the analytical methods presently available do not cover the local boiling region. This region is important because the experimental curve (A-a-b-C) lies above the calculated curve (A-B-b-C). An analytical method for the prediction of pressure drop over the local boiling region would be a helpful working tool and could be used to fill in the gap in the characteristic pressure drop flow curve.

FIG. 1
CHARACTERISTIC PRESSURE DROP
VS FLOW CURVE

The prediction of the characteristic pressure drop flow curve by analytical methods would be an aid in the design of water-cooled reactors, since the general shape of this curve for individual parallel channels in a reactor is the criterion for flow stability.

II. PURPOSE AND SCOPE

The purpose of this investigation was to measure experimentally the static pressure drop of water over the local boiling region, during forced flow through a uniformly heated tube, and to analyze and correlate the experimental data with the operating variables of subcooling, heat flux, mass velocity, and absolute pressure.

The experimental work was limited to the forced circulation of distilled water through a uniformly heated horizontal test section. The test section was a Type 347 stainless steel tube, 3/8 in. ID by 1/2 in. OD, having a heated length of 6 ft. The approximate range of operating variables to be covered were:

Heat flux: 130,000 to 304,000 Btu/(hr)(sq ft)

Mass velocity: 434 to 652 lb/(sec)(sq ft)
(Inlet velocity: 7 to 10.6 fps)

Absolute pressure: 45 to 100 psia

Bulk water temperature: operating below saturation temperature

III. LITERATURE SURVEY

The study of pressure drop for water flowing in a uniformly heated channel during local boiling is very limited.⁽³⁾ Some local boiling pressure drop data were collected at the University of California at Los Angeles, Massachusetts Institute of Technology, and Purdue University. The systems used were basically the same - each contained a vertical tube of small diameter electrically heated to produce high heat fluxes. Water under high total pressures was pumped upward through the tube. In each instance, the system was operated up to at least 2000 psia system pressure, 600F temperature, 7,650,000 lb/(hr)(sq ft) mass velocity, and 3,500,000 Btu/(hr)(sq ft) heat flux.

Qualitative analysis of these data showed that the total pressure drop across the tube during local boiling was greater than the frictional pressure drop based on average liquid densities. The difference between the actual pressure drop and frictional pressure drop is due, in part, to the energy lost in accelerating the fluid from the inlet to the outlet of the tube.

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Except for certain limited observations, no definite conclusions were made nor correlations found to describe pressure drop with heat input in the local boiling region.

IV. EXPERIMENTAL APPARATUS⁽⁴⁾

A. Pumping System

The test apparatus, shown schematically in Figure 2 and pictorially in Figures 3 and 4, is a closed loop filled with distilled water.

The water is pumped from the bottom of the supply tank by a 2-stage APCO Turbine Pump. This pump was chosen because of its steep head-discharge curve, which offers the advantage that a large increase in pressure drop causes a relatively small decrease in flow. Figure 5 shows the pump characteristics for a motor speed of 1750 rpm used in this experiment.

The pump discharged into parallel orifice assemblies. The flow could be directed through either of the 2 calibrated orifices by means of the gate valves in the assembly. The orifices were machined and assembled in 1-in. pipe unions in the manner described by Grace and Lapple.⁽⁸⁾ The thin-plate orifices were machined with edges 0.005 in. or less instead of the 0.001 in. or less for the knife edge orifices used by Grace and Lapple. Figure 6 shows a comparison of the orifice coefficients (C), obtained by weigh tank calibration with the Grace and Lapple coefficients, at different β values (ratio of orifice diameter to pipe diameter). It is believed that the duller edges account for the lower orifice coefficients.

B. Flow Measurement and Control System

The flow measurement and control system is shown schematically in Figure 7. The orifice pressure taps were connected to the differential pressure transmitter and to the Meriam 60-in., U-tube manometer which was connected in parallel with the transmitter. The flow rate was determined from pressure drop measurement across the orifice indicated on the U-tube manometer, chosen because of its accuracy. The transmitter was used in the air-operated flow control system. The 3- to 15-psi air signal from the transmitter was balanced by the flow controller which sends a 0 to 15 psi signal to the air-actuated throttle valve, thereby opening or shutting in response to the transmitted signal.

C. Preheater

The water from the flow throttle valve entered the 40-kw, 440-volt, 3-phase Calrod immersion preheater where it was heated to the desired sub-cooled condition. The power to the preheater was controlled by manually operated Powerstat Variable Transformers Type 1256.

FIG. 2
SCHEMATIC OF LOCAL BOILING
PRESSURE DROP TEST APPARATUS

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FIG. 3
VIEW OF EQUIPMENT FROM END OF CONTROL PANEL

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FIG. 4
CONTROL PANEL

FIG. 5
CHARACTERISTIC CURVES FOR MODEL D5T
AURORA TURBINE-TYPE PUMP

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FIG. 6
CALIBRATION CURVES FOR 0.2765-
AND 0.429-INCH ORIFICES

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FIG. 7
 FLOW MEASUREMENT AND CONTROL SYSTEM

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D. Inlet Water Thermocouple

The water at the desired subcooling entered the unheated portion of the test section where the inlet water temperature and pressure were measured. The temperature was measured with a No. 30 iron-constantan thermocouple mounted inside a 1/8 in. by 1/16 in. copper tube, silver-soldered shut at the end. The tube was centrally mounted in the fluid stream, parallel to the direction of flow for a distance of 4-1/2 in. A Bourdon-tube gage connected to the first pressure tap was used to measure the inlet pressure.

E. Power Supply

The test section was resistance heated with alternating current, the power supply being through copper connections silver-soldered to the surface. The alternating current was supplied by 3 welding transformers (Lincoln Fleet-Arc 500 Industrial Type Welders, rated at 500 amp at 40 v on a 60 % duty cycle, with 70 v on open circuit) connected in parallel. Motor drive through chains and sprockets provided the current variation; the transformers shared the load equally at the various settings.

F. Outlet Water Thermocouple

The water near saturation temperature left the test section through a pair of Teflon-insulated flanges. The temperature of the fluid at the outlet was measured in the same manner as the inlet water thermocouple. The water then passed through a 3/8-in. sight glass, which permitted visual examination of the flow leaving the section.

G. Exhaust Header and Pressure Control

The water then entered the exhaust header, which was made of 4-in. Schedule 80 stainless steel pipe. The system pressure was controlled by building up the back pressure to the desired amount by use of the 1-in. and 3/8-in. globe valves in parallel after the exhaust header. The fluid near its saturation temperature, after passing through the throttle valve, flashed at atmospheric pressure. The air-cooled condenser and water-cooled condenser were provided to condense the steam before it entered the condensate tank. A float control in the condensate tank intermittently operated the condensate pump, which returned the condensate to the supply tank. A 10-micron Cuno Filter was located between the condensate pump and the supply tank to remove any foreign particles from the system.

H. Ion Exchanger

A small ion exchanger was employed in the system to maintain the purity of the water. The water was pumped to and from the supply tank through the ion exchanger by a separate pump.

I. Test Section

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The test section was a Type 347 stainless steel tube, $1\frac{1}{2}$ in. OD by $\frac{3}{8}$ in. ID by 7 ft long. A flange was welded to each end. Teflon ring-joint gaskets and flange bolt sleeves were used to insulate the test section electrically from the remainder of the grounded apparatus. Two copper lugs, each $\frac{3}{8}$ in. thick, were welded to the test section at a point 6 in. from each flange.

The pressure taps were formed by drilling $\frac{1}{32}$ -in. holes through the tube wall at the positions indicated in Figure 8. A $\frac{1}{8}$ in. by $\frac{1}{16}$ in. stainless steel tube was silver-soldered to the test section at each pressure tap hole; care was taken to prevent the entry of solder or flux. Upon completion of each stage of assembly the inside surface of the tube was polished with emery cloth to remove any burrs or foreign matter. Figure 9 shows a cutaway view of the pressure tap made in this manner; when viewed with a magnifying glass the tap appeared to have square edges with no burr.

A series of No. 30 iron-constantan thermocouples were attached to the test section at intervals of $1\frac{1}{2}$ in. over the entire heated length in order to determine the point where local boiling starts.⁽⁵⁾ The 2 end couples were placed $1\frac{1}{2}$ in. from the inside surface of the copper lugs. Each couple was insulated from the test section with a sheet of mica one mil thick and held to the outside surface of the tube by high-temperature glass electrical tape. Mica was used to prevent arcing at the selector switch. The glass tape in turn was held down by spring-wire clips, one on each side of the thermocouples. Each thermocouple was wrapped around the tube, approximately one-third of a turn before it was led out through the heat insulation in an attempt to avoid error from axial conduction along the wires.

As a check on the uniformity of heat generation in the test section, voltage taps were attached by wrapping one turn of copper wire around the test section at distances of 11, $22\frac{3}{4}$, 35, $46\frac{3}{4}$ and 59 in. from the face of the copper lug at the inlet end of the test section. Voltage taps were also connected directly to the 2 copper lugs.

J. Temperature Measurement

The inlet and outlet water thermocouples were led from the test section through individual lengths of copper shielding directly to a Leeds and Northrup Portable Precision Potentiometer. An ice junction was used as the reference junction for the potentiometer.

The 48 thermocouples used to measure the wall temperature of the test section were led through individual lengths of copper shielding to a 2-in. square duct and then to a junction box. Here the iron-constantan wires were connected to a copper lead wires which were led through conduit to a Brown, Forty-Eight Point, Electronic Precision Temperature Indicator. The

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FIG. 8
LOCATION OF PRESSURE TAPS ON TEST SECTION

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FIG. 9
CUT-AWAY VIEW OF PRESSURE TAP

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instrument operates on 0-300F and 300-700F temperature ranges and provides its own room-temperature compensation. The junction box was at room temperature.

K. Pressure Measurement

Pressure drop measurements were made with four 60-in. Meriam U-tube manometers which were converted to well-type manometers, as shown in Figure 10. Two stainless steel wells were constructed of 6-in. Schedule 40 pipe, so that the 4 manometers provided 8 simultaneous pressure drop readings. The first 4 readings could be referenced to the first pressure tap, while the last 4 readings referenced to the fifth pressure tap, or all 8 readings could be referenced to the first pressure tap.

The pressure measurement was made with a Heise Precision Bourdon-tube gage. The measurement was taken at the eighth pressure tap, which was located 3 in. upstream from the outlet power lug.

L. Power Measurement

The power received by the test section from the 3 welding transformers was measured with a calibrated wattmeter. The wattmeter received its voltage from a step-up transformer (Westinghouse type PV-130 Potential Transformer, 5, 4, 2 to 1 ratios) and its current from either of 2 current transformers (Westinghouse type U-5, 1500 to 5 amp; and Type CT-2.5, 600 to 5 amp), depending upon the current range in use.

V. EXPERIMENTAL PROCEDURE AND RESULTS

A. Procedure

The pump was started and a back pressure built up in the system by use of the exhaust throttle valves. When sufficient pressure was built up, the system was bled. The flow rate was set by adjusting the air pressure to the flow control system until the correct pressure drop reading across the flow manometer was obtained. A predetermined amount of power was applied to the test section and the outlet pressure adjusted. The power to the preheater was then adjusted to obtain an outlet temperature just below saturation. When the flow rate, pressure, water temperature, and power were adjusted to the desired values, and the system was operating steadily, a "run" was started and the following data collected:

1. Power to the test section
2. Pressure drop across the orifice
3. Outlet pressure

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FIG. 10
PRESSURE DROP MEASUREMENT APPARATUS

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4. Inlet and outlet water temperatures
5. Temperature of the outside wall along the length of the test section
6. Pressure drop measurements along the test section
7. Barometric pressure

B. Results

Table I shows the converted and corrected experimental data; each run represents an average of from 4 to 8 complete sets of data taken after steady state had apparently been reached for a particular setting of variables. The heat flux and mass velocities were calculated from the wattmeter and flow manometer readings, respectively. The absolute pressure is the summation of the corrected gage pressure and barometric pressure. The location of the inception of local boiling was determined from plots of the heater or wall temperature along the heated length. Figure 11 shows a typical plot of the outside wall temperature along the heated length of the test section. The heater or wall temperature was assumed constant over the length of local boiling.

Figure 12 shows typical isothermal pressure drop curves at various mass velocities.

Figure 13 is a plot of friction factors (f) versus Reynolds Numbers (N_{Re}) determined experimentally on the apparatus used for this analysis. The experimental data are approximately 7 to 8% higher than the smooth tube values reported by Moody.⁽⁷⁾

Figures 14, 15, and 16 show typical experimental pressure drop curves at different mass velocities, absolute pressures, and heat fluxes, respectively. These curves show the pressure drop along the length of the heated section. The point where local boiling started in each run presented was approximately 48 in. from the inlet copper lug (or from the beginning of the heated length). It should be noted on each curve that just past the point where local boiling begins there is a plateau, or a tendency of the pressure drop to level off. This phenomenon occurred in all runs. The plateau could be moved along the length of the tube by increasing or decreasing the bulk water temperature with the power, pressure, and mass velocity held constant. Therefore, it was assumed that the plateau was not caused by faulty pressure measurement, but by the phenomenon of local boiling.

Throughout the experiment uniform heat generation was assumed along the length of the heated section. The basis for this assumption is presented in Figure 17; the voltage drop at various heat fluxes is linear along the heated length.

LOCAL BOILING AND NON-BOILING PRESSURE DROP DATA

Table I

Run No.	q'' Heat Flux Btu/(hr) (ft ²) $\times 10^{-5}$	P Pressure, psia	G Mass Velocity, lb/(sec) (ft ²)	Water Temp., F		Inception* of Local Boiling, in.	Pressure Drop, (in. of H ₂ O)** (Δp) from N_0 to N_n					
				Inlet	Outlet		N_n 1	2	3	4	5	6
							N_n 1	(2)	(3)	(4)	(5)	(6)
61	1.304	44.49	434.4	209	269	48	4.37	9.32	15.85	22.68	28.61	31.53
67	1.304	59.45	434.4	228	290	54	4.93	10.39	16.24	22.29	29.00	30.36
73	1.304	74.45	434.4	243	301	51	5.13	10.78	16.83	23.26	28.98	30.93
79	1.304	99.54	434.4	263	322	48	3.35	8.81	14.86	21.88	27.83	31.53
91	1.304	44.54	543	223	271	51	7.88	16.07	25.23	34.79	44.48	47.01
97	1.304	59.54	543	242	290	48.0	7.29	15.48	24.45	34.40	43.88	47.38
103	1.304	74.51	543	255	303	49.5	8.46	16.26	26.79	39.08	48.01	56.0
116	1.304	44.49	651.6	230	270	49.5	11.43	23.32	36.39	50.04	63.65	67.94
122	1.304	59.45	651.6	250	289	48	11.23	23.32	36.39	50.23	64.25	69.13
128	1.304	74.54	651.6	262	301	51	9.87	20.98	34.44	49.26	61.31	67.94
60	1.738	44.49	434.4	184	266	46.5	4.93	10.49	16.05	22.58	28.61	31.18
66	1.738	59.45	434.4	206	287	49.5	5.32	10.98	16.83	23.07	30.17	31.34
72	1.738	74.45	434.4	221	301	48.0	4.93	10.39	16.24	22.29	29.39	30.95
78	1.738	99.54	434.4	242	322	48.0	4.74	10.39	16.44	20.73	29.97	31.34
90	1.738	44.54	543	205	270	49.5	5.93	14.31	23.67	33.03	43.49	48.85
96	1.738	59.54	543	224	288	49.5	7.68	15.87	25.04	34.40	45.04	47.38
102	1.738	74.54	543	234	303	48.0	7.88	16.26	25.23	35.48	47.01	49.55
108	1.738	99.49	543	259	322	49.5	8.07	16.65	25.43	35.37	48.38	50.13
115	1.738	44.49	651.6	216	270	51.0	11.04	22.93	35.61	49.45	63.86	67.18
121	1.738	59.49	651.6	235	288	51.0	11.23	22.93	36.00	49.84	65.03	68.35
127	1.738	74.54	651.6	249	300	49.5	11.23	22.93	35.41	48.09	63.26	67.88
132	1.738	99.54	651.6	269	322	49.5	10.65	22.35	35.02	48.67	63.45	67.94
59	2.173	44.49	434.4	164	267	48	4.64	10.30	15.85	22.58	29.29	30.07
65	2.173	59.45	434.4	184	286	48	5.13	11.17	17.02	23.07	29.97	30.95
71	2.173	74.45	434.4	198	300	48	4.15	9.81	15.46	22.09	28.80	30.36
77	2.173	99.54	434.4	220	321	49.5	2.96	9.98	14.47	21.29	27.83	30.36
89	2.173	44.54	543	188	270	49.5	5.15	13.53	22.89	32.06	42.92	43.89
95	2.173	59.54	543	207	288	49.5	6.12	15.29	24.45	33.03	43.89	45.65
101	2.173	74.51	543	222	303	48.0	6.90	15.87	24.26	34.40	46.62	49.35
107	2.173	99.49	543	243	323	48.0	7.24	16.44	24.65	34.79	49.18	49.96
114	2.173	44.49	651.6	202	270	49.5	10.65	22.93	35.61	49.26	64.06	66.59
120	2.173	59.49	651.6	222	289	51.0	9.67	21.96	35.02	48.48	63.67	67.37
126	2.173	74.54	651.6	230	299	49.5	10.84	33.13	34.83	48.48	63.47	67.37
131	2.173	99.54	651.6	255	322	49.5	11.04	22.74	35.02	48.87	65.42	68.74
58	2.607	44.49	434.4	144	268	48	4.45	10.20	15.46	22.48	28.80	29.58
64	2.607	59.45	434.4	163	286	48	4.74	10.88	16.83	23.46	29.58	30.36
70	2.607	74.45	434.4	177	300	48	2.96	9.59	15.25	21.68	28.22	29.58
76	2.607	99.54	434.4	198	320	48	2.97	9.98	14.47	21.49	28.61	30.56
88	2.607	44.54	543	172	270	49.5	5.34	14.12	22.89	32.84	43.89	44.87
94	2.607	59.54	543	190	288	49.5	6.12	15.29	24.26	33.23	44.67	45.65
100	2.607	74.51	543	206	304	48.0	6.51	15.29	23.67	34.20	47.42	49.18
106	2.607	99.49	543	226	323	48	6.32	16.44	23.48	33.81	48.98	49.37
113	2.607	44.49	651.6	188	270	49.5	10.65	22.93	35.22	49.06	64.08	66.61
119	2.607	59.49	651.6	207	289	51.0	9.48	21.76	34.83	48.48	64.45	66.61
125	2.607	74.54	651.6	222	300	48	10.26	23.13	34.24	48.28	64.06	68.15
130	2.607	99.54	651.6	239	322	48	9.87	23.13	34.05	47.89	65.81	68.15
57	3.042	44.49	434.4	120	270	48	4.06	9.91	15.46	23.65	28.24	29.80
63	3.042	59.45	434.4	144	286	49.5	4.25	10.98	16.34	24.18	29.13	29.97
69	3.042	74.45	434.4	147	301	48	3.18	9.81	15.66	22.68	28.61	29.19
75	3.042	99.54	434.4	178	321	46.5	2.18	9.20	13.69	21.10	28.41	29.97
87	3.042	44.54	543	154	268	51.0	5.73	14.51	22.89	32.64	43.70	43.89
93	3.042	59.54	543	173	289	49.5	6.32	15.29	24.26	33.23	45.08	46.06
99	3.042	74.51	543	188	303	49.5	6.51	15.09	23.67	34.20	48.20	49.18
105	3.042	99.49	543	208	322	48.0	6.12	16.26	23.09	33.62	49.96	49.18
112	3.042	44.49	651.6	173	270	49.5	10.65	22.54	34.63	48.28	64.08	65.83
118	3.042	59.49	651.6	193	289	49.5	9.48	21.76	34.83	48.48	65.25	66.81
124	3.042	74.54	651.6	208	300	48.0	11.23	23.52	34.05	48.09	65.44	67.78
129	3.042	99.54	651.6	227	323	48.0	8.09	22.52	32.27	46.90	65.44	67.39
151		44.5	325.8	102	102	---	4.04	9.01	13.20	17.69	22.13	24.47
152		44.5	325.8	160	160	---	3.74	8.03	11.84	15.89	19.79	21.94
153		44.5	217.2	94	94	---	2.16	4.70	6.84	9.18	11.56	12.73
154		44.5	217.2	158	158	---	1.77	4.11	6.06	8.01	9.98	10.96
155		44.5	434.4	102	102	---	6.10	12.54	19.56	26.07	32.31	35.72
156		44.5	434.4	160	160	---	5.71	11.76	17.80	24.04	29.87	32.99
157		44.5	543	92	92	---	10.24	20.96	32.86	43.19	53.66	59.12
158		44.5	543	150	150	---	9.24	18.80	29.04	38.79	48.18	53.25
159		44.5	651.6	90	90	---	14.34	30.36	46.45	61.17	75.89	83.60
160		44.5	651.6	133	133	---	13.10	27.83	42.74	60.49	69.95	77.24

**Distance in in. from inlet copper lug (see Fig. 8).

** N_n = reference tap (located 3 in. upstream from inlet copper lug). N_0 = refers to any pressure tap downstream from N_n . L_n = distance of pressure tap (N_n) downstream from the reference tap (N_0) in ft.

FIG. 11
TYPICAL PLOT OF OUTSIDE WALL TEMPERATURE
VS HEATED LENGTH OF TEST SECTION

FIG. 12
ISOTHERMAL PRESSURE DROP MEASURED
AT VARIOUS MASS VELOCITIES

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FIG. 13
FRICTION FACTORS VS REYNOLDS NUMBERS
FOR SMOOTH TUBES SHOWING DEVIATION OF
TEST DATA FROM MOODY SMOOTH TUBE CURVE

FIG. 14
 TYPICAL EXPERIMENTAL CURVES
 WITH DIFFERENT MASS VELOCITIES

FIG. 15
TYPICAL EXPERIMENTAL CURVES
WITH DIFFERENT PRESSURES

FIG. 16
TYPICAL EXPERIMENTAL CURVES
WITH DIFFERENT HEAT FLUXES

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FIG. 17
VOLTAGE DROP ALONG TEST SECTION
AT VARIOUS HEAT FLUXES

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VI. ANALYSIS

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The first step in the analysis was to plot the pressure drop data for pressure taps N_4 , N_5 , N_6 , and N_7 against length from the inlet copper lug; a typical plot is shown in Figure 18. Tangents to the curve were drawn at points 48, 51, 54, 57, 60, 63, 66, and 69 in. from the inlet copper lug. The slope of the tangent at any point $(dp/dL)_L$ represents the local boiling pressure gradient at that point.

Next, the isothermal pressure drop data from runs 151 - 160 were plotted against length and the isothermal gradient $(dp/dL)_0$ determined for each temperature and mass velocity. A plot of $(dp/dL)_0$ versus water temperature at the different mass velocities was made as shown in Figure 19. From Figure 19 the isothermal pressure gradient was determined at the average bulk fluid temperature and mass velocity for each run. A ratio of the local boiling point-wise pressure gradient $(dp/dL)_L$ to the isothermal pressure gradient $(dp/dL)_0$ was determined at the average bulk water temperature and the mass velocity for that particular run. This pressure gradient ratio $(dp/dL)_L / (dp/dL)_0$ was used for the final analysis.

Using the inlet and outlet water temperature and the saturation temperature at the absolute pressure, the subcooling at any point along the length of the heated section was determined. Subcooling (Δt_{sub}) is the difference between the saturation temperature and the bulk water temperature at any point. The change in bulk water temperature was assumed to be linear from inlet to outlet. This assumption was confirmed by Figure 17.

Subcooling values were determined at the point where local boiling starts $(\Delta t_{sub})_0$ and points along the length of the heated section undergoing local boiling corresponding to the points (L) where the local boiling pressure gradients $(dp/dL)_L$ were taken. The subcooling values taken at these points are referred to as $(\Delta t_{sub})_L$.

An expression which relates the operating variables in question was derived from the heat balance equation

$$q = W c_p \Delta t$$

where:

$$q = q'' A_s$$

$$W = G' A_f$$

$$\frac{A_f}{A_s} = \frac{D}{4 L}$$

$$\Delta t = t_L - t_0$$

$$t_L = t_{sat} - (\Delta t_{sub})_L$$

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FIG. 18
METHOD USED TO DETERMINE LOCAL
BOILING PRESSURE GRADIENT

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FIG. 19
VARIATION OF ISOTHERMAL PRESSURE GRADIENT
WITH TEMPERATURE AT VARIOUS MASS VELOCITIES

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$$t_0 = t_{\text{sat}} + (\Delta t_{\text{sub}})_0$$

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therefore:

$$q'' A_s = G' A_f c_p \Delta t$$

$$q'' = G' \frac{A_f}{A_s} c_p \Delta t$$

$$q'' = \frac{G' D c_p \Delta t}{4 L}$$

or

$$\Delta t = (\Delta t_{\text{sub}})_0 - (\Delta t_{\text{sub}})_L = \frac{4 q'' L}{G' D c_p}$$

Dividing both sides of the equation by $(\Delta t_{\text{sub}})_0$ gives

$$1 - \frac{(\Delta t_{\text{sub}})_L}{(\Delta t_{\text{sub}})_0} = \frac{4 q'' L}{G' D c_p (\Delta t_{\text{sub}})_0} = \frac{L}{L_T} \quad (1)$$

It was found that, by plotting $(dp/dL)_L / (dp/dL)_0$ versus $1 - \frac{(\Delta t_{\text{sub}})_L}{(\Delta t_{\text{sub}})_0}$, the pressure gradient ratio was practically independent of mass velocity and absolute pressure, but dependent upon heat flux (q''). Figure 20 shows a typical plot at variable pressure and mass velocity and constant heat flux.

VII. CORRELATION OF LOCAL BOILING PRESSURE DATA

For different values of heat flux it was found that the individual plots shown in Figure 20 may be represented by curves (Figure 22) described by the equation

$$\frac{\left(\frac{dp}{dL}\right)_L}{\left(\frac{dp}{dL}\right)_0} = 0.5 (e^{azL} + e^{-azL}) = \cosh azL \quad (2)$$

where the parameter "a" is related to the heat flux as shown in Figure 21, and "z" is defined by the equation:

$$zL = 1 - \frac{(\Delta t_{\text{sub}})_L}{(\Delta t_{\text{sub}})_0} = \frac{4 q'' L}{G' D c_p (\Delta t_{\text{sub}})_0} = \frac{L}{L_T}$$

Integration of Equation (2) in the form

$$\left(\frac{dp}{dL}\right)_L = \left(\frac{dp}{dL}\right)_0 \cosh azL \quad (3)$$

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FIG. 20
 VARIATION OF LOCAL BOILING: ISOTHERMAL PRESSURE
 GRADIENT RATIO WITH EXPERIMENTAL VARIABLES

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FIG. 21
VARIATION OF PARAMETER "a" WITH HEAT FLUX

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FIG. 22
VARIATION OF LOCAL BOILING: ISOTHERMAL
PRESSURE GRADIENT RATIO WITH EXPERIMENTAL
VARIABLES

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gives an expression for the total pressure drop along the length of the local boiling region; thus

$$\int_0^L \Delta P_{L.B.} \frac{dp_{L.B.}}{dL} = \left(\frac{dp}{dL} \right)_0 \int_0^L (\cosh azL) dL$$

$$\Delta P_{L.B.} = \left(\frac{dp}{dL} \right)_0 \frac{1}{az} \sinh azL \quad (4)$$

A graphical comparison of the local boiling pressure drop correlation with the isothermal pressure drop is given in Figure 23.

VIII. CONCLUSIONS AND RECOMMENDATIONS

The local boiling pressure drop data, for the forced circulation of distilled water in a uniformly heated, horizontal Type 347 stainless steel tube, were correlated by the equation

$$\Delta P_{L.B.} = \left(\frac{dp}{dL} \right)_0 \frac{G' D c_p (\Delta t_{sub})_0}{4 a q''} \sinh \left[\frac{4 z q'' L}{G' D c_p (\Delta t_{sub})_0} \right]$$

within $\pm 20\%$ over the range of variables tested.

In an attempt to predict the local boiling pressure drop at extended variables, the existing UCLA⁽⁶⁾ local boiling pressure drop data were checked against the correlation. It was found that the local boiling pressure drop could be predicted within 50% for the following range of variables: heat fluxes from 70,000 to 500,000 Btu/(hr)(sq ft), mass velocities of 265 and 1060 lb/(sec)(sq ft), and absolute pressures of 500 and 2000 psia. These data were collected for a vertical tube having an inside diameter of 0.226 in. and a heated length of 24.6 in. For heat fluxes above 500,000 Btu/(hr)(sq ft), values from the correlation did not agree with the UCLA data.

Further investigation of local boiling pressure drop should be made to extend the correlation over a wider range of variables for both vertical and horizontal tubes. It is believed that the most important variable is heat flux; however, extended values of pressure, mass velocity, and tube diameter may show some affect on the local boiling pressure drop. More data at heat fluxes ranging from 300,000 to 2,000,000 Btu/(hr)(sq ft) may alter the equation for the parameter "a" in the correlation, so that it may be used at higher heat fluxes.

Further work should be done to investigate the phenomenon causing the plateau in the pressure data shown in Figures 14, 15, and 16. The data obtained in this experiment were insufficient to draw any conclusions as to the cause of this plateau.

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FIG. 23
VARIATION OF TOTAL LOCAL BOILING: ISOTHERMAL
PRESSURE DROP RATIO WITH EXPERIMENTAL VARIABLES

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APPENDIX

METHOD FOR DETERMINATION OF INCEPTION
OF LOCAL BOILING AND $(\Delta t_{\text{sub}})_0$

Inside wall temperatures may be obtained analytically by use of the forced convection equation and the Jens and Lottes equation* for Δt_{sat} as indicated in Figure 24.

The intersection (o) of the wall temperatures (curves $\overline{ab}$ and $\overline{cd}$) is the point where local boiling starts. From this plot, $(\Delta t_{\text{sub}})_0$ can be determined.

*Mc Adams' equation for Δt_{sat} may be substituted.

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LEGEND:

$\overline{ab}$ DETERMINE FROM $t_{WALL} = \frac{q''}{h} + t$

$$\text{WHERE } h = \frac{0.023k}{D} \left(\frac{G'D}{\mu} \right)^{0.8} \left(\frac{c_p \mu}{k} \right)^{0.4}$$

(FORCED CONVECTION) (9)

$$\overline{cd} \text{ DETERMINE FROM } t_{WALL} = \frac{60 \left(\frac{q''}{10^6} \right)^{\frac{1}{4}}}{e^{\frac{P}{900}}} + t_{SAT}$$

(JENS AND LOTTES EQUATION) (3)

FIG. 24
METHOD FOR DETERMINATION OF INCEPTION
OF LOCAL BOILING AND $(\Delta t_{SUB})_0$

BIBLIOGRAPHY

1. R. C. Martenelli, D. B. Nelson, "Prediction of Pressure Drop During Forced-Circulation Boiling of Water," Trans ASME, 70, 695-702 (1948).
2. D. H. Weiss, "Pressure Drop in Two-Phase Flow," ANL-4916, October 20, 1952.
3. W. H. Jens, P. A. Lottes, "Analysis of Heat Transfer, Burnout, Pressure Drop and Density Data for High-Pressure Water," ANL-4627, May 1, 1951.
4. G. Leppert, "Two-Phase Pressure Drop." Unpublished Ph.D. dissertation, Illinois Institute of Technology, 1953.
5. W. H. McAdams, J. M. Addoms, W. E. Kennel, "Heat Transfer at High Rates to Water with Surface Boiling," ANL-4268, December, 1948.
6. H. Buchberg, R. Bromberg, "Final Report on Studies in Boiling Heat Transfer," University of California, COO-24, March, 1951.
7. L. F. Moody, "Friction Factors for Pipe Flow," Trans. ASME 66, 671-684 (1944).
8. H. P. Grace, C. E. Lapple, "Discharge Coefficients of Small-Diameter Orifices and Flow Nozzles," Trans. ASME 73, 639-647, (1951).
9. W. H. McAdams, "Heat Transmission," (1st ed.; New York: McGraw Hill Book Co. Inc., 1933), p. 169.

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