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LONG TUBE HEAT EXCHANGER
THE FACILITY AND SOME PRELIMINARY TESTS ON THE
DOWN CENTER/UP ANNULAR FLOW CONFIGURATION*

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ABSTRACT

A test facility was designed and constructed to study forced flow boiling heat transfer in a closed loop long tube heat exchanger which is a two concentric-tube vertical design. The system consists of a 12 m long heat exchanger which can be operated at pressures to 689.3 kPa with pumped or natural convection flow rates from 0.0631 to 0.631 liters/second and which can be irradiated with a maximum steady heat flux rate of 50 kW/m² by a set of resistive heaters operable at temperatures up to 1250°C. The facility was also designed so that other heat exchanger configurations can be tested with minimum difficulty (i.e., little or no modification of the system other than to replace the heat exchanger). The preliminary tests indicate that the system can be operated in a stable mode. This facility was motivated primarily by the magma energy research program where energy is extracted from magma by heat exchangers similar to the configuration in this report.

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LONG TUBE HEAT EXCHANGER
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I. INTRODUCTION

The technical feasibility of extracting energy from large bodies of molten rock (magma) buried at moderate depths (2 to 10 km) below the earth's surface is currently under investigation.¹ Any proposed energy extraction method must have the capability of coping with high energy-density fields (at least initially). A downhole heat exchanger with water as the working fluid is one concept that is being studied.

Predictions for such a heat exchanger are difficult because of the complexity of the many two-phase flow patterns which potentially could occur as the quality of the vapor-liquid mixture increases during vaporization. This process is further complicated by the variation in the hydrostatic head as one goes from the top to the bottom of the long tube heat exchanger (LTHE). This hydrostatic head variation causes the saturation temperature of the fluid in the heat exchanger to vary which could cause instabilities to occur, thus promoting film boiling.

Thus, in order to begin the study of the very complex heat transfer and flow in a long tube, downhole heat exchanger, a test facility which is much shorter than 2-10 km has been designed and built. This facility has been designed to provide:

- (a) instrumentation so that local film boiling and flow instabilities can be detected;
- (b) controls so that the significant heat exchanger operating parameters such as surface heat rate, flow rate, and system pressure can be varied to characterize the film boiling and flow instability regimes;
- (c) a capability for easily changing the heat exchanger design so that various designs can be tested;
- (d) initial operating experience for these heat exchanger systems so that insight can be gained for the design of the much longer heat exchanger system required for magma energy extraction.

The data obtained from the experiments conducted in this facility can be used to evaluate various heat exchanger designs. In addition, it could aid in the mathematical modeling and correlation of data so that the "best" design can be chosen for an experiment in which a heat exchanger could be placed into a molten lava lake at much shallower depths. The experiments should also extend the present knowledge of forced convection gas-liquid, two-phase heat transfer to include the effects of hydrostatic head. Finally, the facility could be used as a test facility for other geothermal energy extraction systems and large vertical solar central receivers² now being developed. Also, single-pass boilers (working fluid goes from subcooled* liquid to a super heated vapor in one pass) are being studied for nuclear and fossil-fueled power plants.³

This report provides a description of the LTHE facility and its operation. A brief description of the early "shake-down" tests is given for the facility with a given heat exchanger configuration. Based on these initial tests, recommendations are made for modifying the facility and for additional instrumentation requirements for the actual heat exchanger configuration tested. In addition, the expected results and benefits of a more extensive test program with the facility are discussed.

II. FACILITY DESCRIPTION

The LTHE facility (Fig. 1) consists of a 1 meter diameter by 12 meter deep hole into which the long tube heat exchanger, its associated instrumentation, and the electrical resistance heaters are placed. A steam separator, a sump to supply make-up water, air-cooled condensers, a power controller system, and a data acquisition system are located above-ground adjacent to the LTHE. Water is circulated through the long tube heat exchanger and, depending upon the flow rate and heater settings,

*In the boiling heat transfer literature, "subcooled" means below the saturation temperature. That is the definition used herein.

Figure 1
Schematic of Long Tube Heat Exchanger
Test Facility

either hot water, a steam/water mixture, or superheated steam is produced. The heated fluid next goes into the steam separator, to the vertical airflow condensers, and finally to the sump barrel. This water is pumped by the constant displacement pump into the long tube heat exchanger. The flow rate is controlled by a bypass line which recirculates water not pumped into the heat exchanger through the condenser system. If desired, the steam from the steam separator can be expanded through a vane turbine to produce electricity. The vane turbine is described in detail by Fewell and Montoya.⁴ Provision was made for bypassing the circulating pump in order to perform thermosiphon (self-pumping) experiments. The system will operate at pressures to 689.3 kPa with pumped or natural convection flow rates from 0.0631 to 0.631 liters/second. The condensers can also be bypassed in order to bring the system up to a desired steady-state temperature level in a short period of time.

The basic long tube heat exchanger is a counterflow design consisting of two concentric tubes. Cold water flows down the inner tube and then returns up the annulus between the inner and outer tube. Resistive heaters provide radiant thermal input to the external surface of the outer tube.

The outer tube is a 10.2 cm diameter by 12 m long, schedule 40, type 316 LC stainless steel pipe coated with Tempilac paint,* having an emissivity of 0.99 at the temperature range of operation. The inner tube of the basic design is a 2.5 cm, schedule 40, carbon steel pipe. This tube can easily be interchanged with tubes of other sizes or design. By changing the inner tube, the entire design of the heat exchanger can be modified. For instance, the inner tube could be made larger which would change the flow area of the annulus. Also, an insulated inner tube or a tube with swirl vanes or a helical ribbon attached to its outer surface could be inserted. A swirl flow would separate the water droplets from the steam

*A high emissivity, high temperature capability thermal coating.

and tend to maintain a liquid layer on the hot inner surface of the outer tube. This would retard the onset of film boiling in the heat exchanger. Other designs such as placing holes along the inner tube to allow water to flow into the annulus at various depths can also be tested. The system is designed so that the effect of reversing the direction of flow in the heat exchanger (cold water down the annulus and hot water/steam up through the inner tube) to the steam separator can also be examined.

The resistive heaters surrounding the outer tube were designed specifically for this facility and were built by Lindberg, a division of Sola Basic. The individual heaters are 1.52 m (5 feet) in length of which 1.47 m is heated length. They are capable of producing approximately 16.45 kW/m (length) at temperatures up to 1250°C.* For the geometry of this system, this results in maximum steady heat flux rates of 50 kW/m². For short periods of time, flux rates 2 to 3 times that value may be possible. There is a 2.5 cm long vestibule with a 12.7 cm diameter hole on both ends of each heater. The vestibules serve to center the heaters around the heat exchanger and also reduce convection effects along the length of LTHE. The heating coils are surrounded by Fiberfrax insulation and enclosed in aluminum cans with an outside diameter of 27.3 cm. The inside diameter of the heaters is 17.8 cm. Seven of the individual heaters are required to heat the entire length of the LTHE. The heaters are supported by rods suspended from the top of the heat exchanger. It should be noted that requirements for assembly, space for instrumentation, and the unheated portion of each heater constitutes a total unheated length of 12.7 cm between each of the heaters. The entire assembly can be seen in Fig. 2 prior to being placed in the ground.

The heaters are controlled at the desired power setting by Model 646 Phasers manufactured by Research Incorporated.

*The heating coils are 1 gauge Kanthal-A1 and each heater is rated for 24 kW at 100 amps and 240 volts.

Figure 2

Long Tube Heat Exchanger During Assembly

Each controller is nominally rated for 0-100 amps at 480 volts. They were modified to provide a power feedback circuit from true RMS voltage, current, and power transducers. The bottom heater is individually controlled while the remaining six heaters are controlled in pairs (wired in series) resulting in a total of four controllers. Each controller is independent which allows the capability of varying the flux distribution along the length of the LTHE.

Figure 3 shows the assembled LTHE in the hole. Also seen in the figure is the air blower used for cooling the electrical power lines to the heaters. The area immediately adjacent to the hole is covered with a weather-tight enclosure to protect the heaters. An overall view of the LTHE facility is shown in Fig. 4.

III. INSTRUMENTATION

Heat transfer instrumentation consists of 42 thermocouples. Temperatures are measured at mid-annulus, the outer surface of the center pipe, the outer wall of the heat exchanger, the heater element, the outer can of the heater element, and in the air outside the heater can. These six temperature measurements are made at seven different elevations located at the mid-point of each of the furnace elements. The station locations are given in Table I and shown schematically at a typical heater length in Figure 5.

In addition to the temperature measurements in Table I, thermocouples and pressure transducers were used to monitor the temperature and pressure at the following locations.

1. Inlet to the LTHE
2. Bottom of the LTHE (this pressure transducer was lost before any test data were taken)
3. Outlet of the LTHE
4. Pump inlet
5. Pump outlet
6. Enthalpy tap

Figure 3

Assembled Long Tube Heat Exchanger

Figure 4

Overall View of the Long Tube Heat Exchanger Facility

● Thermocouple Locations

Figure 5
Schematic of the Instrumentation

TABLE I - THERMOCOUPLE STATION LOCATIONS

<u>Station</u>	<u>Elevation (m)</u>
Bottom of hole	-12.2
Bottom of LTHE	-10.67
1	- 9.91
2	- 8.38
3	- 6.86
4	- 5.34
5	- 3.81
6	- 2.29
7	- 0.76
Ground Level	0.0

The enthalpy tap consists of a valve near the outlet of the LTHE which samples the fluid flow and runs the sample through a cooling coil immersed in a container of water. The sample empties into the same container. By measuring the temperature increase and mass increase in the container, the energy available (hence quality) can be readily determined. A throttling calorimeter is also located at the LTHE outlet. This device can measure the quality of higher quality steam/water mixtures.

The flow rate is measured by a flow meter upstream of the inlet to the LTHE. In addition, three threshold flow sensors rated at 0.032, 0.126, and 0.252 liters/second, respectively, were placed in the flow line. These devices indicate whether or not threshold flow rates (their rated value) are maintained. This allows the flow rate to be monitored at a remote location and provides a safety mechanism to make certain the flow rate remains above a certain level.

Acoustical transducers are located on the outer pipe of the LTHE at the midpoint of the space between the heaters.

These transducers were used in an attempt to determine the location of the onset of nucleate boiling.

The data from the various transducers are recorded on a Hewlett-Packard, Model 2010-J, data logger. It can handle up to 95 channels of data and records either on magnetic tape, printed paper tape, or both.

IV. PRELIMINARY TESTS

The primary purpose of these tests was to gain experience operating the facility and to check out the instrumentation and data recording equipment. The tests were conducted for a variety of conditions. Flow rates ranged from 0.0631 to 0.5678 l/s, power input from 5 to 23.4 kW/heater, and inlet pressure from 190.2 to 459.1 kPa. A summary of the run conditions for the first 13 tests is shown in Table II. The outlet conditions varied from 100% liquid (hot water) to superheated steam.

During these shakedown tests most of the instrumentation and recording equipment functioned as designed. Figure 6 shows typical measurements of the fluid temperature in the annular region. Several interesting features show up in these results. For the pure liquid case (run no. 10), the fluid increases monotonically in temperature as it moves up the annulus, as expected. However, for the low quality steam output (run no. 9) the fluid rises to a maximum temperature and then cools as it flows further up the annulus. This result, unexpected initially, is apparently the result of the cold water feed pipe (downcomer) extracting more energy from the flow at the inside wall (due to very efficient condensation heat transfer) than the heaters are able to put into the fluid at the outside wall. The very flat profile from run no. 7 which produced superheated steam would indicate that saturated conditions existed nearly all the way up the annulus and that there was very little pressure differential from the bottom to the top of the LTBE. The reason the outlet temperature in this run is below that of run no. 9 is due to a lower outlet pressure. The

Figure 6

Fluid Temperatures in the Annulus (Upflow) for Runs Nos. 10 (no steam generated), 9 (low quality steam generated), and 7 (superheated steam generated).

TABLE II - RUN CONDITIONS

<u>Run No.</u>	<u>Power (kW/heater)</u>	<u>Flow Rate (ℓ/s)</u>	<u>Inlet Pressure (kPa)</u>	<u>Outlet Pressure (kPa)</u>
1	23.4	0.1891	224.7	276.4
2	15	0.1891	224.7	245.4
3	23.4	0.1262	238.5	293.6
4	23.4	0.1891	459.1	514.2
5	15	0.1891	428.0	441.8
6	10	0.1891	197.1	204.0
7	23.4	0.0631	231.6	252.3
8	20	0.1891	561.8	472.9
9	20	0.1891	252.3	290.2
10	10	0.3785	238.5	231.6
11	5	0.1891	190.2	204.0
12	23.4	0.5678	217.8	210.9
13	15	0.5678	210.9	210.9

flat profile also implies that in this configuration the system will not allow any appreciable superheat to be developed, again due to the condensation cooling effect of the cold downcomer.

Figure 7 shows the outside pipe wall temperature for the same three tests. The fact that the wall temperature in runs 9 and 10 are well above the fluid saturation temperature while the fluid is well below its saturation condition indicates that subcooled nucleate boiling is occurring in those regions. In other words, boiling is occurring at the wall but the vapor bubbles will collapse immediately upon breaking away from the wall, since the bulk fluid temperature is below its boiling point. The unusual behavior of the wall temperature for run no. 9 is likely due to steam/water mixture cooling the outer wall as it in turn is cooled by the downcomer. The very high wall temperature near the top of the LTBE for run no. 7 demonstrates clearly that a "liquid deficient" flow

Figure 7

Outside Wall Temperatures for Run Nos. 10, 9 and 7.

(also called dryout) existed at this location. If this condition were allowed to exist in any high energy-density extraction system, the consequences to the heat exchanger could be catastrophic.

Because this is primarily a facility report, more detailed data from these and other tests on this particular LTBE configuration and a discussion of results are included in Appendix A.

The acoustic transducers were designed to detect the onset of nucleate boiling. However, the data output from these devices does not appear to yield the desired results. Samples of the data are discussed in Appendix B, but it appears that the information gained from this instrumentation will be marginally useful at best.

V. CONCLUSIONS AND RECOMMENDATIONS

The LTBE facility is now operational and can be used to test various heat exchanger design concepts operating in forced flow boiling conditions with up to a 190.2 kPa (35 ft. of water) hydrostatic pressure variation. The system can be operated with stable flow conditions over a range of water flow rates from 0.0631 to 0.631 liters/second with heat flux rates from 0 to 50 kW/m². The heat exchanger outlet conditions can vary from 100 percent liquid to superheated steam. The existing instrumentation is sufficient to determine the bulk (average) operating characteristics and conditions, but cannot detect local flow variations or temperature distributions.

The facility could be improved considerably by making a few modifications, primarily in the instrumentation.

1. The enthalpy tap should be relocated to obtain a more representative sample of the outlet flow mixture.
2. Additional thermocouples are needed.
 - a) Thermocouples should be located at closer intervals (on the order of one foot apart) than the

present five-foot spacing along the LTHE. This is particularly essential in the annular flow region for better resolution of the vertical temperature profile.

- b) Thermocouple rakes should be placed in the annulus in order to obtain a better temperature profile in the flow than the present mid-annulus thermocouple. This would allow more accurate determination of the bulk fluid temperature and, hence, more accurate determination of heat transfer coefficients. Thermocouple rakes could also give an idea of whether separated flow is occurring, i.e., regions of vapor flow next to the outer wall and region of liquid flow mid-annulus and next to center wall, as possibly in the case of run no. 7. This would be very important in the prevention of tube burnout. A minimum of one such rake is needed near the LTHE outlet.
 - c) Thermocouples should be added to the downcomer to determine temperatures of the downcoming fluid along the length of the downcomer. This would give information on the relative amount of condensation taking place along the downcomer and its effect on the upcomer flow conditions.
- 3. A better means of measuring the temperature of the heater coils is needed to allow accurate determination of the axial heat flux variation along the LTHE. The existing instrumentation gave measurements that were erratic and nonreproducible.
 - 4. Pressure taps should be placed at various locations along the length of the LTHE. This would aid in the determination of the saturation temperature in a much more accurate way than that used in the present experiments. In addition, these could give an indication of the flow regimes existing in the upcomer.

5. It is recommended that the acoustic transducers not be used in this facility since, in this application, there needs to be further developmental effort.

A variety of specific tests can be recommended to obtain a fundamental understanding of forced flow boiling heat transfer under a pressure variation, and its particular application to the magma energy extraction program. Due to the very pronounced cooling effect of the downcomer, tests should be conducted with an insulated inner pipe. A carefully controlled parametric variation of flow rates, thermal flux rates, and pressure should be performed. A swirl flow annular condition should be investigated to evaluate the ability of such a system to delay dryout with its attendant problems.

The initial operation of this facility indicates that a closed-loop long tube heat exchanger concept is a technically feasible method of energy extraction from high energy-density fields. Whether or not it is also practical and economical must be determined by further study.

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APPENDIX A

Discussion of the Temperature Data

Nomenclature

A	heat transfer area
C_p	specific heat
h	convection coefficient
Δh	change in enthalpy
k	thermal conductivity
L	length
l/s	liters/second
$\dot{m}$	mass flow rate
Q	energy input rate
Q_{DC}	energy input rate to downcomer
r_i	inner radius
r_o	outer radius
T_B	bottom temperature
T_f	mid-annulus fluid temperature
T_{in}	inlet temperature
T_{iw}	inner pipe wall temperature
T_{out}	outlet temperature
ΔT_{Bin}	$T_B - T_{in}$
ΔT_{ow}	temperature drop through pipe wall
T_{sat}	saturation temperature of fluid
x	quality
η	calorimetric efficiency

Thirteen preliminary tests were conducted. The operating conditions for these tests are given in Table II. These runs can be subdivided into the following groups:

Group I (no steam generated): run nos. 5, 6, 10, 11, 12, 13

Group II (steam generated): run nos. 1, 2, 3, 4, 8, 9

Group III (dryout--wall temperature exceeds Leidenfrost temperature): run no. 7

A. Efficiency

The calorimetric efficiencies are given in Table A-I. Calorimetric efficiencies for Group I are calculated with the following:

$$\eta = \frac{\text{Energy Input Rate}}{\text{Total Power}} = \frac{\dot{m} C_p (T_{\text{out}} - T_{\text{in}})}{\text{Total Power}},$$

where $\dot{m}$ is the flow rate and T_{in} and T_{out} are the inlet temperature and outlet temperature, respectively.

The efficiencies for Group II were obtained from the enthalpy tap. An enthalpy tap takes a known quantity of the exiting low quality water/steam mixture and mixes it with a known quantity of water at a known initial temperature. The temperature of the final mixture is measured; thus, the difference in energy of the initial mixture and final mixture is known. Thus, the efficiencies for Group II are calculated in the following manner:

$$\eta = \frac{\Delta h (\dot{m})}{\text{Total Power}}$$

The efficiencies obtained in this manner will be lower bound numbers due to the location of the enthalpy tap in relation to the exit from the LTBE and due to the fact that the connecting pipe was not insulated for these tests. The Δh , change in enthalpy, for these tests indicate qualities of the exiting water/steam mixture to be on the order of 2%. This quality change in the fluid represents a 15-20% change in volume flow rate, however.

B. Temperature Drop Through Outer Pipe

Temperature drops through the outer pipe wall are calculated using the actual power input by the following relation:

$$\Delta T_{ow} = \frac{Q}{2\pi kL} \ln \frac{r_o}{r_i} .$$

These temperature drops are also given in Table A-I.

C. Energy Into the Downcomer

The transfer of energy into the downcomer from the annulus particularly in the runs of Group II is surprisingly high. Temperatures at the bottom of the LTBE were measured as the fluid exits from the downcomer. These are presented in Table A-II along with the inlet temperatures to the downcomer. The energy into the downcomer is then calculated by:

$$Q_{DC} = \dot{m} C_p \Delta T_{Bin} .$$

TABLE A-I EFFICIENCIES AND TEMPERATURE DROP

<u>Run</u>	<u>Cal. Eff. (%)</u>	<u>Actual Power Input/Heater (kW)</u>	<u>ΔT_{ow} (K)</u>	<u>Actual Power Input Total (kW)</u>
Group I				
5	79	11.9	7.6	83.30
6	69	6.9	4.8	48.30
10	76	7.6	5.3	53.20
11	70	3.5	2.4	24.50
12	95	22.2	14.2	155.40
13	81	12.2	8.4	85.40
Group II				
1	61	14.3	8.4	100.10
2	--	--	--	--
3	56	13.1	8.0	91.70
4	57	13.3	8.1	93.10
8	72	14.4	10.1	100.80
9	71	14.2	9.9	99.4
Group III				
7	--	--	--	--

The percentage of the actual input energy going into the downcomer is also given in Table A-III. Because of the previously mentioned problem with the enthalpy tap measurements, the percentages for the runs of Group II represent an upper bound on this energy transfer.

TABLE A-II DOWNCOMER TEMPERATURE DIFFERENCE

<u>Run</u>	<u>T_B</u> <u>(K)</u>	<u>T_{in}</u> <u>(K)</u>	<u>ΔT_{Bin}</u> <u>(K)</u>
Group I			
5	363.3	292.2	71.1
6	321.1	287.4	33.7
10	295.8	288.8	7.0
11	294.8	284.1	10.7
12	310.3	294.9	15.3
13	297.3	291.7	5.6
Group II			
1	397.3	298.9	98.4
2	393.8	294.9	98.9
3	404.4	308.3	96.1
4	419.1	306.7	112.4
8	416.5	302.9	113.6
9	398.1	303.1	95.0
Group III			
7	404.0	303.4	100.6

TABLE A-III ENERGY RATE TO DOWNCOMER

<u>Run</u>	<u>Input (kW)</u>	<u>Downcomer (kW)</u>	<u>%</u>
Group I			
5	83.3	56.7	68.0
6	48.3	26.9	55.7
10	53.2	11.2	21.1
11	24.5	8.5	34.7
12	155.4	36.7	23.6
13	85.4	13.3	15.6
Group II			
1	100.1	78.5	78.4
2	--	78.8	--
3	91.7	51.1	55.7
4	93.1	89.6	96.2
8	100.8	90.6	89.9
9	99.4	75.7	76.2
Group III			
7	--	26.7	--

D. Group I Experiments

This group consists of those experiments where only water was present at the exit of the LTHE. There are three subdivisions in this group. They are:

1. heating of subcooled water--runs 10 and 11 (Figures A-1 and A-2, respectively).

Figure A-1

Temperature Profiles for Run 10--10 kW/heater, 0.3785 l/s, and 231.6 kPa outlet pressure

Figure A-2

Temperature Profiles for Run 11-5kW/heater, 0.1891 l/s, and 204.0 kPa outlet pressure

Figure A-3
Temperature Profiles for Run 6--10 kW/heater, 0.1891 l/s, and 204.0 kPa outlet pressure

Figure A-4

Temperature Profiles for Run 13--15 kW/heater, 0.5678 l/s, and 210.9 kPa outlet pressure

Figure A-5

Temperature Profiles for Run 5--15 kW/heater, 0.1891 l/s and 441.8 kPa outlet pressure

Figure A-6

Temperature Profiles for Run 12--23.4 kW/heater, 0.5678 ℓ/s , and 210.9 kPa outlet pressure

2. heating of subcooled water with subcooled boiling just beginning at the top of the LTHE--runs 6 and 13 (Figures A-3 and A-4, respectively).
3. heating of subcooled water with subcooled boiling beginning near the bottom of the LTHE--runs 5 and 12 (Figures A-5 and A-6, respectively).

The saturation temperature is plotted on all of these figures and those following. The plot is based on the outlet pressure at the top of the LTHE which increases due to hydrostatic head as the elevation down the tube is decreased. In category 1, the temperature corrected to the inside wall (given by the dashed lines in the figures) is below the saturation temperature curve. In category 2, the inside wall temperature just intersects the saturation temperature curve at the top of the LTHE. In category 3, the inside wall temperature is above the saturation temperature. In all of these cases, however, the fluid temperature is much below the saturation curve. Thus, for the cases where the wall temperature is above the saturation curve, subcooled boiling could occur, i.e., boiling occurs due to the high wall temperature but as the bubbles break away from the wall, the fluid is cold enough to cause bubble condensation to occur. Note also that there is a change in the slope of the fluid temperature curve as the fluid rises in the upcomer. This is the result of the cold fluid in the downcomer. The outer temperature of the decrease toward the bottom of the LTHE. This occurs since cold fluid exiting at the bottom of the downcomer is heated as it travels upward and then is cooled in the upper part of the upcomer due to the cold fluid in the downcomer in that region.

E. Group II Experiments

This group of experiments produced low quality steam at the exit of the LTBE. The subcooled fluid enters the bottom of the annulus, is brought up to saturated conditions and then starts to boil as it travels up the annulus. As the cold fluid comes down the inner tube it causes a cooling effect on the fluid in the upcomer. This cooling effect could cause the steam in the steam/water mixture to condense on the downcomer. Because of the decrease in saturation temperature with the increase in elevation it is possible for the steam/water mixture in the upcomer to reach a maximum temperature and then start to decrease as the fluid travels upward.

The test data from this group of tests show some scatter about the saturation line. Those points below the saturation line are physically possible while those above the line would require a jump into the superheat region as soon as the fluid reached the saturated liquid point. This indicates that extrapolating the saturation pressure based on the outlet pressure and the hydrostatic head is only approximate. Note, however, that the general trend of the fluid temperature is parallel to the saturation temperature curves. These are illustrated in Figures A-7 through A-12, which are plots of the data from the runs of Group II. These runs also indicate that the fluid is experiencing subcooled boiling at the bottom since the wall temperatures for these runs are well above the saturation temperature at this point.

Figure A-7
Temperature Profiles for Run 1--23.4 kW/heater, 0.1891 l/s, and 276.4 kPa outlet pressure

Figure A-8

Temperature Profiles for Run 2--15 kW/heater, 0.1891 ℓ/s , and 245.4 kPa outlet pressure

Figure A-9

Temperature Profiles for Run 3--23.4 kW/heater, 0.1262 l/s, and 293.6 kPa outlet pressure

Figure A-10

Temperature Profiles for Run 4--23.4 kW/heater, 0.1891 ℓ/s , and 514.2 kPa outlet pressure

Figure A-11

Temperature Profiles for Run 8--20 kW/heater, 0.3785 l/s, and 472.9 kPa outlet pressure

Figure A-12

Temperature Profiles for Run 9--20 kW/heater, 0.1891 l/s, and 290.2 kPa outlet pressure

Figure A-13

Temperature Profiles for Run 7--23.4 kW/heater, 0.0631 l/s, and 252.3 kPa outlet pressure

F. Group III Experiment

This experiment (run no. 7) underwent dryout at the wall near the exit of the LTBE since a temperature excursion occurred here and reached approximately 811 K. Dryout occurs when the inner wall temperature exceeds the Leidenfrost temperature of the liquid at that point. A temperature record of the system at this particular time is given in Fig. A-13.

G. Determination of Steady-State in the System

Whether the system is at steady state is determined by examining the fluctuation in temperatures at the various stations along the LTBE. Typical illustration of the systems in steady-state condition is given in Fig. A-14. This figure shows the temperature history of Station 7 and the outlet fluid temperature for run no. 3. Note that the temperature fluctuations are small; thus, for all practical purposes this system is in steady-state operation.

Figure A-15, however, illustrates a situation where the system is undergoing severe fluctuations. Given in this figure is the temperature at Station 7 and the outlet fluid temperature for run no. 7. Recall that this run experienced dryout at the wall toward the top of the LTBE. Dryout is known to occur since the temperature of the wall rose indicating a drastic decrease in heat transfer which is indicative of heat transfer to a vapor. During this run the system was also very noisy (acoustical) which probably indicates that some instabilities are taking place. It's interesting to note that the fluid temperature in this run has very little fluctuation during the time that the pipe wall temperature is going up.

Figure A-14

Illustration of Temperature History of a System at Steady State Operation

Figure A-15

Illustration of Temperature History of a System Undergoing Severe Fluctuations

This would also indicate that at mid-annulus the fluid still consists of a large quantity of liquid, possibly again due to the cold downcomer. The thickness of the vapor layer cannot be determined by the existing instrumentation. Thus, in this case, just examining the fluid temperature would not give an accurate assessment of the events taking place. Unless the wall temperature was monitored, burnout could very likely take place. Note also that the outlet temperature does not fluctuate much but that it is about the fluid temperature at Station 7. This would indicate that the fluid at the station is probably at high quality. This is indeed the case since dry steam existed at the exit.

H. Convection Heat Transfer Coefficients

Convection heat transfer coefficients are defined in the following manner:

$$h = \frac{Q}{A(T_{iw} - T_f)} , \text{ for subcooled fluids}$$

and

$$h = \frac{Q}{A(T_{iw} - T_{sat})} , \text{ for saturated fluids}$$

where T_{iw} is the temperature corrected to the inside wall of the tube. Figure A-16 gives the heat transfer coefficients for the Group I experiments. These were calculated from the first equation above. Figure A-17 gives the heat transfer coefficients for the Group II experiments. Since the exact T_{sat} is not known for the experiments because the exact local pressures are not known, T_f is also used to calculate these

Figure A-16

Heat Transfer Coefficients for Group I Experiments

Figure A-17
Heat Transfer Coefficients for Group II Experiments

heat transfer coefficients. The values of the heat transfer coefficients for these two groups are very close to one another since Group I is subcooled and Group II, while vaporization is occurring, is very low in quality.

The heat transfer coefficients for Group I are probably closer to the true value than are those of Group II. This is because the bulk fluid temperature is probably close to that measured by the annulus thermocouple in Group I. For Group II, however, the bulk temperature would probably be higher than that obtained from the annulus thermocouple measurement. This is illustrated by the annular temperature profiles given in Figure A-18 for runs 1 and 5. A thermocouple rake across the annulus would give a much better definition of the true bulk temperature of the fluid in the annulus.

Figure A-18

Comparison of Typical Annular Temperature Profiles Between Group I and II

APPENDIX B

Discussion of Acoustic Transducer Data

Numerals Denote Transducer Number

Figure B-1

Acoustical Transducer Signals for Run 3

Figure B-2

Computer Interpretation of Boiling Sites in Run 3

The acoustic transducers are designed for detection of the location of first nucleate boiling. Once this has happened, they are supposed to become relatively useless since they would be swamped by the signal coming from the upper parts of the LTBE. In addition, if subcooled boiling occurs before saturated nucleate boiling takes place, interpretation of the transducer signals could be confusing.

Figure B-1 gives the signal obtained for run no. 3. The transducers are numbered "1" at the top to "8" at the bottom of the LTBE. The jaggedness of the signals indicate that some form of boiling is taking place in the vicinity of transducers #1 through #7. Number 8 is quiet, which is as it should be, since cold water exits from the downcomer at this point. Transducer #5 appears to be malfunctioning.

When these signals are unfolded through the computer program written for this purpose, a result such as that given in Figure B-2 is obtained. This indicates that most of the activity is occurring close to the top of the tube. It may be that subcooled boiling is filtered out by this process and that nucleate boiling is dominant in signal amplitude. Figure A-9, the temperature record for this run, could also be interpreted in this manner, in subcooled boiling up to about the two uppermost thermocouple stations where saturated nucleate boiling probably starts. The fact that transducer #5 may be malfunctioning, however, could invalidate any interpretation of Figure B-2.

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