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Third Quarterly Progress Report for
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LOW HEAT-FLUX BOILING

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ABSTRACT

This report deals with progress made in the design and construction of an experimental system to study boiling of water from the outer surface of tubes at low values of heat flux (from 5,000 to 100,000 Btu/hr ft^2) and pressures up to 2,000 psia for both natural and forced convection.

The revised flow diagram is included. There is a discussion of the status of the main test vessel, primary flow loop, purification loop, and pressure control system.

The calibration of the thermocouples will be done in a constant-temperature block which will be held at a known temperature to ± 0.001°F. The design of this block is described.

I. INTRODUCTION

This is the third quarterly progress report of The University of Michigan under Contract No. AT(38-1)-260 of the U.S. Atomic Energy Commission, Savannah River Operations Office. It covers the period January 1, 1962, to April 1, 1962.

The first two quarterly reports[1,2] included initial design work, but were mainly devoted to a comprehensive literature survey pertaining to low heat-flux boiling. The survey will be extended in a later report to cover recent and newly discovered references.

This quarterly report is concerned with progress made in the design and fabrication of experimental equipment necessary to conduct tests of low heat-flux boiling.

II. EXPERIMENTAL APPARATUS

A. GENERAL

The general schematic arrangement of the experimental equipment is shown in Fig. 1, the flowsheet. The equipment consists of a test vessel into which may be inserted either a vertical or horizontal test section. The system is designed to permit pool boiling or forced-circulation studies of water, nearly saturated, at pressures of 500 psia to 2000 psia. The primary area of interest centers on low heat-flux boiling in the range of 5,000 to 100,000 Btu/hr ft^2. This boiling takes place on the outside of a heated test section consisting of a 3/4-in. (o.d.) by 0.049-in. wall tube. The tube is heated electrically by direct current resistance heating caused by a current which passes axially along the tube.

In order to maintain specified conditions of pressure, water purity, and flow velocity, auxiliary equipment external to the test vessel is required. This auxiliary equipment is described in separate sections. Throughout this section on Experimental Apparatus, all numbers in parentheses refer to the item number in Fig. 1.

B. TEST VESSEL

The design of the test vessel (1) was completed during the quarter and placed on order with the Taylor Engineering Corp., Detroit, Mich. The vessel is shown on Fig. 2. The principal test chamber consists of a cylindrical cavity 10.75 in. in diameter and 36 in. long. The test section (2) is supported between flanges N and Q for horizontal tests and between flanges A and CC for vertical tests. Visual observations of the bubble formation on the test section is permitted by three sight glasses, O, P, and R, which are located around the periphery of the test chamber at the same level as the test section. These sight glasses are 1-1/2 in. in diameter; they are manufactured by PresSure Products and will permit the use of back lighting or oblique front lighting. They were placed on order during the quarter.

The test vessel has threaded connections for the insertion of 12 immersion heaters of an 8.1-KW total rating. These heaters will provide means for the initial heating of the vessel and water, and means also for generating excess steam for pressure-control bleed. The heaters were ordered from Watlow Electric Mfg. Co. during the quarter. The vessel also has connections for the upper and lower liquid-level legs, low-level shutoff switch, and thermocouple probes. After erection in the laboratory, the entire vessel will be insulated to reduce power consumption and maintain a nearly isothermal system.

The water from the test vessel is conducted to the main circulation loop by a 4-in. pipe, with the offtake located 11 in. above the test section. The return from the loop is through a 3-in. connection at the lower end of a 73-in.-long section of 6-in. pipe protruding downward from the principal test chamber. This long length of 6-in. pipe is necessary to provide a uniform velocity profile, as the flow approaches the test section. The vessel will be fitted with a baffle to effectively close off the 6-in. pipe from the principal chamber during pool boiling studies.

The entire test vessel is made of type 347 stainless steel in order to minimize the formation of corrosion products which would contaminate the water. The vessel is designed to the A.S.M.E. Pressure Vessel Code, Section VIII, for a rating of 2000 psia and 635°F.

C. TEST SECTION

The test section (2) consists of a 6-in. length of 3/4-in. (o.d.) tubing, with an 18 gage (.049-in.) wall thickness. Tube materials will be Monel, Inconel, and carbon steel. The design of the test section was discussed in the earlier progress reports,[1,2] and remains unchanged. The test section will be assembled with 12 thermocouples in place against the inner wall. The assembly will then be calibrated as described in Section III of this report.

D. PRIMARY FLOW LOOP

The primary flow loop (4) consists of a 4-in., schedule 80 stainless steel pipe leading from the test vessel to a Melrath canned rotor circulating pump (3). This pump delivers 140 gpm against a head of 40 ft. After leaving the pump, the flow is directed through a straight 60-in. length of 3-in., schedule 80 stainless steel pipe leading into the orifice meter. The pressure differential across the orifice is measured by a Minneapolis-Honeywell differential pressure indicator (34). The quantity of water circulated, and hence the velocity of the water past the test section, is manually regulated by a Powell valve (5). After the water leaves the throttling valve, the water temperature is raised to near saturation by an infinitely variable heater (6). The heater consists of 6 Watlow immersion elements whose total rating is 18.2 KW. The temperature of the water after leaving the heater is monitored by a thermocouple inserted into the center of the stream and encased in a stainless steel sheath. The flow then returns to the bottom of the test vessel.

During this quarter the main circulating pump, the immersion heaters, and the entire piping loop were placed on order. The loop order includes all the required material and fabrication except for the differential pressure indicator, which was ordered separately. The piping loop thermal expansion was analyzed and spring hangers were ordered; the latter will provide the flexible but non-restraining support required.

E. WATER-PURIFICATION LOOP

The water will be continuously purified by the circulation of one gallon per minute through the purification or de-ionizing loop. This flow is caused by the main circulating pump (3) or by the A.E.C. furnished auxiliary pump (11). The water to be purified is cooled from the main-loop temperature of about 500-600°F in a countercurrent heat exchanger (12). It is further cooled by heat exchange with city water to less than 100°F. The flow will be passed through a laboratory owned ion exchanger (15) employing Rohm and Haas MB-1 Amberlite Resin. This resin removes both anions and cations. Solid particles are filtered out of the stream by porous metal filter elements after it leaves the resin bed. The purified stream is warmed to within 50°F of operating temperature in the heat exchanger (12) and returned to the main flow loop prior to the line heaters.

The electrical conductivity of the water will be measured by an Industrial Instruments electrolytic conductivity cell (17). The pH of the water will be measured by a Leeds and Northrup Model 7401 indicator (18).

F. PRESSURE-CONTROL LOOP

The pressure in the system is determined by the saturation pressure of the boiling water. This is measured by a precision Heise pressure gauge (31) attached to the test vessel. This gauge was ordered and received during the quarter.

The vapor generated by the boiling around the test section and also by the auxiliary electrical immersion heaters passes out of the test vessel into the steam condenser (8). Material for fabrication of the condenser was received during the quarter. The condenser is cooled by a stream of compressed air from the laboratory air supply. The warmed air is vented to the atmosphere after passing through the condenser.

The condenser returns most of the steam to the test vessel as condensate. A small excess amount of steam is generated and the precise pressure is maintained by bleeding this steam from the system by the Research Controls valve (10). This valve is controlled by a Fisher pressure controller (9). The controlling medium is instrument air, supplied by a small filter regulator (29). Shutoff of the electrical heaters by the action of the Barksdale pressure switch (30) prevents dangerous over-pressure. This switch has an adjustable set point from 500 to 2000 psig. The pressure switch will be set at a pressure about 100 psi greater than the pressure being held on the system by the pressure controller. The ultimate safety device is a spring-loaded Farris safety relief valve (7), set at 2000 psig. In the event the safety valve blows, steam is vented to the atmosphere and lost. All of the above items except for the Barksdale switch were received during the quarter.

G. STRUCTURAL FRAMEWORK

The structural framework which will support the test vessel was designed and fabricated during the quarter. This framework has been erected in the laboratory and is ready to receive the vessel. It is positioned over a 4-ft. by 4-ft. hole in the floor. This positioning will permit installation and removal of the 12-ft.-long vertical test sections without any clearance problems.

III. THERMOCOUPLE CALIBRATION

To achieve the greatest precision, thermocouples must be calibrated by comparison with an accurately known temperature in the region of temperatures to be measured. For the subject investigation, temperature measurements will be made between 450°F and 650°F. The only primary fixed points (1948 ITS) near this range are the steam point (212.00°F) and the sulfur point (832.28°F); the secondary fixed points are the tin point (449.42°F), the lead point (621.14°F), and the mercury point (677.44°F). The gaps between these fixed points are quite large.

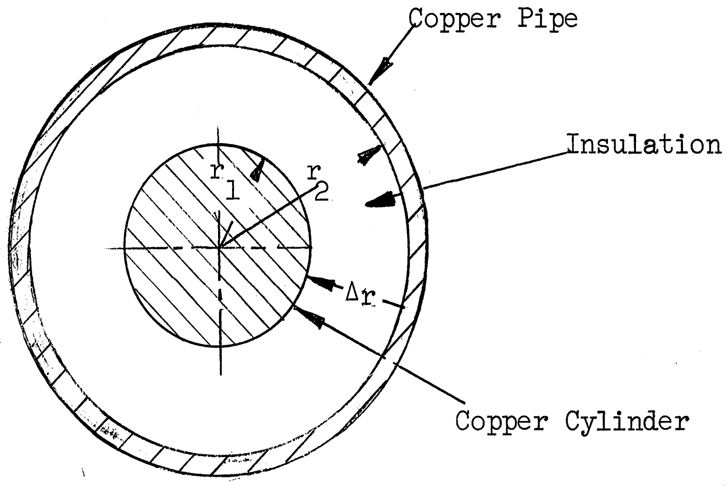
By calibrating a platinum resistance thermometer at the fixed points, thermocouples can be calibrated at intermediate points by comparison with the platinum resistance thermometer. By virtue of its stable temperature-resistance characteristics, the resistance thermometer acts as an interpolation device.

To make the comparison, a reservoir is needed whose temperature can be regulated at a steady value and at the same time be varied to cover the desired range. The wide range of temperatures desired in a single apparatus (ambient to 1000°F) ruled out the use of a thermostated liquid bath. Therefore a solid copper cylinder 6 in. in diameter and 18 in. long was selected as the controlled isothermal medium.

Direct-temperature regulation of this cylinder ±0.1°F would be difficult because the cylinder is a system having a large thermal inertia and there would be a lag in feedback response. Therefore the cylinder is surrounded by but thermally well insulated from another system having a large thermal inertia. This system takes the form of a copper pipe capped at both ends and approximely 11 in. o.d., with a 3/8-in. wall thickness. The configuration is shown in Fig. 3.

The temperature of the outer pipe is permitted to vary periodically by on-off operation of electrical heaters clamped to the outer surface of the pipe. The heaters are in turn activated by an on-off potentiometer-type electronic controller operating from a thermocouple embedded in the pipe. Thus the cyclic variations in the pipe temperature are damped considerably by the time the energy diffuses into the center cylinder.

In order to obtain a quantitative estimate of the dynamic behavior of the system, a simplified analysis was made. The system is represented in the sketch below.



In the analysis the following assumptions are made:

(1) The temperature of the pipe varies sinusoidally. (In reality the temperature most likely will rise and fall linearly.)

(2) The thermal capacity of the insulation need not be considered. (In reality its effect would be to further damp out the oscillations.)

(3) The cylinder can be treated as a lumped system.

(4) End effects can be ignored.

The following nomenclature is used:

C_p - Specific heat of copper cylinder

D - Defined by Equation 4

F - Amplitude of pipe temperature

k_i - Thermal conductivity of insulation

ℓ - Unit length of pipe and cylinder

t_c - Cylinder temperature

t_p - Pipe temperature

t_o - Mean level of cylinder and pipe temperature

$t_x - t_c - t_o$ - Departure of cylinder temperature from mean level

θ - Time

ϕ - Phase angle between pipe and cylinder temperature

ω - Frequency of temperature oscillations

ρ - Density of copper cylinder

Let the equivalent thermal resistance of the insulation be represented by:

$$R_t = \frac{\Delta r}{k_i 2 r_1 \ell \pi} \qquad (1)$$

The pipe temperature is given by:

$$t_p = t_o + F \sin \omega\theta \qquad (2)$$

Applying the First Law of Thermodynamics to the copper cylinder results in:

$$\frac{dt_c}{d\theta} = (t_o - t_c + F \sin \omega\theta)D \qquad (3)$$

Where:

$$D = \frac{2k_i}{(\Delta r)(r_1 \rho C_p)} \qquad (4)$$

Making the transformation $t_x = t_c - t_o$ and solving Equation (3) by the LaPlace transform method results in the following solution:

$$\frac{t_x}{F} = \frac{\sin(\omega\theta - \phi)}{\sqrt{1 + (\frac{\omega}{D})^2}} \qquad (5)$$

Where ϕ is the phase lag given by:

$$\phi = \arctan(\frac{\omega}{D}) \qquad (6)$$

Since only the maximum amplitude of t_x with respect to F is of interest, Equation (5) can be replaced by:

$$\frac{t_x}{F} \doteq \frac{1}{\sqrt{1 + (\frac{\omega}{D})^2}} \tag{7}$$

If the amplitude of the pipe temperature (F) is taken as 1°F, readily obtainable with the available control system, then from Equation 7 the amplitude of the temperature in the cylinder (t_x) will be 0.001°F if $\omega/D = 1000$.

For the physical system D = .0518 radian/hr. then for $\omega/D = 1000$, $\omega = 8.25$ cycles/hr, which is a reasonable value. The frequency in the actual system can be controlled by adjusting the rate of power into the control strip heaters of Fig. 3. As shown in Fig. 3, holes are drilled into the copper cylinder for the insertion of the thermocouples, the platinum resistance thermometer, and the test section. Strip heaters are attached to the cylinder to assist in bringing the cylinder up to the desired temperature level. The cylinder is supported from the pipe by means of chains for thermal isolation. Access to the thermocouple holes is provided by a thin, segmented, stainless steel access tube.

The entire assembly is installed in a modified 55-gallon drum and suspended by means of a series of stainless steel channels, with knife edges to further reduce heat losses. Thermocouples are embedded at a number of points in the cylinder and pipe to check for uniformity of temperature. To prevent deterioration of the copper due to oxidation at the upper temperature limit of 1000°F, the pipe and cylinder have been given a coating of hard chrome.

The construction of the components is complete, and assembly is now taking place.

REFERENCES

1. J. A. Clark, H. Merte, E. R. Lady, J. Vander Veen, and W. J. Yang, Low Heat Flux Boiling, Univ. of Mich. ORA Report 04653-1-P, Ann Arbor, January, 1962.

2. J. A. Clark, H. Merte, E. R. Lady, J. Vander Veen, and W. J. Yang, Low Heat Flux Boiling, Univ. of Mich. ORA Report 04653-2-P, Ann Arbor, April, 1962.