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Final Summary Report
EXPERIMENTAL INVESTIGATION OF
THE EFFECTS OF ULTRASONIC VIBRATIONS ON
BURNOUT HEAT FLUX WITH BOILING WATER

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FOREWORD

This final report, prepared by Advanced Technology Laboratories for the Joint U.S. -EURATOM Research and Development Board under Contract No.. AT(04-3)-250, Project Agreement No. 9, covers the experimental investigation of the effect of ultrasonic vibrations on burnout heat flux with boiling water. This work was conducted during the period 3 October 1960 through 31 July 1961.

SUMMARY

Experimental results have been obtained on the effect of an ultrasonic field on the burnout heat flux for water flowing, at atmospheric pressure, through an annular flow channel formed by a 1/4-inch-diameter electrically heated tube and a concentric glass tube of 3/4-inch ID. The active length of the central heating element was $5\frac{1}{2}$ inches. The ultrasonic transducer, which was operated at 25,000 cps and a maximum electrical input of 300 watts, was located at the inlet end of the flow channel. The ultrasonic waves were propagated in the water in the direction of flow and thus parallel to the surface of the heating element.

Burnout conditions covered channel inlet flows from 1.61 to 6.25 ft/sec and sub-cooling from 16 to 28°F. No effect of the ultrasonic field on the burnout heat flux or on the visible boiling phenomena at burnout conditions was detectable.

During boiling at heat fluxes well below burnout, the effect of the ultrasonic field was a reduction in the diameter of the envelope of bubble activity surrounding the heating element. Visual inspection appeared to show that this reduction was associated with a smaller average bubble size and a greater frequency of bubble formation. However, all evidence of the presence of the ultrasonic field vanished as the flow velocity increased or as the heat flux increased to the burnout level.

INTRODUCTION

In the design of heat-transfer equipment using boiling liquids, the most important single piece of data is the specification of the heat flux at which the boiling mechanism departs from the nucleate boiling regime. In equipment in which the heat-transfer rate (or heat-generation rate) is sensibly independent of the boiling phenomena, as in nuclear reactors and electrically heated equipment, an increase in heat flux above the heat flux at transition from the nucleate regime will produce film boiling. With film boiling, the thermal resistance between the heat-transfer surface and the boiling liquid is quite high because of an insulating vapor blanket that forms over the heating surface. Consequently, the surface temperature abruptly increases with the advent of film boiling. In many applications, the equilibrium surface temperature is above or near the melting point of the surface material, and failure of the equipment ensues transition from the nucleate regime.

A recent analysis^{1,2} of the peak heat flux attainable in saturated pool boiling has succeeded in predicting the peak heat flux by purely analytical means; no experimentally determined constants are required for the expression for peak heat flux. The theory is based on a hydrodynamic stability analysis of the vapor-liquid interface during transitional boiling from a flat horizontal surface. One of the essential features brought out by this analysis is that the vapor-liquid interface exhibits a geometric structure characterized by the ejection of vapor at definitely spaced intervals over the heated surface. This structure can be predicted in terms of a stability analysis of the interface between two fluids of different density.

The maximum heat flux in the transitional regime is equal to the heat flux (burnout flux) at transition from the nucleate regime. At this maximum, the frequency of bubble departure from each of the vapor ejection points can be predicted through stability considerations. The boiling mechanism at burnout in pool boiling is thus characterized by two principal phenomena: a wave-like structure of the liquid-vapor interface, and a predictable frequency of bubble release. One is thus led to conjecture on the effect of an ultrasonic field on the two phenomena and hence on the effect of the field on the burnout heat flux.

1. See list of references, page 19.

PREVIOUS WORK

Several investigators have explored the effect of an ultrasonic field on the burnout heat flux in pool boiling. Isakoff³ used an electrically heated platinum wire suspended in water at the saturation temperature. The electro-acoustic transducer was located $\frac{1}{2}$ inch below the wire and operated at a frequency of 10,000 cps and about 2 watts/cm² at the oscillating diaphragm. With this apparatus, the burnout heat flux, with the oscillator operating, was increased about 50%.

Ornatskii and Shcherlakov⁴ report a similar pool-boiling experiment at atmospheric pressure. An electrically heated Nichrome wire (0.4 mm dia.) was suspended in water above an electro-acoustic transducer operating at 1 megacycle and an electrical input of 400 watts. The acoustic power in the water was stated to be from 1.5 to 2 watts/cm². With this apparatus, the burnout flux in saturated water was increased about 30%. They found that the burnout effect of the ultrasonic field increased as the water temperature was decreased. For example, the burnout heat flux with the ultrasonic field was increased 80% with a water temperature of 20°C (80°C subcooling). The visible effect of the field was an increase in the frequency of bubble separation from the wire.

A pool-boiling experiment using isopropanol at saturation temperature is reported in reference 5. A 3/8-inch-diameter copper tube heated by condensing steam was suspended over an ultrasonic transducer which was operated over the frequency range 20 to 38,000 cps. An increase in burnout heat flux of 20 to 50% was obtained by operation of the transducer. The maximum increase (50%) occurred at 4000 cps, even though the maximum acoustic power (specifically, pressure amplitude) was realized at 38,000 cps.

BACKGROUND CONSIDERATIONS IN PRESENT WORK

The experimental work covered in this report differs in two major aspects from the experimental programs mentioned above:^{4,5} 1) the boiling liquid flows by forced convection past the heating element; 2) the direction of acoustic-wave propagation is parallel to, rather than normal to, the heating surface.

Although the burnout mechanism in a flow system is not well understood, there is good evidence that flow (or mass rate) stability of the coolant is highly important. Evidence for this statement is afforded by boiling burnout experiments reported by Lowdermilk, et al,⁶ at atmospheric pressure (as in the present experiment) and by Miropolskii, et al,⁷ at 1470 psia. A flow restriction (e.g., a valve) was located upstream from the test section in both experiments. In successive burnout determinations, the restriction (and thus pressure drop across the restriction) was increased; the pressure upstream was correspondingly increased in order to produce the same test-section pressure, mass rate, and inlet temperature for a sequence of burnout determinations. In both experiments, the burnout heat flux increased as the pressure drop across the restriction was increased to a critical value and remained constant for further increases in restriction pressure drop. For example, the results of the atmospheric-pressure tests show an almost threefold increase in burnout heat flux as the pressure drop across the restriction and test section was increased from 25 psi to the critical value^{*} of 100 psi. Burnout effects of comparable magnitude were observed in the 1470-psia tests.

In supplementary atmospheric-pressure tests by Lowdermilk, et al,⁶ a compressible volume was provided between the restriction and the test section. With a fixed mass rate, inlet temperature, and test-section pressure, and with the pressure across the restriction greater than "critical," the burnout heat flux decreased from 1.4×10^6 Btu/hr-ft² with no compressible volume to 0.3×10^6 Btu/hr-ft³ with the largest compressible volume tested.

The most direct interpretation of these experimental observations is that burnout in flow systems is a strong function of the constancy of flow. A more exact statement

* This "critical" pressure difference is for the specific mass rate, test section, and inlet temperature of the test condition.

of this interpretation would be that the change in mass rate produced by a change in test-section pressure drop should be small for attainment of high burnout heat fluxes. Because high pumping costs prevent provision for high pressure losses upstream of a boiling heat-transfer section, it is also evident that potential burnout in the great majority of technical applications will be closely associated with small momentary coolant-flow variations that can arise from the random nature of nucleate boiling. Thus, one might anticipate an increase in burnout heat flux if an ultrasonic field were found to "smooth out" the nucleate boiling mechanism by increasing the frequency of pressure disturbances to a range above the response of mass-flow changes or by decreasing the amplitude of the disturbances.

Applications of boiling heat transfer in flow systems will usually involve, as in a nuclear reactor, many parallel flow channels. Thus, propagation of an ultrasonic field in the boiling liquid must be in the direction parallel to the heat-transfer surfaces forming the flow channels. Good coupling between the transducer and the coolant would appear to require that the transducer be located at the channel entrance, where the coolant is subcooled liquid. Thus, the ultrasonic power must pass through the highly attenuating two-phase coolant to the point of burnout which, for uniform heat input, is at the downstream end of the channel. The fact that the power would therefore be highly attenuated at the burnout location is also a reason for investigating the potential of "smoothing out" the boiling process over the length of the conduit by application of an ultrasonic field.

The experimental system described in the following section should maximize the effect of an ultrasonic field. In particular, the ratio of flow area to heat-transfer area is large, so that the length of travel of the ultrasonic waves is short and the area for propagation is large.

EXPERIMENTAL APPARATUS

The flow-system diagram is shown in Figure 1. The function of each component is described below in order of its appearance on the flow diagram, starting at the exit to the test section.

A. Storage Tank

The storage tank, a 42-gallon galvanized-steel tank fitted with a sight glass, is located at the high point of the system. Water and steam from the test section enter the bottom of the tank. The tank is vented to the atmosphere.

B. Circulating Pump

The centrifugal pump is driven by a $\frac{1}{4}$ -hp motor. In the range of use, 0 to 10 gpm, the head across the pump varies from 29 to 28 feet. The pump thus operates at essentially a constant head in this application.

C. Heat Exchanger

The degree of subcooling of water delivered to the test section is controlled by the heat exchanger. A subcooling range of 0 to 140°F is available with the bulk temperature of the loop at saturation and under full flow conditions.

D. Temperature Gage

The temperature of water delivered to the test section is measured by means of a standard industrial thermometer. The scale range is 50 to 300°F, and rated accuracy is 1% of full scale.

E. Flow Meter

Flow to the test section is measured by a Rotameter having a rated accuracy of 2% of full scale. Two flow tubes and three floats for the Rotameter permit selection of six float-tube combinations having maximum scale readings corresponding to flow rates of 1.90, 2.52, 3.92, 5.12, 6.88, and 9.65 gpm. These flow rates correspond to liquid velocities in the annular test section (0.253" ID $\times$ 0.717" OD) of 1.72, 2.29, 3.56, 4.65, 6.23, and 8.75 ft/sec, respectively.

F. Pressure Gage

Pressure is measured by means of a standard Bourdon-tube gage having a scale range from 0 to 15 psig. Rated accuracy is 1% of full scale.

FLOW SYSTEM DIAGRAM
ULTRASONIC HEAT-TRANSFER EXPERIMENT

FIGURE 1

G. Ultrasonic Transducer

The ultrasonic transducer operates at a nominal frequency of 25,000 cps and is supplied by a power supply that is variable from 0 to 300 watts. The circular radiating surface has a 3/4-inch diameter and is located at the end of a solid horn, the other end of which is roughly 2½ inches in diameter. The latter end is welded to a steel plate attached to the driving crystal. The manufacturer claims an electrical-to-sonic efficiency of 90% for the transducer with the horn removed. The horn reduces this efficiency, but the amount of reduction is unknown. In any event, cavitation of the hot water near the radiating surface does not permit good coupling between the water and the radiating surface in the higher ranges of power. Thus, the actual efficiency is very considerably less than 90%. No measurement of sonic power was made.

H. Test Section

A drawing of the test section is presented in Figure 2. Water enters the bottom (right side of drawing) of the test section and flows upward in the annular conduit formed on the outside by a 3/4-inch (nominal) ID glass tube and on the inside by the heating element. In flowing from the inlet plenum to the annular flow conduit, the water passes through a wire screen provided to remove any swirling component of the flow.

The 0.253-inch-OD element is made of a 304 stainless steel tube with a 0.012-inch-thick wall and has a heated length of 5½ inches. Electric resistance heating is provided by axial conduction of a 60-cycle current through the tube wall. Current is carried to the free end of the bayonet-type element by a central copper core 0.202 inch in diameter. Power generation in the copper core is about 1.1% of that generated in an equal length of the stainless steel heating tube. The annular electrical insulating gap between the copper core and the inside surface of the stainless steel tube is therefore filled with a silicone rubber in order to afford a low-resistance thermal path from the core to the steel tube and thus prevent excessive core temperature. The silicone rubber is suitable for continuous operation at 500°F and has a thermal conductivity of about 0.25 Btu/(hr-ft² -°F/ft).

An insulated Alumel wire is attached to the outside surface of the heating tube 1.5 inches below the top of the active length of the heating element. The wire serves as a voltage tap for use in the bridge of the burnout-detector system.

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TEST SECTION
ULTRASONIC HEAT-TRANSFER EXPERIMENT

FIGURE 2

Chromel/Alumel thermocouples are installed in the inlet- and outlet-plenum areas of the test section. Use of the thermocouples allows heat-balance computation when conditions that do not result in net vapor generation exist.

I. Test-Section Power Supply

Electric power to the test section is supplied by a saturable reactor in series with a low-impedance transformer required to match the low-impedance heating element. Variation of the direct current in the control circuit of the saturable reactor permits stepless variation of power from about 0.8 to 1.2 kw to a rated output of 50 kva at 2000 amperes. A power dissipation of 10 kw in the element corresponds to a heat flux of 1.122×10^6 Btu/hr-ft² at the surface of the element.

J. Power Instrumentation

Electric power input to the test section is measured by a wattmeter with 4½-inch scale and a range from 0 to 20 kw. Accuracy is 2% of full scale. The current terminals are connected to the secondary of the low-impedance transformer through a 2000-to-5 current transformer. Auxiliary measurements of heating-element voltage and current are made for monitoring purposes with a 0- to 30-volt voltmeter and a 0- to 2000-ampere ammeter, which are also connected through the current transformer.

K. Burnout Detector

The detector compares the electrical resistance of the top portion (water-exit end) of the heater element with the resistance of the remaining portion. Upon inception of film boiling, which occurs toward the upper end of the element, the local temperature, and hence the electrical resistance of the upper portion, increases. This resistance increase unbalances a bridge, two legs of which are formed by the two portions of the heater element, and thereby generates a signal that is used to open the saturable-reactor dc control circuit. The decay of power to the test element after opening of the control circuit was not measured, but visual observation of the wattmeter needle led to an estimate of less than ½ second for the decay time constant. The burnout-detector circuit is shown in Figure 3.

BURNOUT-DETECTOR CIRCUIT

FIGURE 3

EXPERIMENTAL PROCEDURE

The desired flow rate was set by throttling the flow with the globe valve upstream from the Rotameter. (The valves between the Rotameter and the test section and between the test section and the water tank are isolating valves that were always fully open during system operation.) The desired inlet water temperature was established by circulating water through the test section, in which heat was supplied by the test element.

For burnout runs, the heat input to the test section was slowly increased until the burnout detector tripped or until the heating element showed a red hot spot. The burnout detector was inoperative during all burnout determinations taken with the ultrasonic field, presumably due to an electrical interaction between the burnout-detector circuit and the power generator for the ultrasonic transducer. For all of these runs, and for most of the "non-ultrasonic" runs, burnout was indicated by the sudden appearance of a red hot spot at or near the downstream end of the heating element. Actual destruction of the element was prevented by a rapid manual opening of the 460-volt supply to the saturable reactor.

EXPERIMENTAL RESULTS

A. Burnout Results

A summary of burnout data taken with and without the ultrasonic field in operation is given in Table I. The data are also presented in Figure 4, which shows the burnout heat flux as a function of flow rate. The inlet temperatures, which are indicated next to the data-point symbols, varied over the range from 185 to 200°F. Inspection of the graph reveals no detectable effect of the ultrasonic field on the burnout heat flux.

At heat fluxes appreciably below burnout level, the ultrasonic field had an effect on the boiling phenomena that was visible at low flow velocities. When viewed from sufficient distance, this effect was a narrowing of the envelope of bubble activity surrounding the heating element. Closer inspection suggested that the average bubble size had decreased and that, possibly, the frequency of bubble formation had increased. The number of nucleation points did not appear to be influenced by the ultrasonic field. However, the use of photography to remove the subjective aspects of visual, unaided observation would be desirable.

During exploratory runs at heat fluxes well below burnout, oscillations of system pressure and boiling phenomena were observed. The presence of the oscillations was clearly indicated by the boiling phenomena, the pressure-gage needle, and, if severe, by a jiggling motion of the Rotameter bob. For some, but not all, of the oscillation conditions, the ultrasonic field was sufficient to stop the oscillations that were in the frequency range of 10 or 20 cps. At heat fluxes approaching the burnout condition, the boiling phenomena became more violent and random and no effect of the ultrasonic field was discernible.

B. Pressure-Flow Characteristic of System

As noted earlier, there is good evidence that the mass-rate change produced by an increase in test-section pressure is an important parameter in determining the heat flux at burnout. The relationship between mass flow and pressure changes is a dynamic one and can conveniently be expressed, for small linear disturbances, in the form of a transfer function involving system dynamics upstream of the test section. The zero-frequency value of the transfer function defines the steady-state mass-rate change produced by a sustained change in test-section pressure. This zero-frequency relation is easily measured for most experimental systems and has been measured for the test loop.

EXPERIMENTAL BURNOUT DATA

FIGURE 4

TABLE I

SUMMARY OF BURNOUT DATA

Run No.	Mass Rate (lb/hr)	Inlet Velocity (ft/sec)	Inlet Temperature (°F)	Inlet Subcooling (°F)	Burnout Heat Flux (10^3 Btu/hr-ft ²)	Transducer Input (watt)	Type of Burnout*
1	859	1.61	192	21	224	0	Red
2	"	"	189	24	258	300	Red
3	"	"	187	26	236	0	Red
4	"	"	186	27	281	300	Red
5	"	"	187	"	270	0	Red
6	1669	3.12	190	23	383	0	Trip
7	2140	4.01	"	"	"	0	Red
8	1669	3.12	187	26	405	300	Red
9	"	"	185	28	"	0	Trip
10	3340	6.24	190	23	742	300	Red
11	"	"	189	24	786	0	Trip
12	"	6.25	197	16	"	0	Red
13**	"	"	"	"	718	300	Red
14**	"	"	"	"	629	0	Red
15	2380	4.47	196	17	573	300	Red
16	2390	4.46	192	21	"	0	Red
17	4530	8.51	200	13	1020	0	Red

* Red: red hot spot observed, manual power trip.

Trip: burnout detector cut power.

** Element was bent such that the lower, free end very nearly touched the glass wall of test section.

The experimental method involved setting a flow rate by means of the globe valve upstream of the Rotameter, with the gate valve downstream from the test section wide open. The changes in test-section pressure and mass rate were then recorded as the gate valve was closed in a succession of steps. Data obtained by this procedure are shown in Figure 5 for three initial flow rates. The slopes at zero pressure increase are given in Table II. It will be observed, for example, that at a flow rate of 8.75 ft/sec ($\sim 1.9 \times 10^6$ lb/hr-ft²), an increase of 1 psi in test-section pressure (drop) will cause a mass-rate reduction of about 5%. No theoretical basis for a logical comparison of this number with that for the experimental equipment of Lowdermilk, et al,⁶ is available. However, at the same mass flux (1.9×10^6 lb/hr-ft²), and with a critical pressure drop across the upstream restriction, it can be estimated that a 1-psi increase in test-section pressure drop would produce a reduction in mass rate in their apparatus of about one-tenth of the measured mass-rate change in the present system. It would therefore appear reasonable to conclude that burnout in the present system was affected by flow fluctuations. This conclusion was supported by the observations of the boiling phenomena at burnout.

Table II

Pressure-Flow Characteristic of System

<u>Flow Rate</u> <u>(ft/sec)</u>	<u>$\frac{1}{m} \frac{dm}{dp}$</u> <u>(1/psi)</u>
8.75	-0.0497
4.38	-0.0372
2.19	-0.0358

C. Heat-Balance Calculation

The experimental procedure used during burnout determinations did not permit collection of data under burnout conditions for heat-balance calculations. Heat-balance data were therefore collected under sub-burnout boiling conditions. In nine runs made to establish heat balances, the inlet temperature was varied from 87 to 198°F and flow from 2400 to 5010 lb/hr. The average value of the ratio of electric power input to the heat rate, determined by mass rate and enthalpy difference of the water, was 0.94, with a standard deviation of 0.13.

PRESSURE-FLOW CHARACTERISTIC OF SYSTEM

FIGURE 5

CONCLUSIONS

1. The ultrasonic field had no detectable effect on burnout heat flux or on visible boiling phenomena at or near burnout heat fluxes.
2. For boiling at below-burnout heat fluxes, visual evidence suggested that the effect of the field is a reduction in mean bubble size and an increase in frequency of bubble formation.
3. The ultrasonic field stopped boiling oscillations in a few instances at appreciably lower-than-burnout heat fluxes. At heat fluxes approaching burnout level, the field had no observable effect.
4. Experimental measurements, interpreted with use of information available in the literature, led to the prediction that burnout in the apparatus was closely associated with flow stability. Observations of burnout phenomena confirmed this prediction.

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