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by Vernon H. Gray
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Cleveland, Ohio

TECHNICAL PAPER proposed for presentation at
Intersociety Energy Conversion Conference
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FEASIBILITY STUDY OF ROTATING BOILER FOR HIGH-PERFORMANCE RANKINE CYCLE POWER GENERATION SYSTEMS

by Vernon H. Gray[1]

ABSTRACT

A small-scale experimental study of the feasibility of a rotating boiler was undertaken using water as test fluid. Rotational accelerations up to 500 gravities were investigated. High speed photographs of the boiling fluid were taken and heat-transfer coefficients were obtained. The tests demonstrated several advantages of rotating boilers, chiefly: stable interface between liquid and vapor, high exit vapor quality, high heat flux rates, and freedom from gravity field and orientation. A concept for heating a rotating boiler with a liquid flowing in a surrounding annulus is discussed. Advantages and problems with this application are considered using an example of a boiler rotating at 14,000 rpm.

INTRODUCTION

The use of nuclear reactors as heat sources for Rankine cycle power generation systems, both on Earth and as proposed for space flights, has brought about the forced-flow, heat-exchanger type of "once-through" boiler. With it has come serious problems of flow instabilities in the boiler. These disturbances are associated with time-wise variations in void fraction, pressure, temperature and flow rate of the boiling fluid, as well as interactions with the feed system.

One possible way of overcoming these forced-flow boiler instabilities is to rotate the boiler and use high centrifugal accelerations to separate

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the vapor from the liquid phase. Several possible advantages of a rotating boiler may be cited (ignoring temporarily the mechanical problems caused by rotation). The interface between liquid and vapor should be rather sharp, yielding a high quality vapor and a steady flow of both vapor and liquid. In addition, the boiler should be independent of gravity field and orientation, should have a low pressure drop, and could have heat fluxes considerably higher than for pool boiling at normal Earth gravity.

The object of this investigation was to determine if these apparent advantages could be realized experimentally, and to apply the results to a Rankine cycle boiler rotating at high shaft speed and heated by a liquid flowing in a surrounding annulus.

This study was conducted at the NASA Lewis Research Center, Cleveland, Ohio.

TEST BOILER

The experimental rotating boiler is shown schematically in figure 1. It consists essentially of an electrically heated hollow copper cylinder mounted on top a hollow shaft. Distilled water, pressure-fed, flows into the hollow shaft through a rotating graphite face-seal at the bottom end. The shaft is rotated up to 3000 rpm by a V-belt from a variable-speed drive. At the top of the shaft, the water flows through a conical control valve actuated by a rotating float. The water sprays through the valve and collects on the inside surface of the cylinder, where it forms an annulus of liquid. Liquid then passes up through small holes into the heated zone to replace that which has boiled off. The float valve maintains the annular liquid level nearly constant, regardless of heating rate and rotational speed. The liquid in the heated zone rotates synchronously with the heated cylinder, essentially in wheel-flow, except for slight secondary flows caused by the boiler action and density gradients.

Electrical resistance elements, imbedded in the copper cylinder and energized through slip rings and brushes, can deliver more than 25 kilowatts to the boiling liquid. The copper cylinder is four inches in inside diameter and two inches in vertical height. Part of the top end of the heated zone is a transparent annular window for viewing and photographing the boiling activity and the liquid-vapor interface. Vapor is generated in the heated annulus of liquid and moves radially inward. After breaking through the interface, the vapor flows out of the top of the spinning cylinder along the axis of rotation. Here, the outlet duct passes through a soft, ring-type rubbing seal to a stationary atmospheric spray-condenser.

Instrumentation is provided for measuring fluid flow rates, heating fluxes, rotational speeds, exit vapor quality and boiling heat-transfer coefficients. Two thermocouples rotate with the boiler: one (imbedded) measures the heated cylinder surface temperature midway between ends, and the other measures the fluid bulk temperature 1/8-inch radially inward from the heated surface midway between ends. The outlet vapor temperature was measured by stationary thermocouples, along with other system temperatures and pressures.

EXPERIMENTAL RESULTS

The following results are typical and illustrative of a much larger body of data taken with this installation.

Stability of liquid-vapor interface. - At rotational accelerations above about 25 gravities, the effect of orientation to Earth gravity is insignificant. The liquid-vapor interface, although actually a paraboloid, is essentially cylindrical in the area of observation herein, and is concentric with the cylindrical heated surface.

Study of high-speed motion pictures taken through the annular top window discloses that the vapor bubbles move radially inward, normal to the heated wall, and break at the interface. The bubbles grow in size as they traverse the liquid annulus, and appear to accelerate as they near the interface. The number, size and breaking action of the bubbles vary greatly with the imposed acceleration field. Figure 2 presents three frames from 16 mm movies taken at about 8000 frames per second. Figure 2(a) is a sketch showing the features to be seen in the subsequent photographs. The outer circular arc is the edge (end view) of the heated cylinder. The thin annulus of boiling fluid lays against this heated surface. The 1/16-inch diameter rod shown in the photographs (for scale) turns with the boiler: it is dark with a white band 1/8-inch long, and it ends 1/8-inch short of the heated surface. The three photographs were taken with the heating rate constant at 4.5 kilowatts, or 88,000 Btu/hr,ft^2. Figure 2(b) shows a very irregular, turbulent interface produced at 25 gravities. It somewhat resembles vigorous boiling at one gravity. Many of the vapor bubbles upon reaching the interface balloon into large vapor "domes" before breaking. The dome to the left of the rod is caught in the act of breaking open (from the left) to let out the vapor. In doing so, the liquid that forms the roof of the dome pulls together into a ring of droplets that fall back into the interface. Occasionally, a drop or a stream of liquid will be propelled far into the vapor region beyond the interface. This liquid generally returns to the interface after completing its trajectory. Curiously, these trajectories are either radial, or arc inward and lead the rotation of the system, apparently in accordance with Coriolis forces. Figure 2(c), taken at 100 gravities, shows a more continuous interface, and regions with fewer bubbles. In figure 2(d), at 400 gravities, the interface is quite smooth and continuous, with only an occasional cluster of bubbles. The fluid in the annulus is mostly clear liquid. The rod can be seen easily, as can one of the liquid-feed holes (dark spot) in the bottom plate of the boiler.

The interface is unquestionably stabilized by high gravities, and in addition, bubbles are less numerous and appear smaller at higher gravity. Both the liquid flow into the boiler and the vapor flow out were steady. It was not necessary to add baffles or vanes in the boiling annulus to correct for interface waviness or unbalance.

Vapor quality. - Outlet vapor quality, as determined by throttling calorimeters, varies as shown in the following tabulation of typical data:

Quality, percent (or vapor superheat, $^{\circ}$F)	Gravities	Heating rate, Btu/hr, ft^2	Liquid inlet temp. below saturated vapor temp., $^{\circ}$F
99.2	21	25,000	107
99.4	25	185,000	27
99.3	81	235,000	19
99.5	200	351,000	20
99.6	230	117,000	140
99.8 (5°)	235	117,000	40
(4° to 6°)	222	58,000	39

The quality readings are slightly conservative because of unavoidable heat losses in the calorimeters. The quality reading of 99.8% was obtained at a time when the outlet vapor temperature was 5° F above the vapor saturation temperature. (Except for these marked cases of exit vapor superheat, the measured outlet vapor temperature agreed with the saturated vapor temperature calculated from measured outlet vapor pressure within ±0.1° F.)

The outlet vapor is always above 99 percent quality. The quality apparently increases with gravity and liquid inlet temperature, and decreases with heating rate. Evidence of vapor superheat is remarkable, because the vapor outflow cannot come in contact with the heated surface. At very high gravities, vapor can apparently leave the interface at temperatures several degrees above the vapor saturation temperature in the core. This behavior is possible because at high gravities the static pressure gradient within the boiling annulus becomes large, causing the saturation temperature at the heated wall to be much higher than in the vapor core. This temperature difference, at 400 gravities herein, is 10.4° F across a 1/4-inch thick annulus of water, corresponding to a 3.3 psi pressure rise. The hotter vapor created near the heated wall is quickly centrifuged through the boiling annulus at high gravities. In addition, the hotter liquid is rapidly convected toward the interface, and evaporation occurs directly across the sharp interface discontinuity. Ultimately, with increasing gravity and a given heating rate, all the vapor is generated by evaporation at the interface, and boiling is suppressed.

Heat transfer. - No attempt was made to determine the peak nucleate boiling, or burn-out, heat flux. The highest heat flux studied is 25.8 kilowatts (505,000 Btu/hr,ft^2) at 200 gravities. This is well above the "burn-out," or peak nucleate boiling condition for pool boiling at one gravity; at 200 g's it produces only moderate, stable boiling.

Boiling heat-transfer coefficients can be obtained from figure 3, wherein heat flux is plotted against the differential between heated wall surface temperature and saturation temperature at the wall. This is shown for five different gravity levels. The fluid bulk temperature is measured

1/8-inch radially inward from the heated wall surface midway between axial ends of the heated cylinder. Wall saturation temperature is calculated assuming the boiling annulus is completely liquid.

Between heat fluxes of about 40,000 and 160,000 Btu/hr,ft^2, a complete reversal in the effect of gravity on heat-transfer coefficient occurs. At low fluxes the coefficients are increased by gravity increases (smaller temperature differentials), characteristic of convection. At high heat fluxes the opposite occurs, although the trend is small (the spread in temperature differential is less than 4° F). In fact, at high heat fluxes, aging and conditioning of the heated surface affects the coefficients as much as do changes in gravity level from 1 to 200. The highest boiling coefficient (heat flux divided by temperature differential) is 8700 Btu/hr,ft^2,$^\circ$F, obtained at the highest heat flux level.

APPLICATION TO RANKINE CYCLE SYSTEMS

Based on the experimental results, several aspects of a rotating boiler as applied to a Rankine cycle system will now be discussed. The boiler concept to be considered is shown in figure 4. The cylindrical boiler is closely coupled to the turbine, and turns with it on the same shaft. This is done for compactness and to achieve very high rotational accelerations. The boiler is heated by a liquid flowing in an annulus between the rotating cylinder and a stationary containment shell. The heating liquid moves in a combination of pumped-axial and induced-circumferential (couette) flows. Heat is conducted through the thin cylindrical boiler wall to boil a thin layer of fluid rotating within the cylinder, as in the experimental tests.

This concept is but one of many possibilities, and admittedly requires extensive development efforts. Many vital engineering problems, such as bearings, seals and structure are not considered herein. These problems, however, are very similar to those of the turbine.

In the concept shown in figure 4, boiler rotation accomplishes several objectives in addition to improving the boiling action. It creates a high convective heat-transfer coefficient on the annulus side of the boiler wall by virtue of the shear (and secondary flow) in the induced circumferential couette flow. It creates a radial density gradient in this flow, sending the hotter liquid to the heat-transfer wall. Rotation can also be used, if desired, to achieve pumping actions on either fluid, and vanes can be used if necessary to recover power from the angular momentum of either the vapor or the heating liquid.

From the heat-transfer and vapor generation viewpoint, the faster the rotation the better. As rotative speed increases, however, hoop-stress limits in the cylindrical boiler wall are reached. These may be relieved considerably, depending on the design, by pressurizing the heating liquid loop (hence the outside of the cylinder).

For purposes of discussion, a shaft speed of 14,000 rpm will be assumed. At this rotation, an 8-inch diameter boiling surface would experience 23,500 gravities. Under this acceleration, a thin film of boiling fluid (1/8-inch or less in thickness) might achieve 100% evaporation at the interface, and up to 100° F vapor superheat. The interface should be very stable. Higher boiling heat-transfer coefficients might result at the higher gravities. Evidence in figure 3 and in the photographs of figure 2 points toward a higher coefficient at increasingly higher heat fluxes, as gravity is increased above 100.

At 14,000 rpm, the heating liquid in the annulus would circulate between the insulated stationary containment shell and the cylinder turning at a peripheral speed of 490 ft/sec. A radial gap of 1/2-inch is assumed for the annulus. Under these conditions, and with the heating liquid more than 100° F hotter than the boiler wall, heat fluxes up to about one megawatt per square foot (3.4 million Btu/hr,ft^2) should be possible with a variety of liquids, including water. This boiler example would then transfer two megawatts of heat per foot of axial length.

Heat transfer and friction in turbulent couette flow are not well known. The power consumption due to rotational friction in the annulus is estimated to be about 8 hp per axial foot of boiler. Some of this power is recovered to the cycle as heat. The power required to pump either fluid axially through the boiler is negligible.

Vapor temperatures and pressures attainable in a rotating boiler are determined by material stress limitations, and fluid properties. The material for the critical heated cylinder wall should have high strength and high conductivity; a likely candidate is molybdenum - 1/2% titanium.

CONCLUSIONS

1. High centrifugal accelerations produce sharp, stable interfaces between liquid and vapor during boiling. Both liquid and vapor exhibit steady pressures, temperatures, and flows.

2. Pool boiling at high accelerations produces high quality vapor, from above 99 percent quality to sizable amounts of vapor superheat.

3. Rotating boilers operate independent of gravity field and orientation.

4. High rotational speeds permit heat fluxes well above the peak nucleate boiling level for normal gravity.

5. For the conditions of the experimental tests, the rotating boiler is quite feasible. As discussed in the conceptual example, it probably is feasible to develop a rotating boiler for a Rankine cycle system, which is liquid heated and directly coupled to the turbine. Such a boiler, at 14,000 rpm, might transfer up to one megawatt per square foot of boiler surface, and deliver up to 100° F of vapor superheat. The boiler could be very compact, and should have very low pressure drops and power losses. Estimates of costs, weights, efficiencies and life are beyond the scope of this study.

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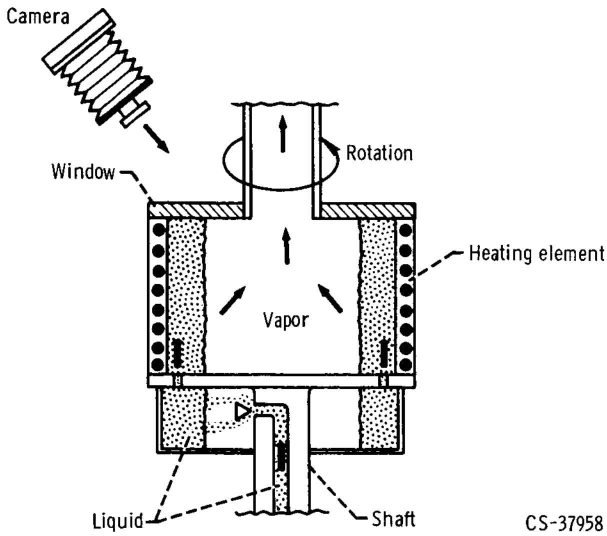
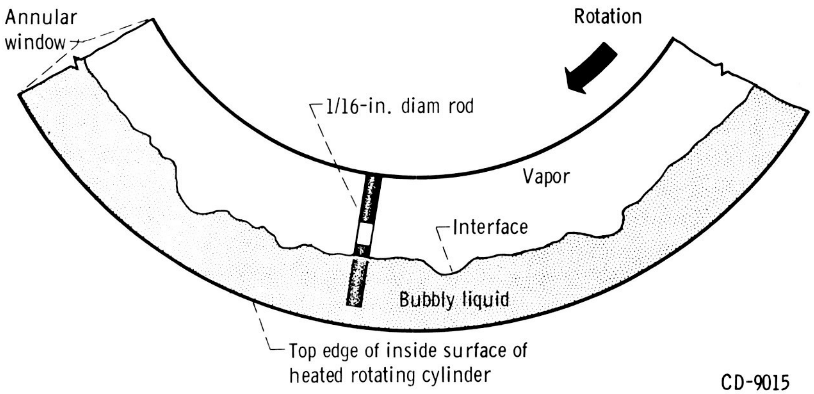
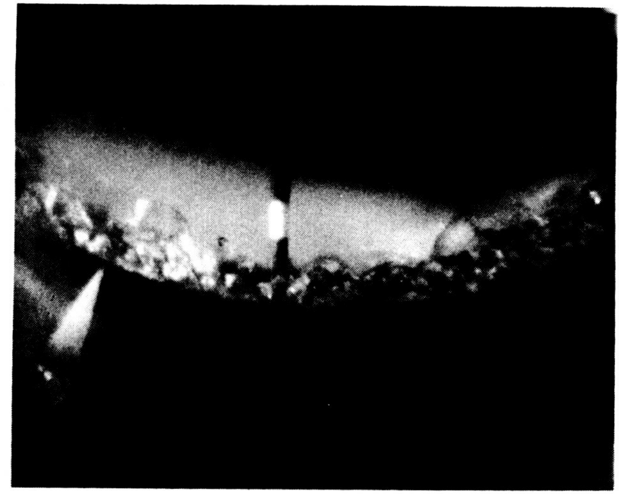


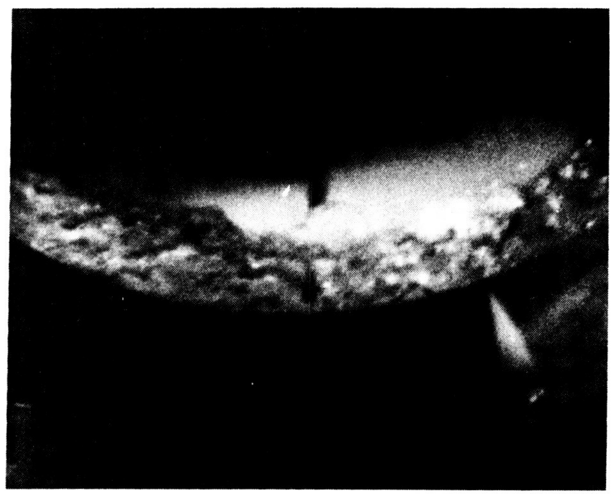
Figure 1. - Schematic diagram of experimental rotating boiler.



(a) Sketch showing typical view through top annular window.



(b) 25 gravities, 88 000 Btu/hr. ft^2.



(c) 100 gravities, 88 000 Btu/hr. ft^2.

(d) 400 gravities, 88 000 Btu/hr. ft^2.

Figure 2. - Effect of gravity on pool boiling.

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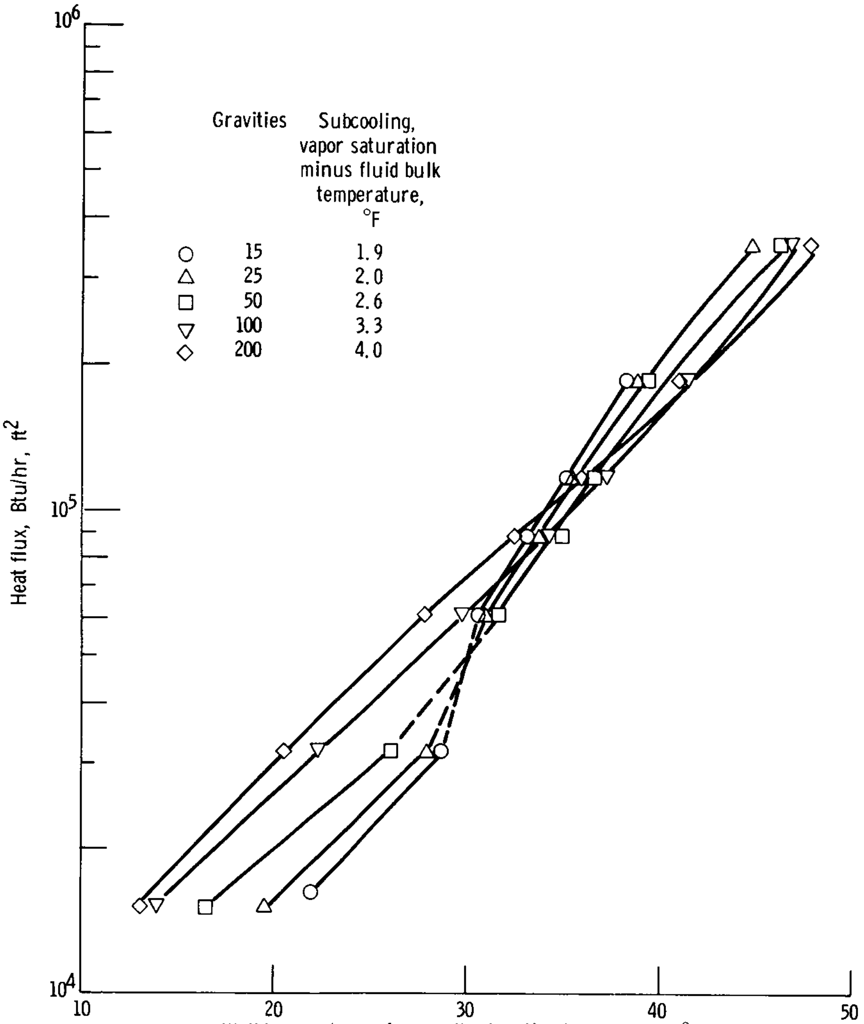

Figure 3. - Effect of gravity on pool boiling heat transfer.

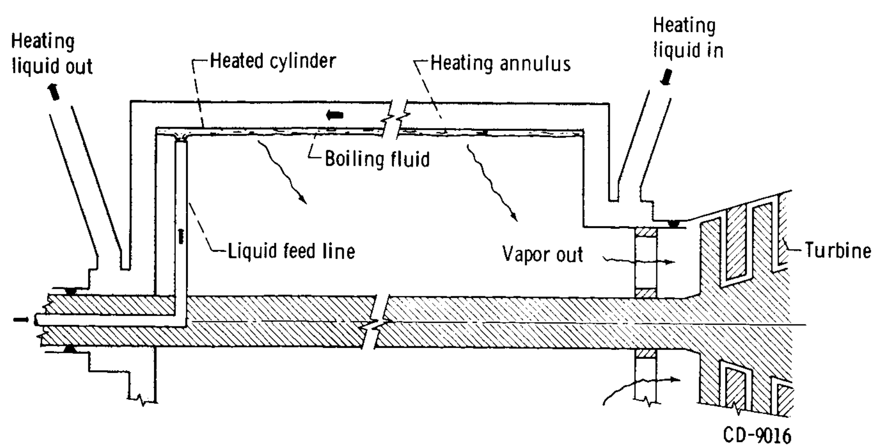

Figure 4. - Conceptual application of rotating boiler to Rankine cycle system.