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Heat Transfer-Seattle 1983

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FOREWORD

This AIChE Symposium Series Volume contains AIChE sponsored session papers accepted for presentation at the 21st National Heat Transfer Conference. The papers are grouped by conference sessions.

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CONTENTS

ENHANCED HEAT TRANSFER

Salim Yilmaz, chairman; Paul Minton, vice-chairman

PROCESS HEAT TRANSFER

A. E. Jones, chairman; C. D. Vickburg, vice-chairman

NUMERICAL METHODS IN HEAT TRANSFER AND FLUID FLOW

D. S. Trent, chairman; Y. S. Tang, vice-chairman

TWO PHASE FLOW IN NUCLEAR REACTORS

J. K. Kim and S. L. Soo, co-chairman

HEAT TRANSFER IN DEGRADED NUCLEAR REACTOR CORE

M. Corradini, chairman; M. S. El-Genk, vice-chairman

THERMAL ANALYSIS OF STEAM GENERATORS

William H. Vance, chairman; Shi-Chune Yao, vice-chairman

MULTIPHASE SYN-FUELS HEAT TRANSFER

A. A. Bishop, chairman; T. R. Galloway, vice-chairman

HEAT TRANSFER IN GLASS

Ihab H. Farag, chairman; Richard L. Curran, vice-chairman

COMPUTATIONAL TECHNIQUES IN TWO-PHASE FLOWS

C. W. Solbrig, chairman; D. Gidaspow, vice-chairman

NUCLEATE POOL BOILING CHARACTERISTICS OF A GEWA-T SURFACE IN FREON-113

A series of measurements were made with a specially fabricated, copper, Gewa-T finned, cylindrical surface. Data were taken after covering the sides of this surface with various shrouds and also after progressively machining away its fins.

Vapor bubbles were observed to burst through the gap between fins at the bottom of the surface as well as at its top. Covering the surface with shrouds to direct the liquid-vapor flow enhanced its performance by as much as 150 percent at low heat fluxes, but deteriorated its performance at high fluxes. The presence of T-shaped caps on the fins increased the heat transfer coefficient by 50 percent. The liquid-vapor motion within the channels of this finned surface plays a significant role in its thermal performance.

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Techniques to enhance nucleate boiling heat transfer are being vigorously pursued as the costs of labor, material and energy continue to escalate, and a variety of enhancement methods have been proposed for commercial use [1]. These enhanced surfaces have been classified into two groups: (1) porous coatings, and (2) integral machined surfaces [2]. Numerous recent studies have measured the nucleate pool boiling heat transfer coefficients of these commercially enhanced surfaces [2,3,4,5,6,7,8], and several investigations have addressed plausible mechanisms for the observed enhancement [4,6,9,10,11,12,].

One particular integral machined surface which has received attention recently is the Gewa-T finned surface manufactured by Wieland-Werke, AG [2,3,5,6]. Figure 1(a) shows a sketch of the cross-sectional representation of this surface, while Figure 1(b) is a photomicrograph showing the details of the fins. The surface is made by taking a standard Gewa type K finned surface and splitting and rolling the fins to form a smaller diameter tube with T-shaped fins. The neighboring T-shaped fins of this surface form a series of tightly wound spiral channels. Yilmaz and Westwater [2] compared the nucleate pool boiling heat transfer performance of a 12.3 mm OD Gewa-T copper surface to a plain tube in isopropyl alcohol at atmospheric pressure. Their results showed that at a heat flux of 40 kw/m^2, the heat transfer coefficient of the Gewa-T surface was 2.0 times that of the plain tube. Yilmaz, Hwalek and Westwater [3] tested a similar Gewa-T surface in p-xylene and, at the same heat flux, their measured heat transfer coefficient with the Gewa-T surface was 5.3 times the plain tube value. Marto and Lepere [5] boiled both Freon-113 and FC-72 from a 17.9 mm OD Gewa-T surface, and at 40 kw/m^2 they measured enhancements of 2.8 and 2.5 respectively. Stephan and Mitrovic [6] studied the performance of an 18.1 mm OD Gewa-T surface in refrigerant-oil mixtures. Their test tube was configured as part of a seven tube bundle, and their heat flux was kept below 20 kW/m^2. At this heat flux, they showed an enhancement of 1.7 when compared to a conventional Gewa finned surface. They postulated that this increase over the straight fins was due to the fact that the T-shaped caps on the Gewa-T surface provide flow channels which don't exist with the straight fins. Their qualitative model is shown in Figure 2 [13].

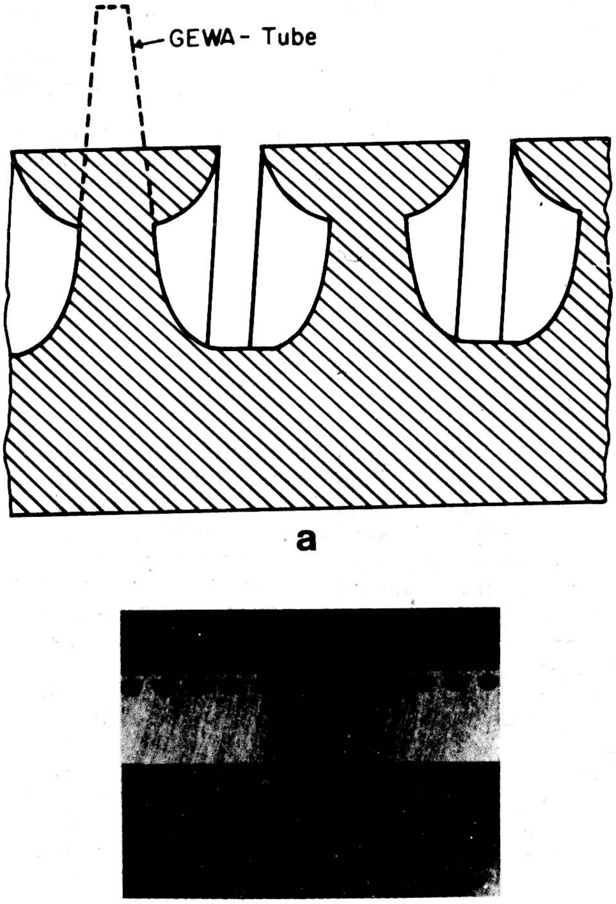


Figure 1. Details of the Gewa-T finned surface.
(a) Schematic representation of the surface
(b) Photomicrograph of the surface (7x)

Because of the presence of the T-caps, at low fluxes, bubbles that form within the channels are constrained to move around the tube more before they depart through the gap at the top part of the tube. As a consequence, these bubbles sweep the surface of other growing bubbles, thereby increasing bubble frequency and hence local heat transfer. At high fluxes, the large number of bubbles present within the channels coalesce, forming a vapor stream in the core of the channel with a thin liquid film

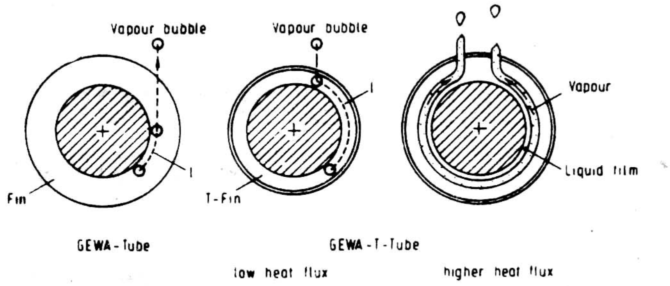


Figure 2. Qualitative behavior of the Gewa Tube and the Gewa-T Tube during boiling [13].

near the wall. At still higher heat fluxes, this thin liquid film completely evaporates, leading to dryout within the channel, and a deterioration of performance.

Because of the importance of the Gewa-T surface in future refrigerant applications, and because the qualitative model of Stephen and Mitrovic has yet to be verified, it was decided to make a systematic series of tests with a single Gewa-T surface in order to ascertain its boiling characteristics and to assist in understanding the physical mechanisms which give rise to increased heat transfer coefficients with this type of surface. As explained in detail below, in order to accomplish this task, a specially prepared Gewa-T surface was instrumented and destructively tested to observe the importance of the T-shaped fins, the flow in the channels, and other operating characteristics.

TEST APPARATUS

The test apparatus was similar to that used in an earlier study [5], and is shown schematically in Figure 3. Boiling occurred from a horizontal copper test surface which was heated on the inside by a cartridge heater. The surface was situated within a glass boiler vessel which was fitted with a thick-walled plexiglas cover. The boiler was heated from below by an electric hot plate to degas the test fluid prior to operation and to maintain the liquid pool at saturation conditions. Air and noncondensable gases produced from the degassing process were expelled to the atmosphere through a vent indentified in Figure 3. This vent permitted the boiler to achieve and maintain saturation conditions at ambient pressure, and consequently prevented pressurization of the boiler. The vapor produced from boiling was condensed with the use of a water-cooled copper primary condenser and glass secondary condenser connected in series, and the condensate was returned to the liquid bath by gravity.

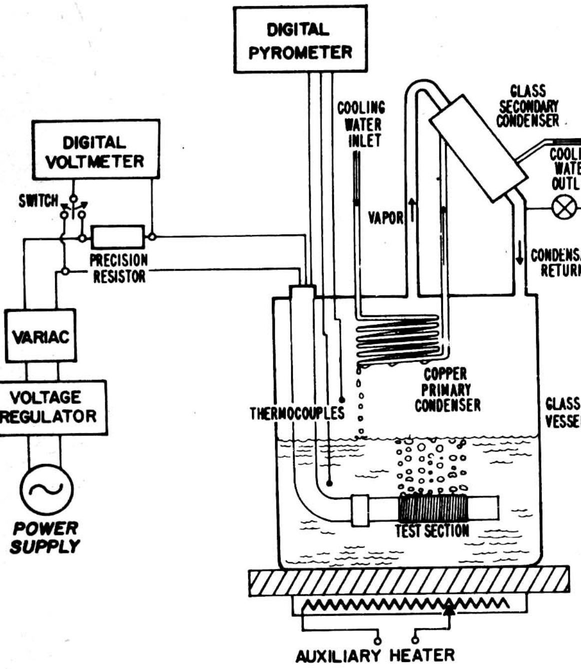


Figure 3. Schematic representation of the test apparatus.

Details of the Test Section

A spirally finned, solid copper rod designated Gewa-T 13515.16, was specially manufactured by Wieland-Werke AG for use in this experiment. Figure 4 illustrates a cross-sectional view of the test section. The outside diameter was 21.2 mm and its total length was 114.1 mm. The Gewa-T surface length was 49.0 mm, and contained 740 fins/meter. A radially-centered hole was drilled through the length of the solid copper rod to accommodate a cylindrical cartridge heater, forming a tube with an inside diameter of 13.3 mm. Next, eight longitudinal 1.6 mm OD holes were drilled in the tube wall up to the test section midpoint at a radius of 8.0 mm. Seven of the eight holes were drilled at intervals of 30 degrees from each other such that they spanned a total arc of 180 degrees. The eighth hole was centered at an interval of 90 degrees from either of the two nearest holes, Figure 4. The Gewa-T surface was then machined off at each end of the tube, producing two smooth ends with an outside diameter of 19.0 mm, and a length of 31.9 mm. Next, the inside wall of the smooth ends was bored out to create a thin wall of 0.35 mm to reduce longitudinal conduction.

Eight copper-constantan thermocouples with an average thermocouple bead diameter of 0.5 mm were manufactured from 0.1 mm diameter, teflon-insulated thermocouple wire. These thermocouples were inserted

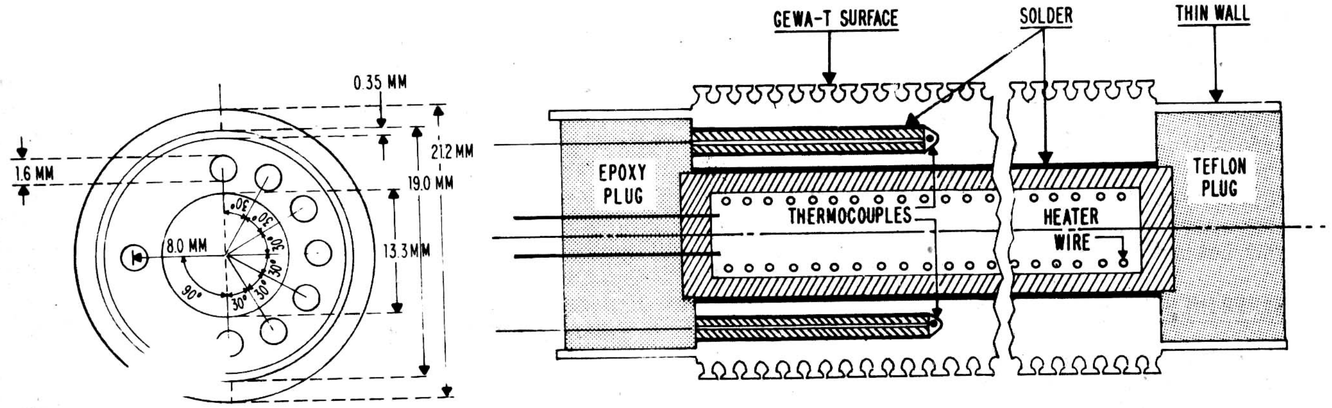


Figure 4. Cross sectional representation of the test section.
(a) End view showing thermocouple locations
(b) Side view showing details of construction

into eight soft-copper capillary tubes whose outside and inside diameters were 1.6 mm and 0.6 mm respectively, and whose outside surfaces were tinned with solder. The thermocouple beads were soldered to the capillary tube end through which they protruded. A cylindrical cartridge heater was radially and axially centered in the test section using a machined aluminum plug. It and the thermocouples were soldered into place using a hot plate as outlined in [14]. Following the soldering operation, after the test section was cooled to ambient temperature, the aluminum plug was removed and replaced with a teflon plug of the same dimensions. The end through which the heater and thermocouple wires protruded was insulated with poured epoxy resin. The entire test section was then immersed in a constant temperature bath and the thermocouples in the test section wall, together with similar ones used to measure the vapor and liquid pool temperatures, were calibrated against a platinum resistance thermometer yielding an uncertainty of ± 0.15 °C. The test section cartridge heater voltage was measured with a digital voltmeter, accurate to 0.01 volts, while the heater current was determined by measuring the voltage drop across a 2.031 Ω precision resistor connected in series with the cartridge heater.

Several runs were made with the test surface covered by various aluminum shrouds having an outside diameter of 22.2 mm and a wall thickness of 0.45 mm. Each shroud measured 51.4 mm in length and had two diametrically opposed windows of various aperture angles as shown in Figure 5. The two windows on each shroud subtended arcs of the following combinations: 60 degrees and 60 degrees, 30 degrees and 30 degrees, 60 degrees and 30 degrees, and 60 degrees and 8.5 degrees. The shrouds were slipped over the test section, providing a very tight mechanical fit, and they were oriented with the apertures centered vertically at the top and bottom of the test section.

EXPERIMENTAL PROCEDURES

The works of Bergles and Chyu [4] and Marto and Lepere [5] showed a dependence of boiling incipience on surface past history, or on surface treatment. Therefore, it was necessary to establish a procedure which could be easily and reliably repeated, and which would permit the comparison of data. In order to compare the data with that obtained by Marto and Lepere [5], a single run was made following procedure A described below. This procedure required the test section to be immersed in the liquid pool overnight. The liquid level was maintained at a height of 102 mm, and the distance of the test section centerline to the base of the glass vessel was 51 mm. At the start of the run, the hot plate voltage was adjusted to the maximum setting and was used to degas the fluid by vigorously boiling the pool for one hour. The plate voltage was then reduced to minimize the boiling intensity and maintain the pool at its saturation temperature. Power was then supplied to the test section heater by adjusting its voltage in increments between 2 and 30 volts up to the maximum power, and then decreased in increments of approximately 10 volts. The system was allowed to stabilize for 5 minutes at each power setting and the following data were recorded: heater voltage, precision resistor voltage, vapor temperature, liquid pool temperature, and the eight test section wall temperatures.

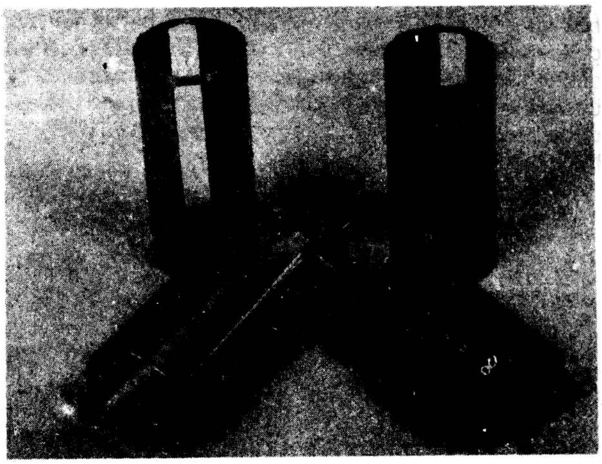


Figure 5. Photograph of aluminum shrouds.

Most of the runs were made after preparing the surface by procedure B. In this case, instead of requiring the test section to be immersed in the pool overnight, the test section was immersed in the pool and subjected to pre-boiling at a heat flux of 30 kW/m^2 for one hour using the cartridge heater while the hot plate voltage was adjusted to its maximum setting. Immediately after this one hour surface aging treatment, the power to the test section heater and the plate heater was secured, and both the test section and the fluid were allowed to cool for one half hour.

The plate heater voltage was then adjusted to the saturation temperature setting, and the cartridge heater voltage was adjusted in various increments as described under procedure A. At each power setting, the same data as described under procedure A were recorded.

The surface heat flux was determined by calculating the heater power from the measured voltage and current, and subtracting from this power the losses due to conduction of heat longitudinally through each of the thin-wall ends of the test sections. This corrected power was then divided by the surface area which was based upon the actual length of the enhanced surface and an effective diameter to the base of the enhancement (i.e., a diameter resulting when the Gewa-T fins were machined off the surface). This same surface area was used consistently to reduce all the data. The average heat coefficient was calculated by dividing the corrected average surface heat flux by the difference between the average tube surface temperature and the saturation temperature of the Freon-113. The average tube surface temperature was calculated by taking the arithmetic average of the eight wall thermocouples and correcting for the radial temperature drop across the copper wall. Although the local wall temperature distribution was measured as a function of position around the tube, no attempt to calculate a local heat transfer coefficient was made. The complete details of this calculational procedure are provided by Hernandez [14].

RESULTS AND DISCUSSION

Thirteen experimental runs were made. Procedure A was employed only once to compare results to the data of Marto and Lepere [5]. Procedure B was utilized in all other runs. Several runs were made to test the reproducibility of the data with varying vertical positions of the test section in the liquid pool. With a pool height of 102 mm, varying the vertical centerline height of the test section from 38 mm to 76 mm made no effect on the measured results. Another reproducibility test was made by rotating the test section clockwise 90 degrees to alter the circumferential position of the thermocouples. No observable differences in the data were apparent. Four runs were made to test the effect of adding the earlier-described aluminum shrouds to the test section in order to investigate the flow in the channels. The fin effect was studied by progressively machining away the fin height in three consecutive data runs. In one data run the fin "T-caps" were removed; in another data run the fin height was reduced to approximately 0.1 mm above the base surface; and in the remaining data run, the fins were completely removed, and the tube was mechanically polished with emery cloth and jeweler's rouge to a mirror finish.

Figure 6 compares the present data to that of Marto and Lepere [5]. Agreement, in general, is very favorable even with respect to the hysteresis trend with increasing versus decreasing heat flux. At higher heat fluxes, the present data fall approximately 20 percent below the earlier data. This may be due to the slightly different diameters used during these investigations. The data of Marto and Lepere [5] were taken using a 17.9 mm diameter surface whereas during this investigation the diameter was 21.2 mm. Recently Cornwell, et al [15] have shown that during pool boiling with Freon 113 from horizontal tubes, an increase of tube diameter decreases the boiling coefficient. Presumably, there is an influence of the tube diameter upon the dynamics of a sliding bubble around the tube, and the subsequent bubble departure angle.

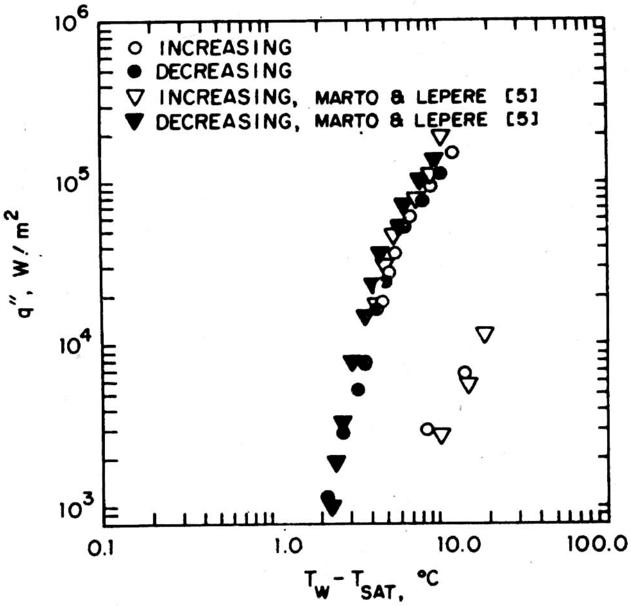
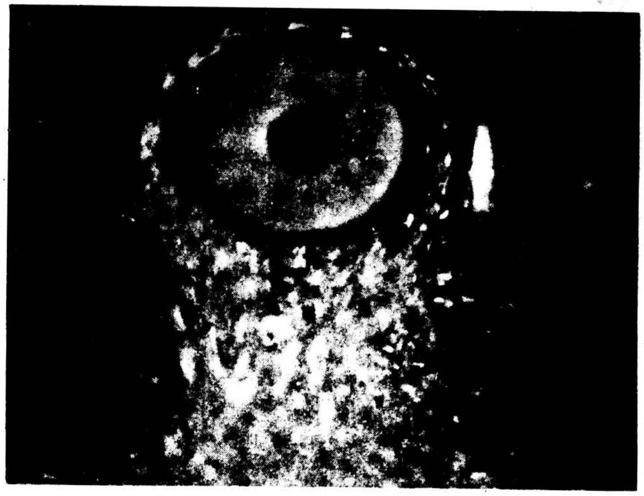


Figure 6. Comparison of present data with that of Marto and Lepere [5].

Figures 7 and 8 show some photographs of the observed boiling action from the Gewa-T surface. Figure 7 shows the boiling action at a relatively low heat flux of 20 kw/m^2 as observed from the end of the test tube (7(a)) and from its side (7(b)). Notice the presence of relatively large vapor bubbles along the bottom of the tube. These bubbles have grown within the Gewa-T channels and have burst out through the small gap between adjacent fins. This phenomenon is different from the proposed mechanism of Stephan and Mitrovic [6] which assumes that the bubbles stay within the channels and depart through the gaps only at the top of the tube. Of course, as can be seen in Figure 7(b), most of the bubble action is from the top part of the tube. Another unusual phenomenon can be seen clearly in Figure 7(b). As shown by the arrow, there appears to be a series of small bubbles nucleating from the tip of the Gewa-T fins along an approximately longitudinal line. This observance was not expected and the tube surface was therefore carefully inspected for any imperfections. Figure 9 shows a photograph of a portion of the test surface as viewed with a scanning electron microscope. Circumferential grooves can be seen in the middle of each of the T-fins. These grooves are made in the manufacturing process as the standard fin is split into two halves and then rolled over. What is more important in the photograph is the presence of small indentations along the surface of the fins. According to the manufacturer, these indentations were caused apparently by a small longitudinal surface crack in the original solid rod from which the specially manufactured finned sample was made. After the finning operation, what was left of this crack was a series of small cavities along the length of the surface. These cavities formed regular active nucleation sites as shown in Figure 7(b) which may have influenced the heat transfer measurements during these tests in a way that would not be expected from a standard commercial Gewa-T surface. Attempts were made to polish the surface to remove these cavities, but it was discovered that they were deep enough so that most of the T-caps would have to be removed in order to get the entire surface to be smooth and cavity-free.

Figure 8 shows the effect of the aluminum shroud in controlling the bubble motion from the test surface at a heat flux of 50 kw/m^2. Figure 8(a) shows both a side view and a bottom view (reflected from a mirror) of the unshrouded surface. Notice



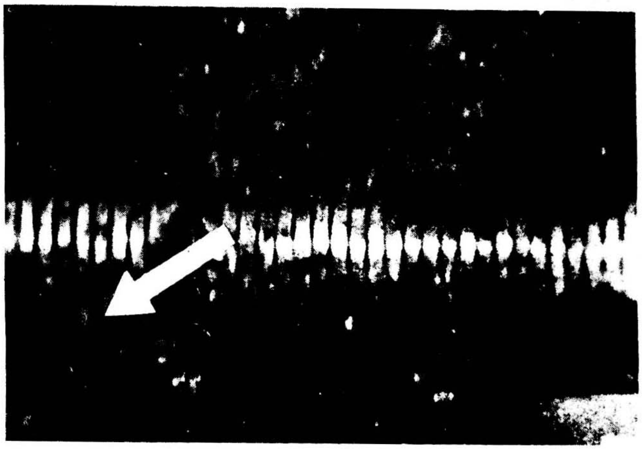


Figure 7. Photographs of boiling action from Gewa-T surface at a heat flux of 20 kw/m^2.
(a) End view
(b) Side view

the presence of large, stagnant vapor bubbles at the bottom of the tube which have penetrated the gap between the fins. Figure 8(b) shows the same two views of the surface when it was covered with the 60-8.5 degree shroud. The view of the bottom of the tube shows the small axial slit with an 8.5 degree aperture. With the the shroud in place, the liquid is forced to enter through the aperture at the bottom and depart with the the vapor out the top. With the small aperture on the bottom, the entering liquid velocities are relatively high. As a result, vapor bubbles which grow in the channels at the bottom of the tube are prevented from bursting out from the bottom. Figure 8(b) still shows the presence of a few vapor bubbles on the bottom. In most instances, these bubbles tried to break out but were forced back into the channels by the flowing liquid.

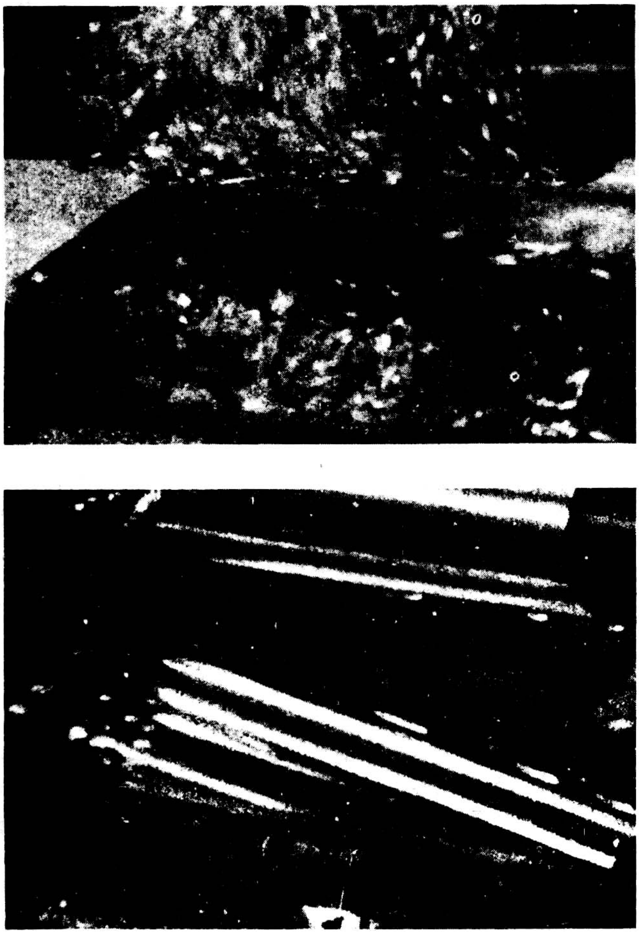


Figure 8. Photographs showing the effect of an aluminum shroud on the boiling action at 50 kw/m^2.
(a) View without shroud
(b) View with 60°-8.5° shroud

Figure 10 shows the data of the unshrouded surface after following pre-boiling procedure B. With this procedure, a smaller temperature overshoot was observed in comparison to procedure A which allowed the surface to cool in the liquid pool overnight. Several runs where made to test the reproducibility of the data observed in Figure 10. Agreement between all the data was excellent, indicating that the data could be utilized as a standard for comparison. Figures 11 and 12 compare the data obtained with two of the shrouds to that of the unshrouded surface. It is evident that the presence of the shrouds increases the boiling heat transfer

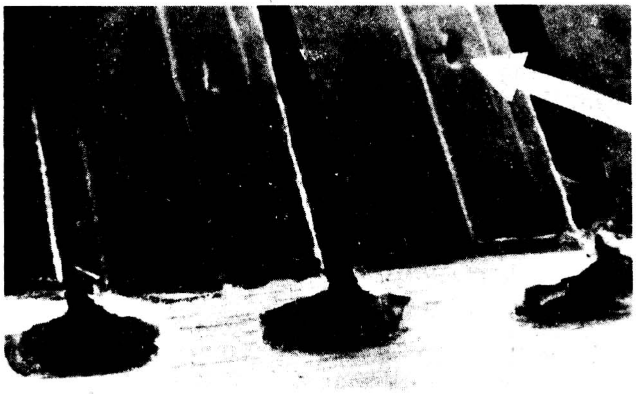


Figure 9. SEM photograph of Gewa-T fin details (25x).

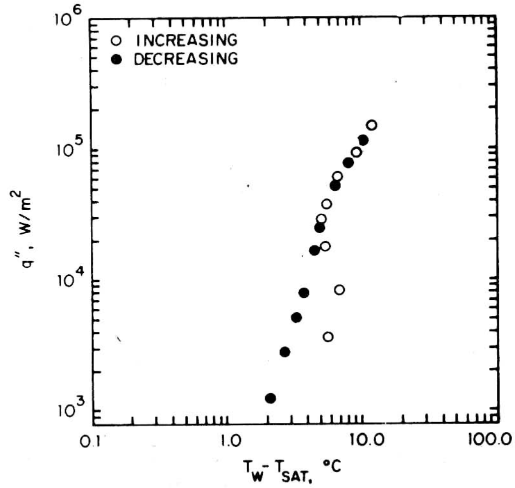


Figure 10. Standard data of Gewa-T finned surface using procedure B pretreatment.

coefficients at low heat fluxes (corresponding to ΔT's of 1-4 °C). For example, at a ΔT of 3 °C, the unshrouded surface would carry a heat flux of approximately 4 kw/m^2 whereas the 60-60 shroud would support 20 kw/m^2 and the 60-8.5 shroud would support 30 kw/m^2, a nearly tenfold increase in heat transfer. Consequently, it can be concluded that the liquid circulation within the channels of the Gewa-T surface is very important in enhancing the boiling heat transfer. The bubbles which nucleate within the channels, as long as they are constrained to move around the tube within the channels and depart only from the top, act as pumps to supply fresh liquid to the surface. If the bubbles stagnate within the channels or push their way out the bottom, the channels become starved of fresh liquid, and the heat transfer coefficient decreases. This latter trend is evident at high fluxes because the presence of the shroud prevents some of the vapor from departing from the surface, and the channels rapidly dry out.

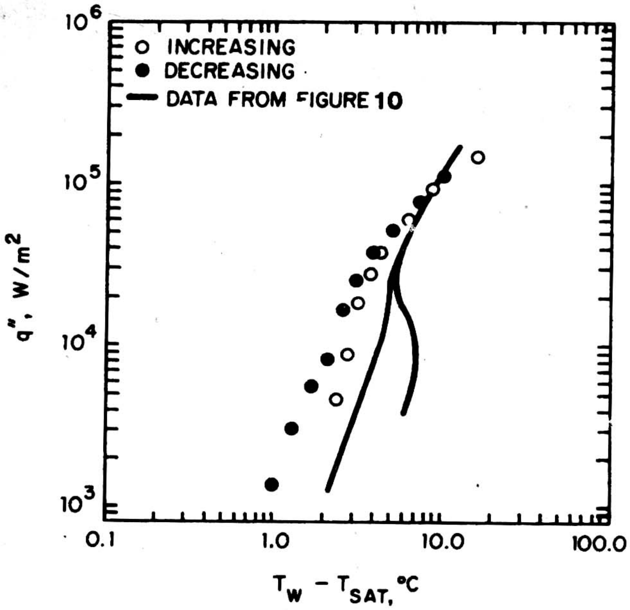


Figure 11. Effect of 60°-60° shroud on Gewa-T boiling performance.

The fin effect of the Gewa-T surface was studied by taking data after progressively machining away portions of the fin height. Figures 13, 14, and 15 show the effects of removing the T-caps, removing the straight fins and polishing the smooth surface to a mirror finish, respectively. It is clear upon examining Figure 13 that removing the T-caps causes a significant reduction in heat transfer of from 50 to 60 percent. This result confirms the importance of the channels in the enhancement of boiling heat transfer. The presence of the straight fins is not as important as the existence of the covered channels. This can be seen upon comparing the results of Figures 13 and 14 which show very little difference except at the very highest heat fluxes. Figure 15 shows the data after following the very last step of the destructive test procedure. The difference between the data in Figures 14 and 15 is due to polishing away all the surface imperfections on the base of the Gewa-T surface leaving a smooth mirror surface to nucleate at higher wall surperheats.

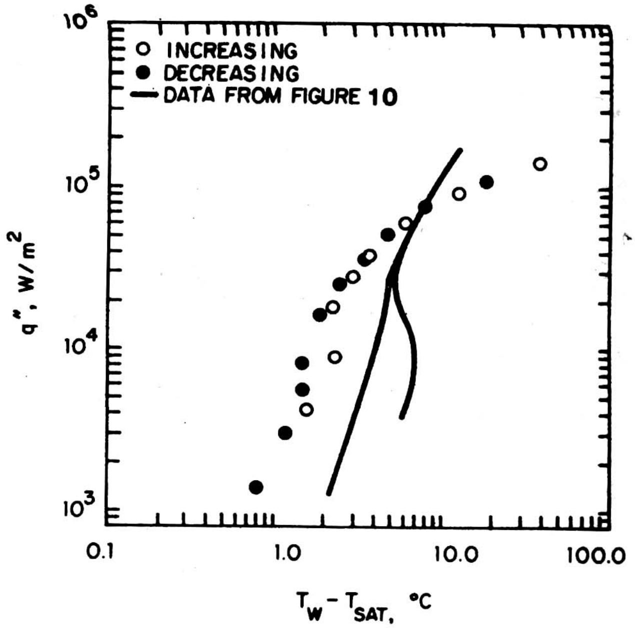


Figure 12. Effect of 60°-8.5° shroud on Gewa-T boiling performance.

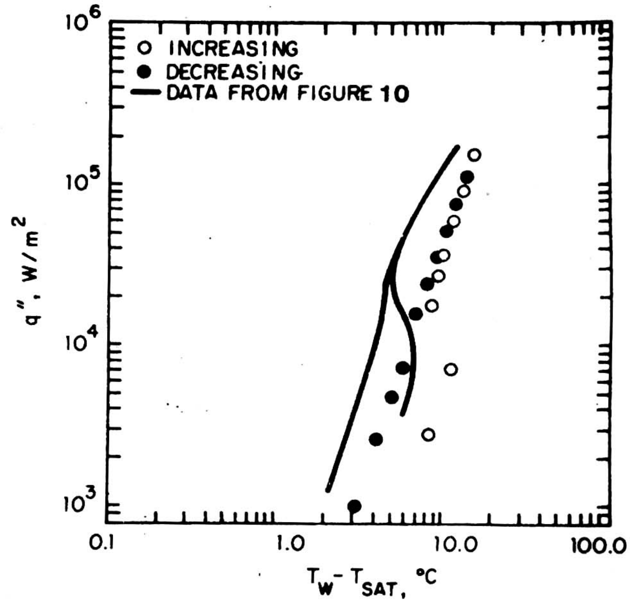


Figure 13. Effect of removing the T-caps from the Gewa-T surface.