Heat Transfer from Multiple Spines to Boiling Liquids

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The value of fins as a means of increasing the rate of heat transfer from a surface is widely known. Early fin analyses by Harper and Brown (*7*) and Gardner considered a constant heat transfer coefficient along the length of the fin. Later studies by Ghai (*4*), Gardner (*3*), Han and Lefkowitz (*6*), and Chen and Zykowski (*2*) modified their analyses by considering the heat transfer coefficient as a function of position along the fin. All of these studies considered using fins in air.

A study by Haley and Westwater (*5*) showed that the heat transfer coefficient along a fin during boiling is a function of temperature along the fin, generally expressed as a boiling curve. Using a numerical technique, they solved the general heat transfer equation and developed a design technique for the use of a fin during boiling. The main assumption in this development was that the heat transfer coefficient at any point on the nonisothermal heating surface is the same as would be obtained if the surface surrounding the point were at the same temperature. Their results were presented as graphs of temperature gradient at the fin base versus metal-to-liquid temperature difference at the base of the fin. A further analysis was made to determine the optimum shaped spine (of minimum volume). The optimum spine was found to be turnip-shaped. One of the main limitations of the optimum fin was the difficulty of manufacture. This has led to the study of approximate optimum fins by Cash, Klein, and Westwater (*1*) and by Siman-Tov (*11*).

In all the previous work with boiling liquids, the interest was centered on a single fin. A discussion of Gardner's (*3*) results, in regard to air flowing past transverse fins, brought out the importance of fin spacing. For no interference it was suggested that fins be at least two boundary layers apart. The most effective spacing was found to be 12% larger than one boundary layer. Although some other studies by Jones and Smith (*9*), Welling and Woodridge (*12*), and Hsu, Vatsaraj, and Hsieh (*8*) considered multiple-fin arrays in free convection, no study has been made of multiple fins during boiling heat transfer. This study was aimed at determining if any effect on heat transfer to boiling liquids is caused by varying the spacing between fins. If an effect is present, how large is it, is it an increase or decrease, and at what spacing does it become noticeable? The spacings in this study refer to the clearance between the fins.

EXPERIMENTAL APPARATUS AND PROCEDURE

A schematic diagram of the equipment is shown in Figure 1. It consisted of a 1-gal. stainless steel boiler with Pyrex plate glass windows in front and back. Vapor rose through 5 ft. of 1-in. stainless steel piping to a condenser. Condensate could be collected during open cycle operation or returned to the boiler during closed cycle operation. The piping and condenser were insulated with a 1-in. layer of 85% magnesia, and the boiler with at least 1 in. of glass wool. Freon-113 and water were the test liquids used throughout the study.

Most of the fins were horizontal cylinders of 0.250 in. diam. made of pure copper. Each fin passed through one wall of the boiler through a Teflon seal and connected to an external heat source. With Freon-113, fin lengths of 1.125 and 0.75 in. were used inside the boiler, whereas with water the length was 0.75

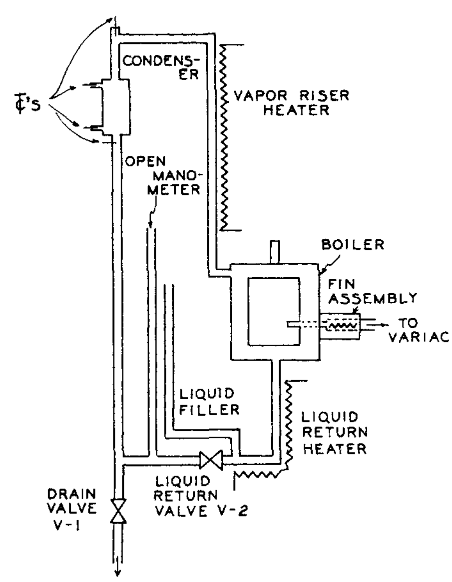

Fig. 1. Boiler and vapor system.

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in. For one and for two fins, individual heat sources were used, namely, a 2-in. diam. copper cylinder, each 3.5 in. long and each containing a 350-w., cartridge, electric heater. For studies of three or more fins in a row or multiple rows of fins, the heater block shown in Figure 2 was designed. The unique feature is the slots which allow variation of the spacing of fins in a row to any spacing desired. Six 350-w. cartridge heaters were used in this larger heater block. With this design it was possible to use ten fins as illustrated in Figure 2 with a heat duty of 200 B.t.u./hr. per fin. The fin temperature at the boiler wall was then 290°F. and at the massive heater block it was about 900°F. The heater block was kept in a nitrogen atmosphere to prevent oxidation. Removable parts of the heater assembly were coated with graphite before assembling. This permitted disassembly later and prevented the accidental occurrence of welding.

Because of the larger heat requirements for water, fins for water were constructed with a larger cross-sectional area outside the boiler while retaining the 0.250-in. diam. test section inside the boiler. The test sections inside the boiler were 0.75 in. long, whereas the portions outside the boiler were 3.25 in. long. Two different designs used are shown in Figure 3. Variations of the fin spacing were easily achieved with these designs. For the water studies, bayonet Globars were used as the heat source in place of the cartridge heaters. Along the fin support rod, between the fin gasket and the heater block, were located three thermocouple wells drilled radially to the rod axis. These temperatures were used with Fourier's first law to calculate the heat duty at the base of the fin. Extrapolating these temperatures permitted calculations of the temperature at the base of the fin. Heat balance checks were obtained either by monitoring the condenser duty or by collecting the condensate. Agreement was usually obtained within 15%. The heat duties presented in this paper are the values based on the thermocouples in the fins.

Before each run the fin surface was cleaned with a commercial copper cleaner and then rinsed and dried. The Freon-113 was DuPont's refrigeration grade, $CCl_2F - CF_2Cl$, 99.9% pure. It has a specific gravity of 1.56, a boiling point of 117.6°F., a surface tension at room temperature of 17.3 dynes/cm., a latent heat of vaporization of 63.1 B.t.u./lb., and a vapor density at the boiling point of 0.46 lb./cu.ft. After two or three runs it was distilled and reused. The water was deionized water obtained from the laboratory supply. Further details concerning the apparatus and procedure are available (*10*).

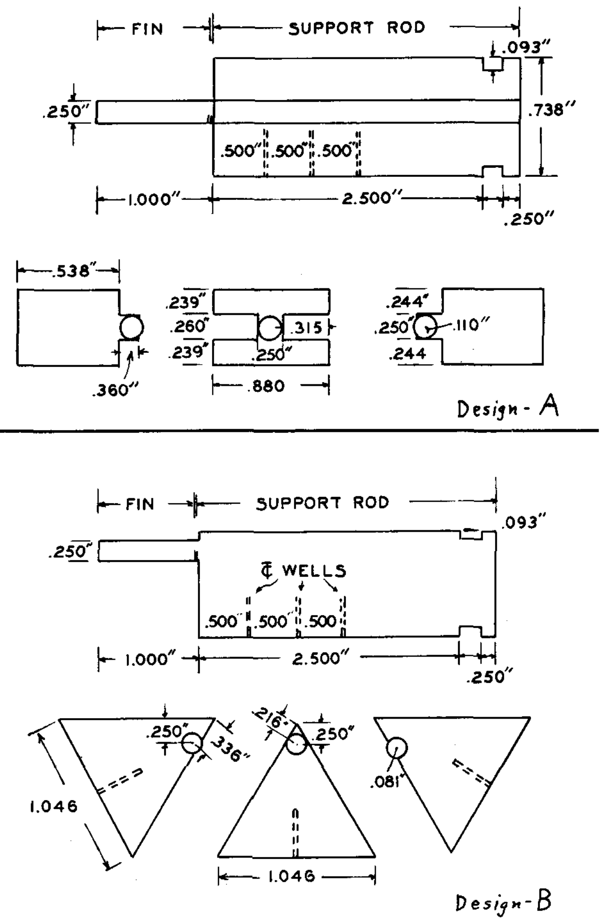

Fig. 3. Two multiple-fin designs used with water.

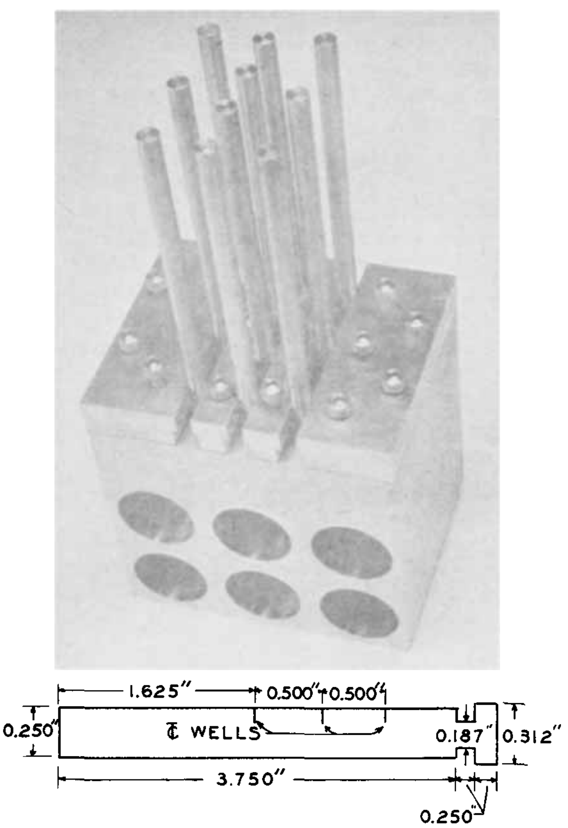

Fig. 2. Ten-fin assembly on heater block. Lower sketch gives details of one of the fins.

PRESENTATION AND DISCUSSION OF RESULTS

Boiling curves for the fins were obtained at various spacings from zero (fins touching) to a clearance as great as 1.1 in. In each case the performance of selected individual fins was monitored and the data herein show the results. For reference purposes the performance of a single fin, tested alone, was obtained also.

Test with Freon-113

Data were obtained for the boiling curve, from free convection through film boiling. The transition region was unstable, because the heat source was electrical, so no data were obtained for that region. The results are conveniently expressed as temperature gradients at the base of the fin (location of the boiler wall) versus temperature difference between the fin and the surrounding liquid. The heat duty per fin is equal to the gradient multiplied by the cross-sectional area and the thermal conductivity. The instrumented fin is shaded in all figures. The amount of data and the scatter of data shown for zero clearance in Figure 4 are representative of all the data obtained throughout the study. The additional curves were obtained from similar experimental points, which, for clarity, are omitted. The detailed data are available (*10*).

Horizontal Spacing. Figure 4 is for two fins with horizontal spacings of 0 to 1.08 in. Independent control of the two fins was available, and it was possible to have either equal heat duties or equal base temperatures (at the boiler wall). At a spacing of 1.08 in. both weie tried; the results indicated that both led to the same conclusions concerning the effect of spacing. For the two-fin study, equal fluxes were selected. For more than two fins, independent fin control was not possible; the heat input to the heater block was the controlling factor. For the spacings from 0.0625 to 1.08 in., there was no significant effect. For a spacing of zero there is a major change in the curve. The peak of the curve has decreased from about 2,600 to 2,150°F./ft. This corresponds to a 17% reduction in the heat duty per fin, from 193 to 159 B.t.u./hr. From observations of the boiling, particularly beneath the fin, it could be seen that as small bubbles of vapor were produced, they coalesced until the entire crevice formed by the two touching fins was filled with a layer of vapor. At low fluxes with no boiling at the cooler ends of the fins the vapor produced at the warmer base of the fins coalesced to form this layer, and then traveled along the crevice and exited at the free tips of the fins. At higher fluxes some vapor exited from the tips and some flowed around the sides of the fins. This vapor layer, covering almost one-quarter of each fin's surface area, was restricting the normal flow of liquid to the fins, thus bringing about the 17% reduction in heat flux.

Figure 5 shows results obtained with three fins with horizontal spacings of 0.0625 and 0 in. For 0.0625 in. there was no significant effect. When the spacing was changed to 0.00 in. the expected result occurred, a decrease in flux of the center fin greater than that obtained with two fins. There was a reduction from 2,660° to

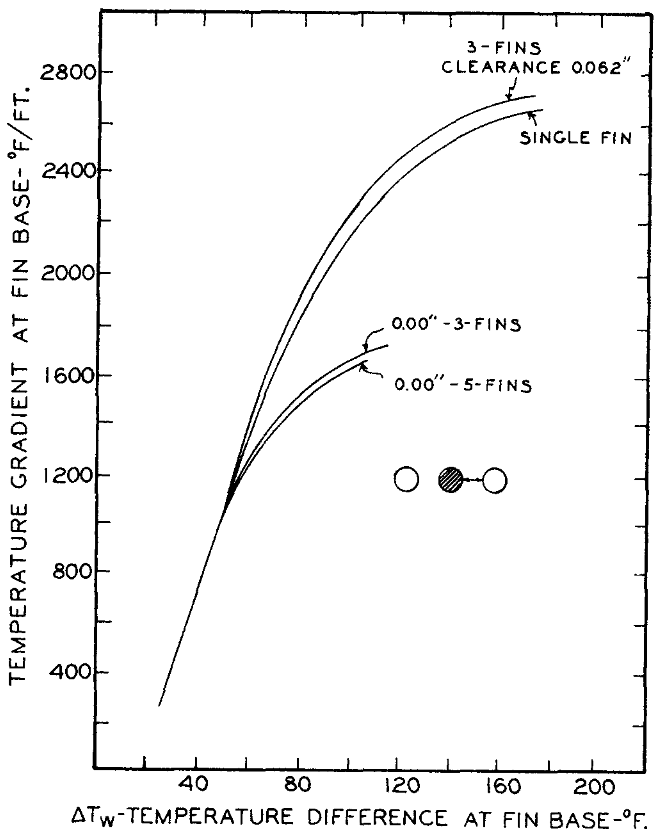

Fig. 5. Effect of spacing for three fins and five fins in Freon-113 in a horizontal row; 0.25 in. wide, 1.125 in. long.

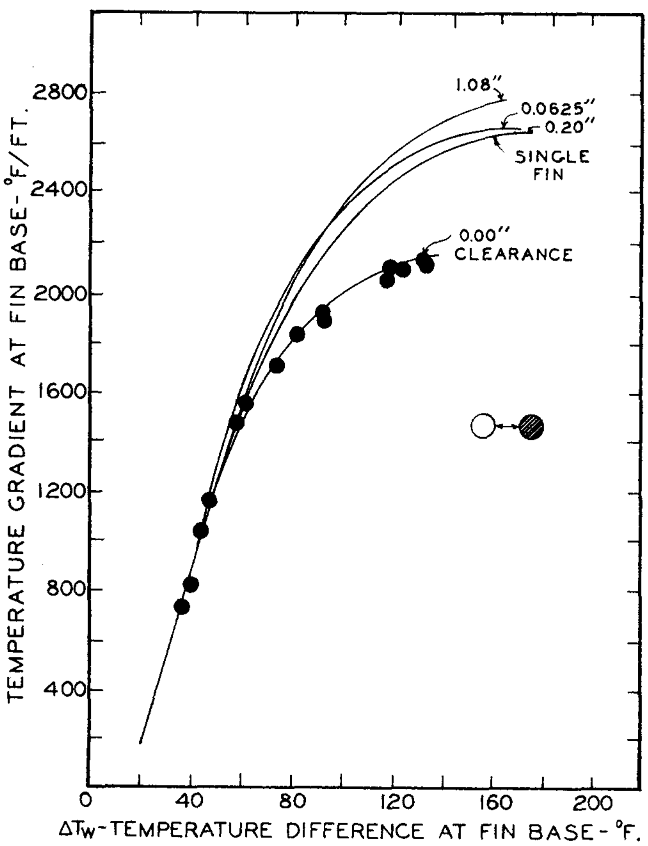

Fig. 4. Experimental data showing effect of horizontal spacing for two copper fins in boiling Freon-113. Each fin is 0.25 in. wide and 1.125 in. long. Data are for the right fin.

1,780°F./ft., about a 31% decrease in flux. As with two fins, the reduction is due to the vapor layer accumulating beneath the fins. Vapor produced beneath the center fin could not escape around the sides of the center fin due to the presence of the other fins on either side. Thus a layer of vapor formed in the crevices beneath the fins. Photographs show that even when the flux is low on the boiling curve, and nucleation sites are just beginning to become active at the base of the fin, there is a large amount of vapor beneath the fins. As the flux increases and the peak boiling moves out along the fin, the rear portion of the center fin becomes completely covered by vapor. The outer two fins behaved similarly to the two-fin arrangement giving a 17% reduction. As a further check on this trapping of vapor, five fins with zero spacing were tested. The results are shown in Figure 5. The center fin behaved almost identically regardless of whether it was in a row of three or five fins. It was noted also that the two fins on either side of the center fin in the five-fin array behaved as the center fin did. The outer fins, although expected to give results similar to the two-fin group, gave results very similar to the other fins in the five-fin row. This further reduction in the outer fins may result because of the larger amount of vapor trapped and then escaping around the outer fins causing a greater portion of the fins to be covered by the vapor.

Horizontal Flat Plates. If the number of horizontal fins with zero spacing is large enough, the appearance of the set is similar to that of a flat plate. With a horizontal flat plate there is the requirement that any vapor produced beneath the plate must travel to the front or sides to escape, the same as the situation for fins with zero spacing. With the plate, however, there are no crevices underneath. It was decided to test a fin in the shape of a horizontal flat plate. A plate similar to three fins touching

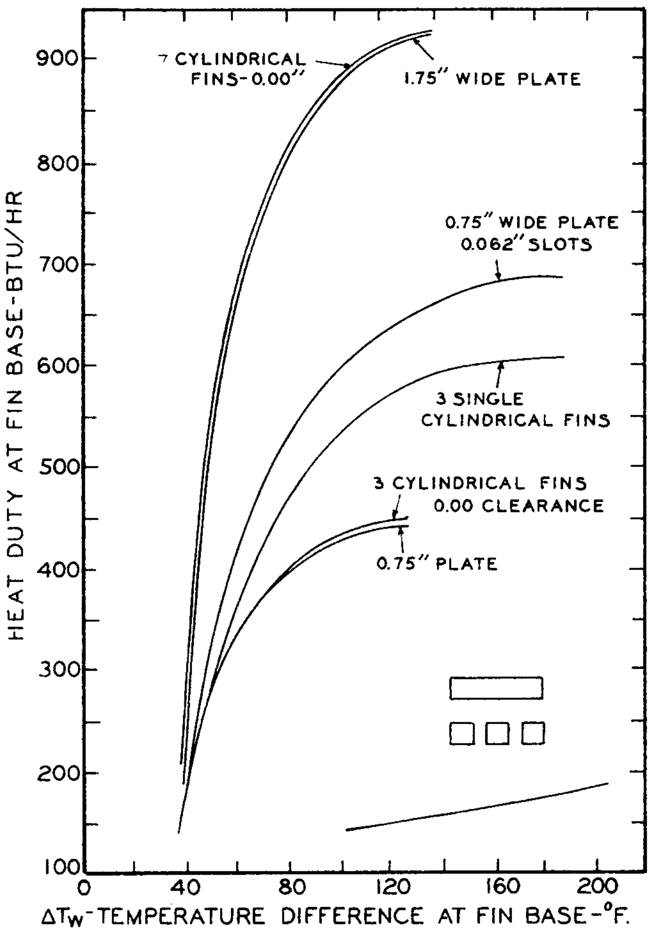

Fig. 6. Comparison of 0.25-in. thick horizontal slab fins with rows of touching cylindrical fins of 0.25-in. diam.; in Freon-113. The length of both is 1.125 in.

was chosen. The boiling length was the same as for the fins, 1.125 in. The plate thickness was 0.25 in., and the width 0.75 in., equivalent to three fins with zero spacing.

With the fins, the data were plotted as the gradient at the fin base, °F./ft., versus ΔT_w, the metal-to-liquid temperature difference at the base. Because of the larger cross-sectional area of the plate, there is automatically a lower temperature gradient for the same heat duty, complicating a comparison between the fins and the plate. For simplicity, the data for plates are plotted as B.t.u./hr. versus ΔT_w. The reference curve for single fins acting independently is the sum of the heat duties for three single fins at a given ΔT_w.

The results for the flat plate, Figure 6, is the sixth curve from the top. It is nearly coincident with the curve for three fins with zero spacing. The plate had 13% less surface area than the fins, but the cross-sectional area of the plate was 21% greater than for the three fins. Apparently these two factors counterbalance. The same conclusion resulted from a comparison of tests with a plate 1.75 in. wide and tests with seven fins touching, as shown by the two upper curves in Figure 6.

On the bottom of the plates large vapor patches accumulated, similar to the vapor layer in the crevices of the fins. Even at low heat duties, small bubbles coalesced into large patches of vapor which, at times, covered up to 75% of the bottom surface of the plate. If the vapor removal could be improved, the heat duty should likewise improve. Therefore two vertical slots were cut parallel to the main axis of the 0.75-in. plate. Each slot was 0.25 in. high, 0.062 in. wide, and 1.125 in. long, resulting in three rectangular fins with a 0.062-in. spacing. The third curve from the top in Figure 6 shows that the heat duty for the slotted plate increased by 57% over the rectangular plate. The increase placed the curve higher than the curve for the three single fins. Although the increase was 57%, 32% of this was due to an increase in the surface area of the plate, the remaining 25% being due to the slots enabling the vapor to pass upward. No formation of vapor patches was detected beneath the slotted plate.

Vertical Spacing. To determine the effects of a fin located below the control fin, vertical spacings of 1.00, 0.50, 0.186, and 0.032 in. were tested. Small differences in the performance curves resulted, but they were not significant. For example, at a spacing of 0.50 in. an increase of 11% in the heat duty occurred, compared to isolated fins. However, two more fins could have been placed in the 0.50-in. spacing, thus greatly increasing the overall heat removed from the base area. A spacing of 1.00 in. also resulted in a slight improvement in the heat duty, compared to isolated fins. This anomalous behavior suggests that bubbles striking a fin from below may disturb the film-boiling regions on that fin and improve the local heat transfer.

Three fins with vertical spacings of 0.047 and 0 in. were tested (Figure 7). No effect was observed for the center fin with a spacing of 0.047 in. For 0.00 in. a 15% reduction occurred because of some trapping of vapor in the crevices between the fins.

Multiple Rows. All the previous runs considered only a single row or column of fins. To consider the effects of a multiple row arrangement, ten fins, in three staggered horizontal rows of three, four, and three fins, were used. Figure 2 is a view of the assembly before connection to the boiler. The horizontal clearance between fins in the horizontal rows was varied, but the vertical clearance between the rows was constant at 0.375 in. The largest horizontal spacing, 0.062 in., showed no effect, as can be seen in Figure 8.

For a 0.032-in. spacing the results were somewhat contradictory. The peak flux for the control fin (shaded in the

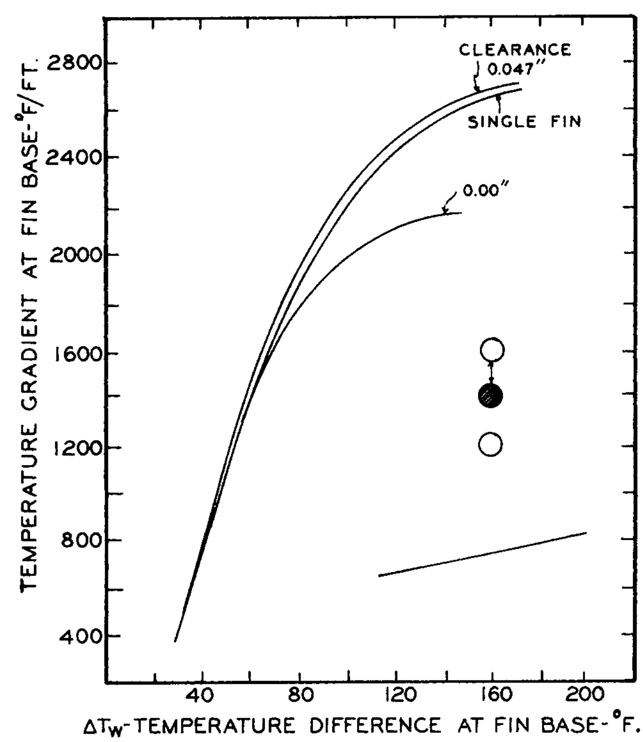

Fig. 7. Effect of vertical spacing, three fins in Freon-113; 0.25 in. wide, 1.125 in. long.

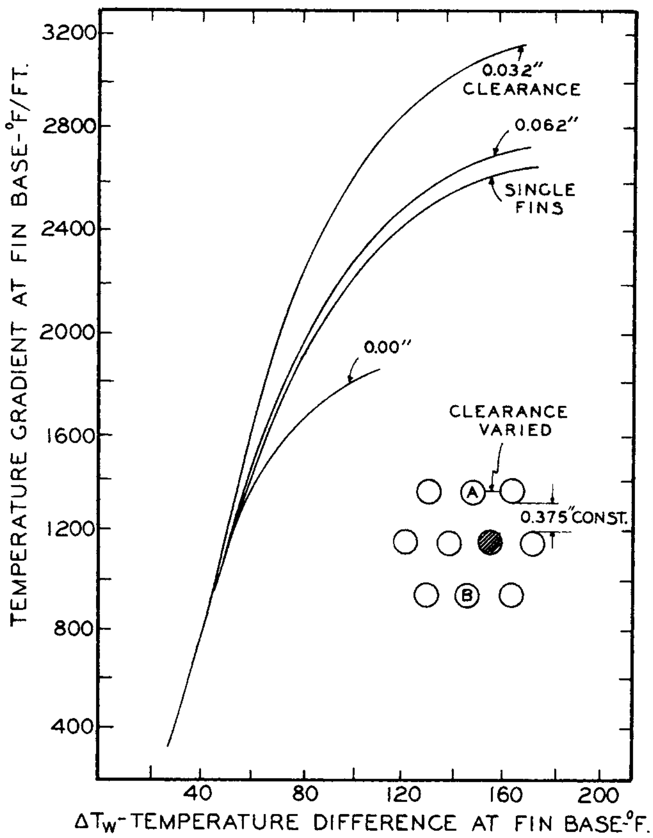

Fig. 8. Effect of horizontal spacing with ten fins in Freon-113. Data are for an inner fin in the middle row; 0.25 in. wide, 1.125 in. long.

sketch) was greater than for a single fin. Although there is nothing definite to which one can attribute this increase, it does prove that there is no decrease in flux. Fin *A*, in the top row indicated in the sketch in Figure 8, was instrumented also and its heat duty was slightly less than the shaded fin in the middle row and another instrumented fin (fin *B*) in the bottom row. But the lower two fins gave heat fluxes about 22% above the single fin curve. The lower two fins were very similar in heat duty, indicating no interaction between the bottom two rows.

For zero horizontal spacing with multiple rows, the results show a 27% decrease in heat duty compared to the single fin. This is nearly equal to the 31% decrease noted for the central fin of a single horizontal row of touching fins shown in Figure 5. The reason for the decrease is the trapping of vapor beneath the fins.

Vertical Flat Plates. The tests with cylindrical fins showed that a horizontal gap as small as 0.03 to 0.06 in. is sufficient for easy escape of the vapor. In order to verify or refute this rather surprising conclusion, some tests were carried out with fins in the shape of parallel, vertical, flat plates. Three plates were constructed, each with a boiling section 1.125 in. long (horizontal), 0.250 in. thick, and 1.500 in. high (vertical). The center plate was used as the control plate. The curves in Figure 9 show that for spacings of 0.187, 0.125, and 0.062 in. there was no effect of spacing. Each plate operated independently of the others. All vapor rose vertically. For the gap of 0.062 in., the vapor production rate corresponds to a calculated exit velocity of 28 ft./sec. from the top of the slots.

For a spacing of 0.032 in. there was a definite effect, causing a reduction in heat duty of about 35%. At this spacing some vapor escaped at the top of the plates, as was normally exhibited for the larger spacings, but some bursts of vapor were issuing horizontally from the front and vertically downward from the bottom of the plates. Because the vapor was exiting from all sides of the space between the plates, the liquid could not easily contact the surface. These tests indicate that a clearance of 0.032 in. is too small, but that 0.062 in. is adequate.

Tests with Water

Water was selected as a second liquid, because its thermal properties are very different from those of Freon-113. The peak heat flux of the ordinary boiling curve is about five times as high for water as for Freon-113. The volume of vapor produced at the peak turns out also to be about five times higher for water. The results for tests with a single horizontal copper fin, 0.25 in. diam. by 0.75 in. long, are shown as the upper curve in Figure 10. Because of the high heat requirements the peak of the curve was difficult to obtain. Therefore a ΔT_w of 200°F. is used hereafter as a reference for the comparisons of effects.

Horizontal Spacings. One arrangement studied with water was three fins with horizontal spacings. The spacings ranged from 0 to 0.25 in., and the results are shown in Figure 10. The results for the center or control fin with 0.25- and 0.062-in. spacing follow the single fin curve almost identically, indicating no effect at these spacings.

Surprisingly, no effect was apparent even at zero spacing (fins touching). When Freon-113 was used, a 31% reduction in heat duty had occurred at zero spacing. High-speed motion picture photography showed that the bubbles of water were much larger than for Freon-113. In addition, after coalescing, the water bubbles formed even larger bubbles. These giant bubbles bridged the crevices beneath the fins, whereas bubbles of Freon-113 tended to lie in the crevices and travel along their axes. Thus the large water bubbles existed around the sides of the fin

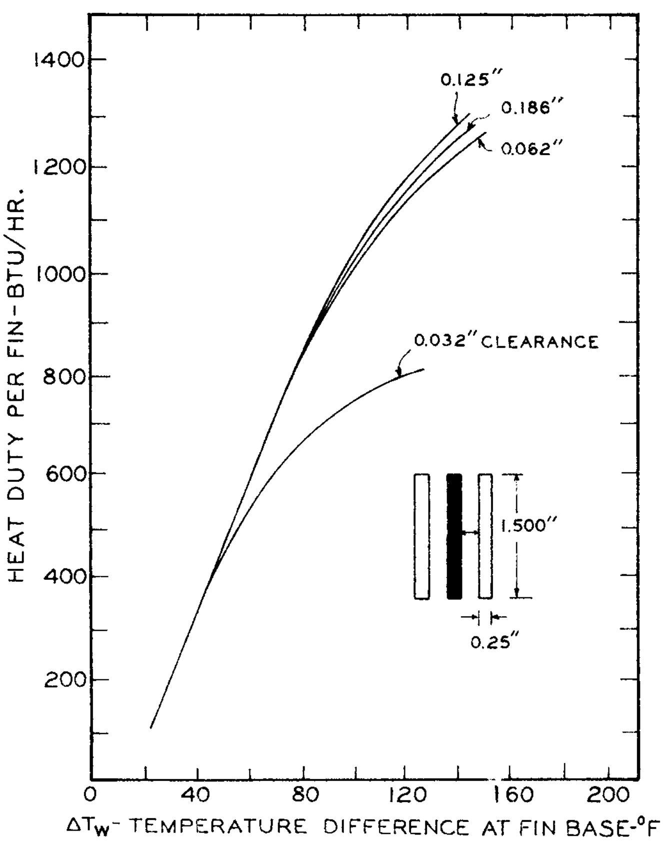

Fig. 9. Effect of spacing for three vertical slab fins in Freon-113. Each fin is 1.125 in. long. The curves are for the middle plate.

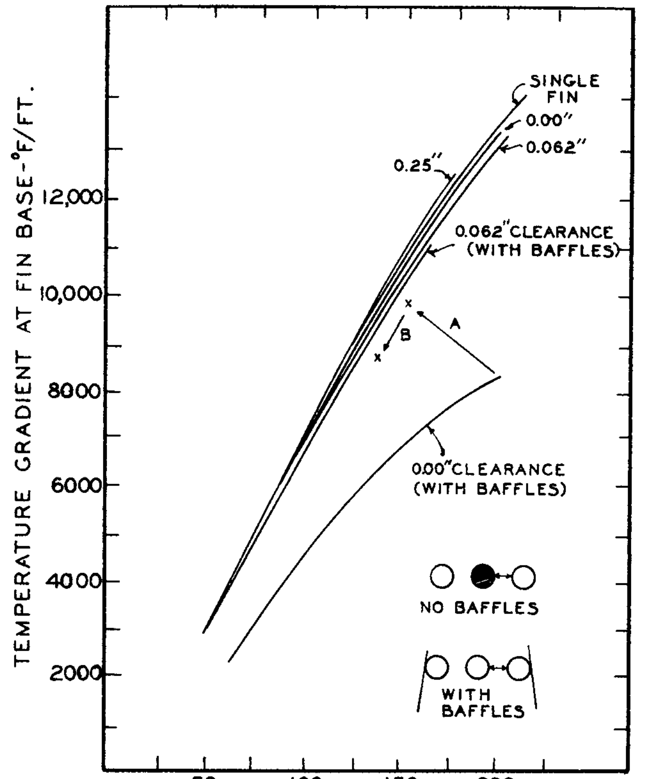

Fig. 10. Tests with water on three fins in a horizontal row. The effect of baffles is illustrated also. The fins are 0.25 in. wide and 0.75 in. long.

assembly as readily as the front. In other words, holdup beneath the fins was nil for water but appreciable for Freon-113.

Horizontal Flat Plate. The fact that a large amount of vapor was exiting around the sides of the fins with zero spacing suggested that a larger number of fins in a row might prevent this and would force more vapor out the front. Because of equipment limitations it was not possible to place any more fins in a row. However, it was possible to test a flat plate, and then place slots in it to show whether this mode of vapor removal would improve the heat duty.

The results, Figure 11, show the curves for a fin in the shape of a flat plate tested alone and the same plate with slots running its entire wetted length. With the plate alone there was much vapor coming from the front, and there was a substantial amount coming around the sides. Vapor patches did form beneath the plate but not to the extent as for Freon-113.

The plate then had 0.062-in. slots cut in it, each slot 0.75 in. long and 0.25 in. high. This gave six fins with dimensions of 0.198 in. wide, 0.250 in. high, and 0.750 in. long. The results show a definite improvement over the plate with no slots, giving about a 26% increase in heat duty. However, by putting the slots in the plate, the surface area was increased by 45%, whereas the cross-sectional area was decreased by 21%. Thus the heat duty increase may be explained as nothing more than a surface area effect. This could still mean that the overall width of the plate was not wide enough to show an effect of width. The increase in heat duty did prove that liquid flowed into the 0.062-in. slots and did form new vapor there.

Another series of tests was made using slots widened to 0.092 in. The results in Figure 11 show the curve falling between the other two. This represents a 10% increase in heat duty over the original plate, resulting from a 39% increase in surface area and a 31% reduction in cross-sectional area. Again the change in heat duty appears to be a surface area effect.

Horizontal Spacings with Baffles. A problem in determining the existence of any effect of horizontal spacings when water was used was that of evaluating the effect of the flow of large amounts of vapor around the sides of the fins. For commercial applications with large arrays of fins, such vapor escape would probably be impossible. To stop this side flow, two baffles were sealed to the outside fins in the horizontal row of three fins. The baffles were pieces of Teflon, 0.75-in. wide, 0.062-in. thick, and extended about 0.75 in. below the fins. They were tangent to the two outer fins sketched in Figure 10.

For zero spacing between fins the results in Figure 10 show a definite decrease in heat duty for the center fin. The decrease is about 32%, almost identical to that obtained with the center fin of three in Freon-113. While the flux was at its peak value, the baffles were knocked off and, as the data show, the center fin demonstrated a dramatic increase in heat flux and a decrease in ΔT_w. The new data point was near the single fin curve. Arrow *A* in Figure 10 indicates the change in flux and ΔT_w experienced by the center fin after the baffles were removed. Arrow *B* shows that the fin continued to follow the single-fin curve as the flux was subsequently decreased. When the baffles were in place, the liquid was forced out the front of the fins, resulting in a large amount of vapor holdup beneath the fin. Because of the large size of the bubbles formed with water, the vapor beneath the fins appeared to be more vigorous in motion than experienced with Freon-113.

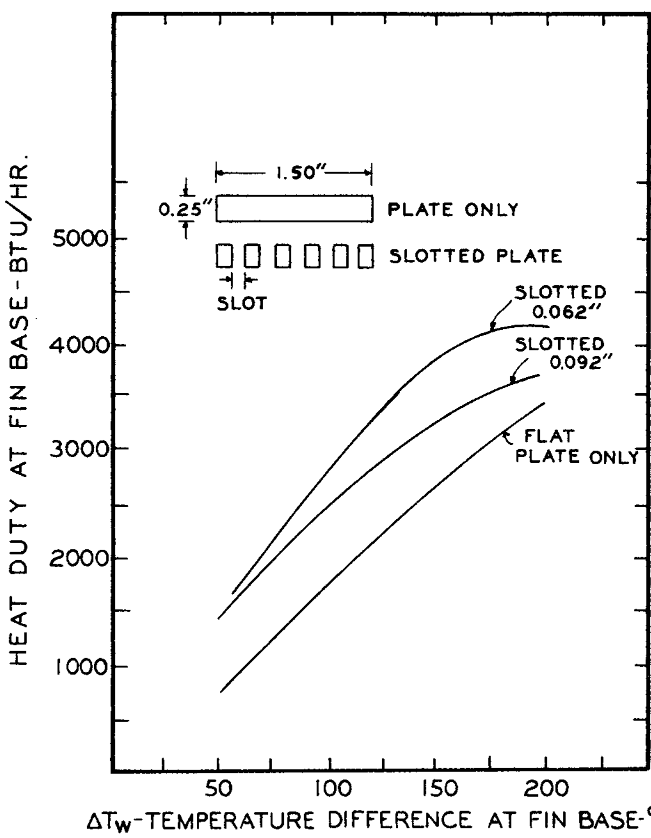

Fig. 11. Effect of slots in a horizontal slab-fin of 0.7y in. long, in water.

To give a further check to the effect on spacing, the baffles were used with the fins having a 0.062-in. spacing, and no effect was observed. Thus 0.062 in. is wide enough to allow water vapor to escape between the fins. The curves are given in Figure 10.

Multiple Rows. Tests were made with an arrangement of nine fins, three rows with three fins each. The vertical clearance between rows was a constant 0.395 in. The clearance between fins in the horizontal rows was varied. An end view of the rectangular array is sketched in Figure 12.

At a horizontal spacing of 0.092 in. no significant effect was present for the center fin in the top row, as shown by the upper two curves in Figure 12. For zero horizontal spacing there was a 30% reduction in heat duty, probably due to the large amounts of vapor engulfing the top row. Photographs indicated that at times only six fins could be seen, whereas the upper three were obscured by a large vapor mass. Thus in a multiple array, the fins should not touch. A horizontal clearance of 0.092 in. is adequate for vapor escape. Probably a smaller clearance would be sufficient.

Comparison of Freon-113 and Water on Identical Fins

The preceding Freon-113 runs were made at a fin length of 1.125 in. and the water runs were at 0.75 in. To determine whether the results are dependent on length in this range, two series of tests were made with Freon-113 at a fin length of 0.75 in.

The first was a determination of the single-fin curve at the shorter length. The other was with three fins with a horizontal spacing of zero. The data showed that the reduction in heat duty for the center fin in the three-fin array was about 32%, almost identical to the 31% reduction obtained for the same array with fins 1.125 in. long. One of the other fins in the row was instrumented also and was found to perform as the longer ones did, giving the expected reduction of approximately 17%. It is concluded that the results in this paper are not dependent on fin length, at least in the range of 0.75 to 1.125 in. It is unlikely that fins longer than this would be used in boiling liquids.

The question could arise as to what effect a slight upward angle in the orientation of the fins could have on the trapped vapor layer. During one of the runs with Freon-113 the fins were deliberately tipped to an angle of 1.44 deg. with the horizontal (with the free tips being elevated). No change in heat duty occurred.

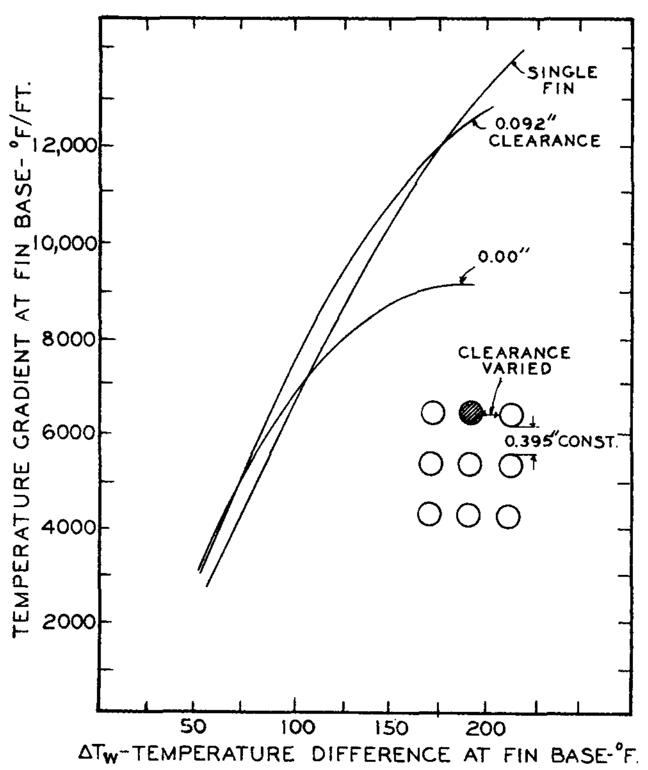

Fig. 12. Effect of horizontal spacing with nine fins in water. Data are for the middle fin in the upper row; 0.25-n. wide, 0.75 in. long.

CONCLUSIONS

For heat transfer to boiling water or Freon-113 at atmospheric pressure:

1. The fins can be brought very close together before any effect of spacing on the heat duty can be detected.
2. A horizontal spacing of 0.062 in. is wide enough to allow all fins to act independently of each other, even for an array of nine or ten fins occupying three rows.
3. This dimension is near the break-off diameter for bubbles of ordinary liquids in nucleate pool boiling.
4. With zero spacing, a trapped vapor layer beneath a row of fins causes a 31% reduction in heat flux for Freon-113; for water the same reduction occurs if sidewise escape of the vapor is prevented.
5. A vertical column of three fins touching experiences a 17% reduction in heat duty.
6. Fins made of parallel, vertical, flat plates show no effect of spacing until the clearance is reduced to 0.032 in., then a 30% reduction in heat duty occurs.
7. Caution should be used when applying these results to arrays of hundreds of fins. New effects might occur when huge amounts of vapor are produced.

ACKNOWLEDGMENT

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