THE EFFECT OF SURFACE THERMAL PROPERTIES AND FINISH ON DROPWISE CONDENSATION

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Abstract—Heat-transfer coefficient measurements for the dropwise condensation of steam at 1 atm on a horizontal surface facing down have been completed using oleic acid as the promoter. The test surfaces consisted of thick discs about 2 in. in diameter and

(a) gold plate on 1·125 in of copper,
(b) gold plate on 0·094 in of zinc and 1 in of copper,
(c) gold plate on 0·12 in of stainless steel and 1 in of copper.

The heat-transfer coefficients were found to be independent of surface subcooling in the range of 2–20 °F and equal to:

$h = 10000$ Btu/h^2 degF for copper,
$h = 4500$ Btu/h^2 degF for zinc,
$h = 2000$ Btu/h ft^2 degF for stainless steel.

It is concluded that: (1) a 20-fold reduction in base material thermal conductivity gives a 5-fold reduction in the heat-transfer coefficient; (2) dropwise condensation heat-transfer coefficients are conduction limited with nucleation effects negligible in the 2–20°F subcooling range; (3) unexplained discrepancies exist between the nucleation effects inferred from these experiments and the direct nucleation measurements presented in the literature.

INTRODUCTION

IN ORDER to make any rational correlation of the dropwise condensation heat-transfer data, it is necessary to have a clear picture of the physical processes involved. When one looks at a surface on which dropwise condensation is occurring, it is observed that drops form, grow, agglomerate, and finally roll down or fall off. This work bears primarily on the problems of drop formation and drop growth.

A horizontal surface facing down was chosen for this investigation because the experiments of Hampson [1] showed this geometry yielded a heat-transfer coefficient that was independent of the condensing rate. It appears that the fraction of the surface which is covered with drops running down is heat flux dependent and this

complication is eliminated with a horizontal surface facing down. For this geometry a change in heat flux simply appears as a change in the time scale of the process. This fact substantially simplifies the interpretation of the experimental results.

This same Hampson data suggests that the condensing heat-transfer process for this geometry is conduction limited. All pure conduction processes have heat-transfer coefficients which are independent of heat flux. Some other heat-transfer processes do also, but when one sees a heat-transfer coefficient which shows no apparent rate effect, the obvious approach is to try to find the conduction process which governs the heat transfer. The most obvious conduction limit for drop condensation is the conduction through the drop and the metal surfaces.

If one writes the equations and boundary conditions for this process, it is apparent that

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surface thermal conductivity could enter into the condensing heat-transfer coefficient as well as the thermal conductivity of the condensate itself. If the surface thermal conductivity is very large, the surface temperature approaches uniformity at a value close to the saturation temperature of the condensate. This tends to give a high heat-transfer coefficient. For low surface conductivity, only a very local cooling occurs in the vicinity of the triple interfaces and a large proportion of the surface is well below saturation temperature. This gives a low heat-transfer coefficient. These ideas suggest investigating surface thermal conductivity over the range of metals used for condenser tubes, that is, stainless steel and copper.

In order to eliminate any effects due to the quality of the promotion, the different metal surfaces were all plated with the same metal, gold. Gold was chosen as it has been found to give a surface that is inert chemically under laboratory conditions.

Another inference that might be drawn from the Hampson data is that the effect of changes in the number of drops on the surface with changing surface temperature is small. That is, no important drop nucleation effects are present so that the heat-transfer geometry is constant. Though drop nucleation is similar to bubble nucleation, it does not appear from his data that nucleation differences on metal surfaces are important in dropwise condensation. A comparison of rough and smooth surfaces would help settle this question.

Therefore, this paper reports the results of an investigation into the effects of surface thermal properties and surface mechanical finish on dropwise condensation.

DESCRIPTION OF APPARATUS

Figure 1 shows a schematic drawing of the experimental apparatus. The condensation took place on the gold-plated horizontal surface of the disc which was always oriented facing down. The disc was mounted on a thick brass plate by means of an O-ring which gave a tight seal.
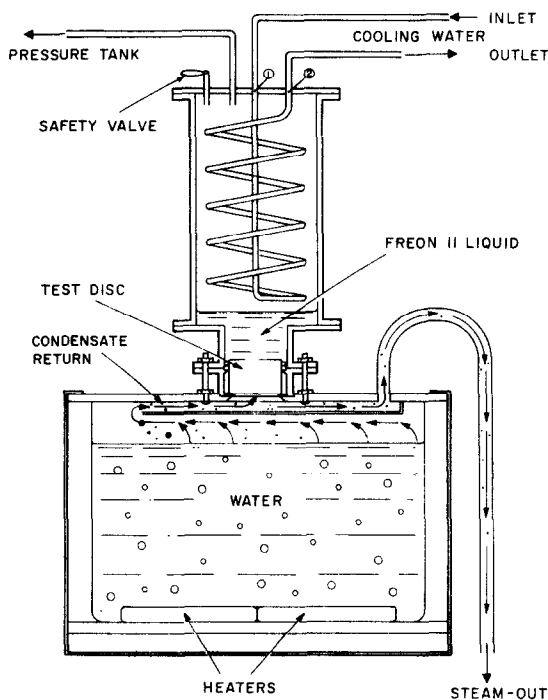

FIG. 1. Diagram of the apparatus. The path of the vapor is shown with arrows while the returned condensate is shown dripping off the scoop.

On the top of the disc boiling Freon 11 was used as a cooling medium. A water-cooled copper coil $\frac{1}{4}$-in I.D. and 50-ft long condensed the Freon which was evaporated. The Freon chamber had a connection to a nitrogen bottle which allowed the pressure in the chamber to be controlled. The maximum allowable pressure in the Freon chamber was 120 psig. The test block was sealed with an O-ring, which was replaced occasionally to prevent leakage.

Below the condensing surface a glass bottomed scoop was attached through which all the steam was passed. The area for the flow of the steam was varied to find the maximum velocity which did not move the drops yet carried off the non-condensables. Below the thick brass top plate, a rectangular Pyrex jar of dimensions $12\frac{1}{8} \times 12\frac{1}{2} \times 12$ in was placed. Inside the jar there were four immersion heaters for the steam generation.

The total output of the four heaters was 3 kW, all of which was used to boil the water.

After filling the jar with water, the boiling was started. Steam thus generated was passed into the glass bottomed scoop. Approximately 5 lb/h of water was boiled away and up to 5 lb/h of water condensed on the test disc. The velocity in the scoop before reaching the test disc was 27 ft/s.

The diameter of the hole in the brass cover plate through which the condensing surface was exposed to the steam was $\frac{1}{8}$ in less than that of the test disc. Sealing the gap between the edges of the test disc and of the brass plate was accomplished with a flat stainless steel ring wound with a Teflon tape. The inner edge of the ring was grooved to center the test disc. The condensing surface could be easily removed from the boiler, without disturbing other major parts, in order to apply the promoter.

Three thermocouple holes (drill size No. 56) were drilled radially into the disc to different depths with the appropriate axial spacing. Thermocouple wells were also placed in the inlet and outlet of the cooling water, and in the condensing steam. All thermocouples used were made of copper–constantan wire of gauge No. 30 and calibrated at the steam point with the reference junction at the ice point.

The thermocouple was read with the Rubicon millivolt null point potentiometer and an external galvanometer.

It was possible to observe the condensation phenomenon on the test surface through the transparent Pyrex jar and the glass scoop. However, the view was sometimes partially obstructed due to the coating of dirt coming from the heaters and from condensation occurring on the Pyrex jar and on the bottom of the scoop.

TEST SURFACE PREPARATION

Properties

Copper ($k = 220$), zinc ($k = 63$), and stainless steel ($k = 10$) were chosen as substrate materials for the condensation surfaces. As is shown in

Fig. 2, the condensing surfaces of all the discs were gold-plated 0·005-in thick in order to secure identical chemical and mechanical surface conditions. The reason for selecting gold as the plating material was first to eliminate any adverse effects due to surface oxidation and second to have a minimum temperature drop across its thickness. For gold plating of this thickness, the drop in temperature was negligible and was neglected in the calculations.

All of the discs were about 2 in. in diameter and $1\frac{1}{8}$-in thick. The copper disc was entirely copper except for the gold-plated surface. The zinc disc was composite material of four different metals, gold, zinc, soft-solder and copper. Similarly the stainless steel disc was composed of gold, stainless steel, silver-solder and copper. All test disc dimensions for each metal layer and thermocouple position are illustrated in Fig. 2.
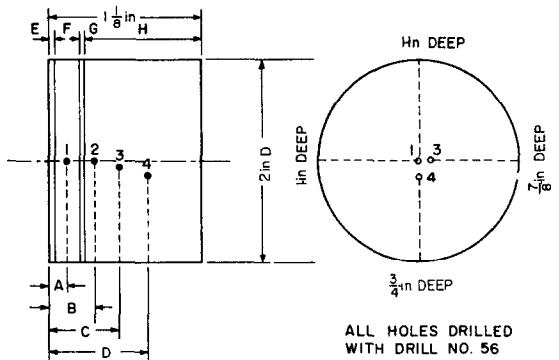
ALL DIMENSIONS IN INCHES

DISC TYPE	Cu FOR H	T. C. POSITIONS				THICKNESS		
		A	B	C	D	E	F	G
Cu	DISTANCE	—	0·085	0·295	0·635	0·005	0	0
	MATERIAL	—	—	—	—	Au	—	—
Zn	DISTANCE	—	0·190	0·380	0·610	0·001	0·094	0·002
	MATERIAL	—	—	—	—	Au	Zn	SOFT SOLDER
S–S	DISTANCE	0·08	0·180	0·465	0·610	0·005	0·120	0·002
	MATERIAL	—	—	—	—	Au	S–S	SILVER SOLDER

FIG. 2 DESCRIPTION OF TEST-DISCS WITH T.C. HOLES

FIG. 2. Detail of the test surfaces. The blanks in column "A" indicate there was no thermocouple in that material. The first couple then is couple "B".

The stainless steel was silver-soldered to the copper in an oven to insure a uniform joint between the two metals. Assuming that no air gap or void exists between the two soldered metals, the temperature drop in the thin layer of solder was neglected because of its small magnitude. The only indication that there is no gap between the stainless steel and the copper is that the condensation was uniform over the surface and the temperature distributions in the stainless steel and copper were consistent with no gap resistance.

Roughness

Three different surface finishes were employed on the gold-plated surface of the copper disc. The first surface used was bright and looked like a mirror. This was accomplished by means of polishing the electroplated gold surface with diamond paste of No. 8 grit size on a polishing wheel. Several scratches remained on this surface. The second surface had lots of scratches in all directions. This was achieved by rubbing the mirror surface with Crocus Cloth. The third one was a rough matte surface which was obtained by means of lapping the emery finished surface with silicon carbide lapping compound of grit size 500 and pure machine oil on the flat glass plate.

Each surface was cleaned in the ultrasonic cleaner in order to get rid of metal chips and to remove the abrasive debris from the cavities and deep scratches on the test surface.

DETAILS ON THE MIRROR FINISH

The gold-plated surface was relatively smooth and bright, but had many small areas on the condensing surface which were found to be covered with orange skin-like spots. In order to eliminate these as possible nucleation sites, the surface was mirror finished on a polishing wheel. First, No. 4 diamond compound paste was put on the center area of the wheel and diluted with kerosene. Then the polishing was started with the wheel turning. The surface was maintained parallel to the plane of the polishing wheel near the edge of the wheel. The direction of polishing was maintained constant while the surface was being ground.

During the polishing operation, kerosene was applied to the compound occasionally to keep the piece cool. In order to go on to the finer grit size, the piece was washed with hot water, then alcohol and finally dried with hot air. Similar procedures were repeated for No. 6 and No. 8 diamond compound wheels. The polishing process continued until the orange skin vanished completely. After the piece was washed and dried, it was placed in the ultrasonic cleaner to eliminate diamond debris and metal chips from the cavities. Finally the surface was washed with alcohol and methyl ether.

EXPERIMENTAL PROCEDURE

Dropwise condensation was promoted with oleic acid, which was usually put on the condensing surface in a thick layer with a small piece of soft cloth. After filling the chamber with Freon 11 the steam generation was started. In order to reduce the heat loss and speed up getting to a steady state, the cooling water in the Freon chamber was shut off at the beginning. As soon as the steam started to leave the system, the pressure in the Freon chamber gradually rose as a result of the evaporation of Freon 11. After the chamber reached the maximum possible pressure, the chamber pressure was controlled by means of an external nitrogen tank connected to the chamber. The lowest heat flux data was taken with a Freon chamber pressure of 120 psig.

Before the readings were taken, approximately $1\frac{1}{2}$ h were required for the full stabilization of the operating conditions. During this period the vapor generated drove almost all of the non-condensable gas out of the system, in addition to degassing the water in the vessel.

The data were taken from a low heat flux to a high heat flux in order to avoid the relatively long initial heating period which took place if the direction of operation were reversed. After the test was run from the low heat load to the highest one, the system was returned to the low

heat load in order to see if there was a drift in the surface conditions or any starting effect due to non-condensable gas which was removed before the end of the run.

Heat flux (and temperature difference) was controlled by means of changing either the pressure of nitrogen or the flow rate of the cooling water.

A heat balance was attempted on the apparatus but high precision was not possible as the heat losses could not be estimated or measured very well. Heat losses or gains of 300 Btu/h from the Freon chamber are reasonable and the heat balance closed to within this figure. That is, the enthalpy carried away in the cooling water was within 300 Btu/h of heat transmitted through the copper disc. Up to 5000 Btu/h were transferred. In any case, the heat-transfer rate was computed from the temperature measurements in the copper disc as this is considered the most accurate method.

When equilibrium conditions were established, the following data were recorded: temperatures of inlet and outlet cooling water, three (or four for stainless steel surface) different positions inside the test disc, the condensing vapor and the room. In addition, the pressure of the Freon chamber, and the power supply to the heaters were recorded. The determination of cooling water flow rate was accomplished by measuring the amount of water in the graduated cylinder collected during a certain time interval for a single operating period of about 4 h.

The effect of steam velocity was first studied with an adjustable area scoop attached below the condensing surface. When the higher steam velocity across the surface was found to give a higher heat-transfer coefficient, due to making the drops slide, the steam velocity was fixed at 27 ft/s in the scoop before the test disc for the later runs by means of a constant geometry scoop. This velocity was high enough to remove non-condensables, but not so large as to make the drops move.

In order to insure reproducible data, a number of tests were run in which the amount of promoter varied. A tolerable reproducibility was realized by wiping a thick layer of promoter on the surface at the start and then keeping the entire boiler-condenser system saturated with oleic acid. Besides the layer of promoter applied on the surface, this method involved placing a small amount of promoter ($0.3–1.0$ cm^3) on the water surface before boiling. This was intended to provide a sufficient amount of promoter to the condensing surface to make up for that washed off. A new application of promoter was made for each run.

The fact that the repeat points (marked "R" on Figs. 4, 6, and 8) are usually quite close to the initial point showed that no great amount of non-condensable gas was present and that the condition of the promoter did not change appreciably during a run.

The surface temperature (T_s) was obtained by the extrapolation of temperature profile in the copper at the steady state. For the composite materials the temperature drop across the layer of the gold and the soldering metal was neglected in the calculation because the magnitude was very small. Heat flux (q/A) was calculated from the measurement of the temperature gradient (dT/dx) and the known thermal conductivity (k), that is $q/A = -k(dT/dx)$. The steam temperature (T_v) being separately measured, the surface temperature drop ($T_v - T_s$) was obtained very easily. The heat-transfer coefficient was calculated from the equation

$$h = \frac{q/A}{(T_v - T_s)}. \tag{1}$$

Only one run was made each day and each condition was duplicated at least once on another day.

<center>RESULTS</center>

Property effects

Figures 3, 4, and 5 show the results of the effect of substrate thermal properties of the mirror finished gold-plated copper, zinc and stainless steel. Comparing the magnitude of the heat-transfer coefficients of the three metals,
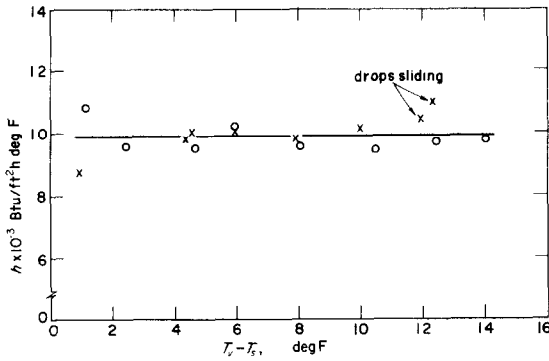
FIG. 3. Heat-transfer coefficient vs. surface temperature drop for a mirror finished copper disc. The two points marked "drops sliding" were taken with a steam leak around the sealing ring which made the drops move and increased the heat-transfer coefficient.
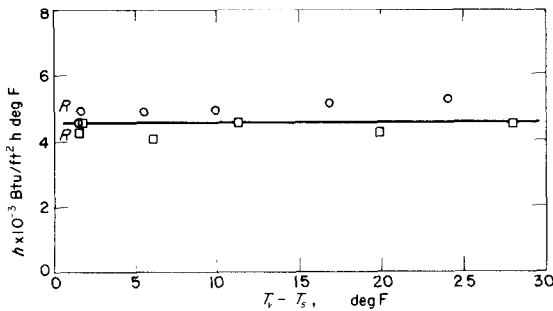
   × Run 16
   ⊙ Run 17

FIG. 4. Heat-transfer coefficient vs. surface temperature drop for a mirror finished gold-plated zinc surface. The points marked "R" are repeat points taken at the completion of the run after about four hours of steady boiling.

   ⊙ Run 27
   ⊡ Run 28

it can be seen that the higher the thermal conductivity of the substrate material, the higher is the heat-transfer coefficient. For all the metals, the average result shows the heat-transfer coefficient is constant for the various degrees of subcooling. In this work the magnitude of the coefficient for gold-plated copper is approximately five times greater than that for gold-plated stainless steel.

The most scattered results were noticed in the case of stainless steel at the low heat load region.
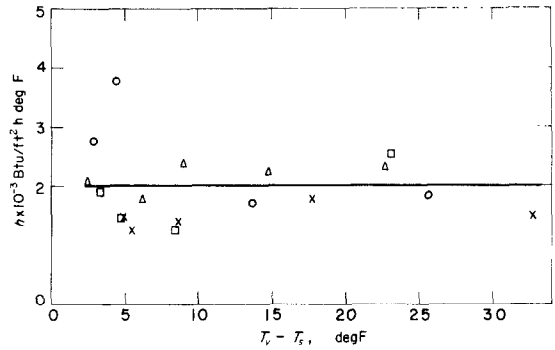

FIG. 5. Heat-transfer coefficient vs. surface temperature drop for a mirror finished gold-plated stainless steel surface

   ⊙ Run 23
   △ Run 24
   ⊡ Run 25
   × Run 26

This error was due to the temperature fluctuations and the steeper temperature gradients across the stainless steel slab. The precision of these measurements is low. The error is about ± 2 degF in the surface temperature.

Roughness and wetting effects

The experimental results in which the surface roughness was varied are shown in Figs. 3, 6, and 7. In all the figures the steam side heat-transfer coefficient was plotted against the
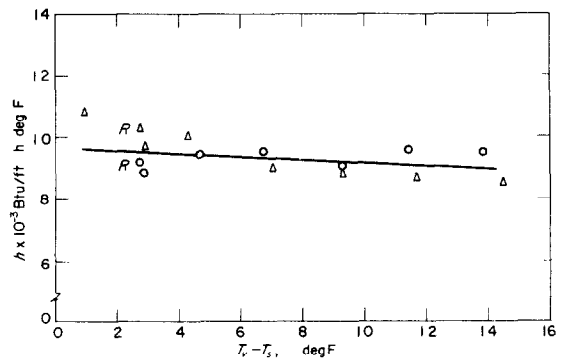

FIG. 6. Heat-transfer coefficient vs. surface temperature drop for emery finished gold-plated copper. The points marked "R" are repeat points taken at the completion of the run after about 4 h of steady boiling.
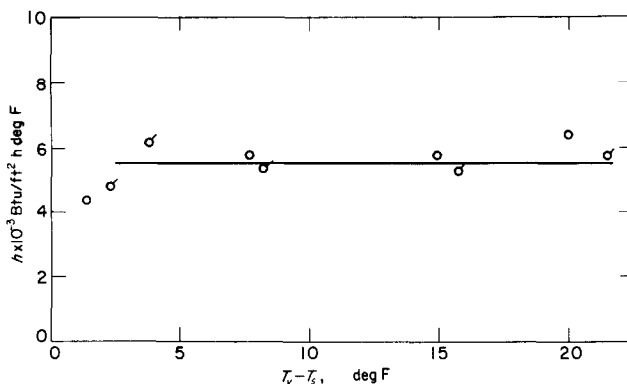
   ⊙ Run 14
   △ Run 15

FIG. 7. Heat-transfer coefficient vs. surface temperature drop for a lapped gold-plated copper surface.

⊙ Run 20A
⊙ˊ Run 20B

temperature difference between the condensing vapor and the surface temperature.

When Figs. 3, 6, and 7 are compared, it can easily be seen that the rougher the condensing surface, the lower the heat-transfer coefficient. At the same time it was observed for the rough lapped copper surface that only an imperfect type of drop condensation was initiated at the low heat load. As the heat load was increased, the contact angle of the drop was increased and the condensation was gradually changed to the good dropwise condensation. For the mirror finished surface it was also noticed that the tiny scratches acted as favorable nucleation sites because they kept on producing the condensing drops. It appears, however, as though the primary effect of roughness is to decrease the apparent contact angle.

Whenever the thick layer of oleic acid was applied, it usually washed away and it appeared that only a thin layer was left. Occasionally a thick layer stuck to the surface, turning into a watery paste which then behaved as an insulator. Therefore, either too thin or too thick a layer of the promoter did not cause good drop-wise condensation. The former can be attributed to insufficient promotion, whereas the latter to the emulsification of oleic acid with the water. Figure 8 shows the effect of the promotion. The
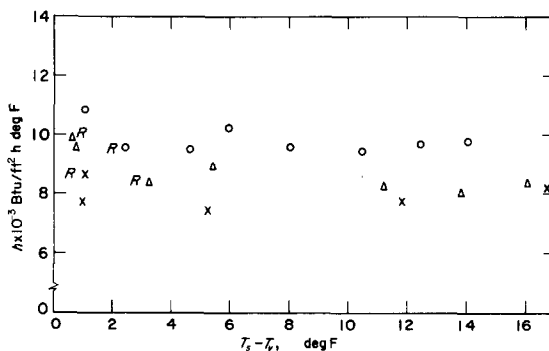

FIG. 8. Heat-transfer coefficient vs. surface temperature drop for a mirror finished gold-plated copper surface with variation in the amount of promoter. The points marked "R" are repeat points taken at the completion of the run after about 4 h of steady boiling.

⊙ Run 17, full promotion
△ Run 19, slight promotion
× Run 18, no promotion

results called "full promotion" were obtained when the entire condenser-boiler system was saturated with oleic acid. The results marked by no promotion were achieved when the entire internal system was completely washed with soap and water, and no promoter was applied on the test surface. A poor dropwise condensation was obtained. The data called "slight promotion" were obtained when the promoter was applied to the test surface after the no

promotion test, but no promoter was put in the water. In Table 1 are listed the amounts of the promoter applied on the test surface and on the water surface in each run.

When leakage of steam and condensate took place through the gap between the test disc and the stainless steel sealing ring, the water drops were found to slide toward the gap. Thus,

Table 1. The amount of promoter applied in each run

Run No.	On water (ml)	On surface
14	0·4	thick layer
15	0·6	thick layer
16	0·4	thick layer
17	0·4	thick layer
18	0	no promotion
19	0	thick layer
20	0·6	thick layer
23	1·5	thick layer
24	1·0	thick layer
25	1.0	thick layer
26	1·0	thick layer
27	1·0	thick layer
28	1·0	thick layer

sliding of drops resulted in raising the heat-transfer coefficient. This is illustrated at the high flux region of the run No. 16 in Fig. 3. The leakage took place in the high flux region when the Freon chamber pressure was low and the test disc parted from the stainless steel ring. In this case, the sealing no longer was effective and the leaking steam caused the drops to slide on the surface.

In general, non-condensable gas tends to lower the heat-transfer coefficient. Usually at the beginning of the run some non-condensables were present. Some indication of this can be seen at the beginning of runs 16 and 20A (Figs. 3 and 7). When this occurred, the run was stopped for a while to allow degassing to take place.

DISCUSSION

The gold-plated copper drop condensation heat-transfer coefficients are almost the same

as the pure copper results of Hampson [1]. The difference between our value of 10000 Btu/h ft^2 (Fig. 3) and Hampson's of 12000 is no greater than one would expect from the use of a different promoter on a slightly different surface. In the light of this check point and the fact that these results are reproducible, it is felt that they are correct. Not all the data in the literature substantiates these findings. Though the geometries are often slightly different, it is felt in general that a strongly drooping heat-transfer coefficient with increasing heat flux is primarily a result of non-condensable gas. A rising coefficient, especially at low temperature differences, is felt to be a result of additional drop nucleation. Though no such trends emerged in these data, they might be expected to occur under different circumstances.

The most important finding in this work is the fact that surface thermal conductivity is an important quantity in dropwise condensation. The heat-transfer coefficient is 10000 for copper, 4500 for zinc and 2000 for stainless steel. This can be seen in Figs. 3, 4, and 5. There is a hint of this in two recent works.

McCormick and Westwater [2] found that drops growing in the vicinity of other drops suffered a decrease in their own growth rate. The implication is that there is an appreciable depression in the temperature of the metal near a drop. One would expect the size and magnitude of the depression to be related to the thermal conductivity of the material.

The other hint in the literature that surface thermal conductivity might be important is contained in reference [3]. Here, a factor of five difference in the heat-transfer coefficient was noticed between copper and stainless steel. In this case, however, the difference was attributed to the differences in the surface chemistry between these two metals rather than the thermal properties of the substrate.

It is by no means obvious that the dropwise condensation heat-transfer coefficient should be a function of the thermal conductivity of the bulk material underlying the promoter. How

this comes about can be seen most easily by considering the heat transfer through and around a drop. Near the triple interface, the conduction path is very short and the local heat-transfer coefficient is very large. On bare surface the heat-transfer coefficient is virtually zero. On the surface near the middle of a drop, the conduction path through the liquid is quite long and the heat-transfer coefficient is very low. One finds then, on the surface, a local heat-transfer coefficient which is a strong function of position. This gives rise to a crowding of the heat flux in certain spots as one gets close to the surface. Locally, this crowding results in an additional temperature drop, the magnitude of which is a function of the thermal conductivity of the bulk material. The way the heat-transfer coefficient is defined* makes the dropwise condensation heat-transfer coefficient then a function of the thermal conductivity of the base material. An effect such as this can occur any time the local heat-transfer coefficient is not constant over the area.

The importance of this effect has not been generally recognized. References [6, 7, 8, and 9] all of which give equations for the heat-transfer coefficient in dropwise condensation fail to include the bulk surface material thermal conductivity as a variable. It turns out to be more important than some variables that are included.

The second finding of importance is that the heat-transfer coefficient is independent of the wall subcooling. This implies that the surfaces used in these experiments were saturated with drops at least in the subcooling temperature

range of 2–20°F. If the condensing geometry, or alternatively the number of drops on the surface, does not change appreciably with additional subcooling, then one might expect the heat-transfer coefficient to be independent of the temperature difference. It apparently is. Additional evidence of this fact is given by the measurements of the effect of roughness on the condensing heat-transfer coefficient.

In these experiments (Figs. 3, 6, and 7) there was actually a decrease in the heat-transfer coefficient with increasing roughness. This is just the opposite of the effect one would expect if the nucleation were improved. Reference [3] reports a similar result. The cause of this decrease was evident from the visual observation. The quality of the dropwise condensation deteriorated with increasing roughness. For the data of Fig. 7, especially at low heat flux, the surface had a small number of relatively large irregularly shaped blobs of liquid which tended to persist. These seemed to decrease the heat-transfer coefficient. Apparently the decrease in the contact angle resulting from increasing roughness more than compensated for any change in the nucleation properties of the surface.

In the light of these findings, it is now stated that in the range 2–20°F subcoolings at atmospheric pressure on horizontal surfaces facing down, drop condensation is heat conduction limited. Nucleation differences between metal surfaces are unimportant and the substrate thermal properties are a first order variable.

These conclusions do not square with the findings of references [4 and 5]. In reference [4] pictures show large bare patches with the sub-subcooling equal to 6°C. Our measurements indicate, indirectly, that the surface is saturated with drops under these circumstances. Though the pressure in these experiments is low, it is not felt that this is an important difference. Reference [5] reports subcoolings of as much as 4°C with no drops forming at all when the contact angle is 70°. The pressure was low in these experiments, too, but these subcoolings

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* In an experiment such as this, the heat-transfer coefficient is defined by extrapolating the temperature gradient a long distance from the surface (where the heat flow lines are straight) to the surface to get the surface temperature. Of course appropriate changes in gradient must be used if the surface is a composite of several different thermal conductivity materials. The gradient in temperature is also used to obtain the heat-transfer rate by means of the definition of thermal conductivity. The surface temperature, along with the saturation temperature for the vapor are then used to define the heat-transfer coefficient as in equation (1).

are so much larger than any we were able to observe that it is felt that there is still some fundamental, unrecognized difference between the two systems. Perhaps the metastable nucleation properties of the surfaces are more important than is generally recognized or the net contribution of the very small drops to the heat transfer is very small so that variations in their number do not matter.

CONCLUSIONS

1. A factor of 20 reduction in the thermal conductivity of the surface results in a factor of 5 reduction in the heat-transfer coefficient with dropwise condensation.

2. For water at atmospheric pressure condensing on a horizontal surface facing down in the range 2–20° subcooling the heat-transfer coefficient is independent of condensing rate or surface finish.

3. An unexplained discrepancy exists between the subcoolings we measured in the experiments with the surface apparently saturated with drops and the subcoolings reported in the literature which are needed to initiate drops.

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Résumé—On a effectué des mesures du coefficient de transport de chaleur au cours de la condensation par gouttelettes de vapeur d'eau à la pression atmosphérique sur la face ingérieure d'une paroi horizontale en utilisant comme déclencheur de l'acide oléique. Les surfaces d'essai consistaient en disques épais d'environ 50 mm de diamètre,
(a) plaqué or sur 28,6 mm de cuivre,
(b) plaqué or sur 2,4 mm de zinc et 25 mm de cuivre,
(c) plaqué or sur 0,3 mm d'acier inoxydable et 25 mm de cuivre.
Les coefficients de transport de chaleur sont indépendants du sous refroidissement de la surface dans une gamme allant de 1,1 à 11°C et égaux à :
$h = 56800$ W/m²°C pour le cuivre,
$h = 25500$ W/m²°C pour le zinc,
$h = 11360$ W/m²°C pour l'acier inoxydable.
On en conclut que : (1) une réduction de 20 fois de la conductivité thermique du matériau de base donne une réduction de 5 fois du coefficient de transport de chaleur; (2) les coefficients de transport de chaleur pour la condensation en gouttelettes sont limités par la conduction, les effets de la nucléation étant négligeables dans la gamme de sous refroidissement allant de 1,1 à 11 °C; (3) il existe des différences inexpliquées entre les effets de nucléation déduits de ces expériences et les mesures directes de nucléation présentées dans la littérature.

Zusammenfassung—Messungen des Wärmeübergangskoeffizienten bei Tropfenkondensation von Dampf bei 1 atm. wurden durchgeführt. Die Kondensation fand an der Unterseite von horizontalen Flächen statt. Als Promotor diente Ölsäure. Als Testflächen wurden dicke Scheiben von etwa 25,4 mm Durchmesser und folgende Materialien verwendet:
(a) Goldüberzug auf 28,6 mm dickem Kupfer,
(b) Goldüberzug auf 2,39 mm Zink und 25,4 mm Kupfer,

(c) Goldüberzug auf 3,05 mm Chromstahl und 25,4 mm Kupfer.

Die gemessenen Wärmeübergangskoeffizienten waren unabhängig von der Unterkühlung der Kondensationsfläche im Bereich von 1,1°C bis 11°C. Sie betrugen:

h = 56 810 W/m²grd für Kupfer,

h = 25 560 W/m²grd für Zink,

h = 11 360 W/m²grd für Chromstahl.

Es wird gefolgert: (1) dass eine zwanzigmal niedrigere Wärmeleitfähigkeit des Wandmaterials einen fünfmal niedrigeren Wärmeübergangskoeffizienten ergibt; (2) dass die Wärmeübergangskoeffizienten bei Tropfenkondensation von der Wärmeleitfähigkeit abhängen, wobei Keimbildungseinflüsse im Bereich von 1,1°C der Wandunterkühlung vernachlässigbar sind; (3) dass ungeklärte Unterschiede existieren zwischen Keimbildungserscheinungen, die aus den Versuchsergebnissen abgeleitet wurden, und direkten Keimbildungsmessungen, wie sie in der Literatur angegeben sind.

Аннотация—Проведены измерения коэффициента теплообмена при капельной конденсации водяного пара при давлении 1 атм на горизонтальной поверхности, обращенной вниз, с олеиновой кислотой в качестве промотора. Экспериментальные поверхности состояли из тодстых дисков диаметром около 2 дюймов с (а) золотой пластинкой на медной подложке толщиной 1,125 дюймов, (б) золотой пластинкой на цинковой подложке толщиной 0,094 дюйма и медной, толщиной 1 дюйм, (в) золотой пластинкой на подложке из нержавеющей стали 0,12 дюйма и медной 1 дюйм.

Установлено, что коэффициенты теплообмена не зависят от степени переохлаждения поверхности в диапазоне от 2 до 20° и равны: h = 10 000 Бте/фут²час °F для меди, h = 4500 Бте/фут²час °F для цинка, h = 2000 Бте/фут²час °F для нержавеющей стали.

В работе сделаны следующие выводы: (1) при увеличении теплопроводности материала подложки в 20 раз коэффициент теплообмена увеличивается в 5 раз; (2) коэффициенты теплообмена при капельной конденсации лимитируются теплопроводностью, причем влиянием образования пузырьков в области переохлаждения от 2 до 20° можно пренебречь; (3) остается неясной причина расхождений между эффектами образования пузырьков, вытекающими из проведенных опытов, и прямыми измерениями образования пузырьков, описанными в литературе.