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# Dropwise condensation of steam on electroplated silver surfaces

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**Abstract**—Electroplated silver surfaces were investigated as promoters of dropwise condensation of steam at atmospheric pressure. The plating thickness varied from zero to 3000 nm. The steam-to-silver $\Delta T$ varied from 1 to 58 K. The heat flux was up to 1.5 MW $m^{-2}$, a value much greater than that observed for filmwise condensation at the same $\Delta T$. Two surface plating solutions were used. The longest lifetime for continuous dropwise condensation, 2400 h, occurred with a 300 nm coating from a cyanide solution applied on electropolished copper. Thicker silver would give a longer life. Auger electron spectroscopy indicated that silver provides a low-oxygen surface which adsorbs trace organics from the surroundings. These promote dropwise condensation. For the first time, a Nusselt type derivation for filmwise condensation on a vertical disc is presented. The correct average vertical length is 0.817 times the diameter.

## INTRODUCTION

SINCE it was first reported in 1930 by Schmidt *et al.* [1], dropwise condensation has been of interest to many investigators. It has higher heat transfer coefficients than those achieved with filmwise condensation. Until 1965 dropwise condensation was achieved by coating the condensing surface with an organic promoter. Unfortunately, these promoters (waxes, oils, greases, soaps) wash off rapidly, and the condensation becomes filmwise. Continuous injection of promoters into steam gives long-lived dropwise condensation, but these added materials are not wanted in commercial systems containing pumps and turbines. Polymer coatings such as Teflon (polytetrafluoroethylene) can produce dropwise condensation, but if the thickness is great enough to give durability, the heat transfer benefits are cancelled by the thermal resistance of the low-thermal-conductivity coating.

Thin coatings of noble metals can serve as promoters of dropwise condensation. These have good thermal conductivities and the possibility of permanence. For example, an electroplate of gold 200 nm thick on copper was found to produce dropwise condensation for over 2500 h [2]. The object of the present study was to determine the characteristics of silver as a promoter for dropwise condensation of steam. Silver usually sells at about 3% of the price of gold. Thus the amount of silver needed on a base substrate and the lifetime of such coatings are of special interest. Also information was sought concerning the chemical analysis of the surface as shown by spectroscopic methods.

## BACKGROUND

Of the noble metals, gold has received the most attention as a promoter of dropwise condensation on base metals. In 1965, Erb and Thelen [3] and also Umur and Griffith [4] reported dropwise condensation of steam on electroplated gold. The deliberate addition of organic promoters was not required. Numerous investigations have confirmed the effectiveness of gold [5–20]. A particularly detailed study showed that a critical plating thickness of about 100 nm is required to achieve dropwise condensation of steam [2]. Below this thickness, filmwise condensation is usually observed. The exact minimum thickness depends on the composition of the plating bath. Auger spectroscopy was a new tool used in that study. This revealed that dropwise condensation was always accompanied by a significant amount of carbon on the surface. This occurred automatically, even when the plating solutions were free of organic material. It was concluded that some unknown, trace organic material was absorbed on the gold and that this was responsible for the dropwise condensation. By contrast, gold surfaces which produced filmwise condensation always showed little carbon but appreciable amounts of oxygen and copper (the base metal).

Plated surfaces of rhodium and palladium were shown to be promoters by Erb *et al.* [10]. Plated surfaces of chromium have been reported, with conflicting results in a number of studies [1, 10, 21–27].

Plated silver as a promoter was reported by Erb and co-workers [3, 5, 10]. A lifetime for dropwise condensation of steam was 3650 h, however the plate thickness was not given [5]. A different paper suggests 380 nm for the minimum thickness for noble metals in general [6], but no data are included with silver of that thickness. In fact, no systematic study of the effect of plating thickness was reported. The plating was done by others, and details of the plating procedure were not published. Chemical analysis of the surface was not performed. The steam-side heat transfer coefficients were not measured. Although Erb's studies show that silver may be attractive for promoting dropwise condensation, the scientific facts concerning its use are quite incomplete.

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## NOMENCLATURE

| | |
|---|---|
| $A$ | heat transfer area |
| $g$ | acceleration of gravity |
| $h$ | steam-side heat transfer coefficient for entire surface |
| $h_{\max}$ | $h$ for fully developed dropwise condensation |
| $h_x$ | average $h$ for vertical strip in Fig. A1 |
| $k$ | thermal conductivity of liquid |
| $L$ | height of vertical strip |
| $L_e$ | effective height for use in Nusselt's equation |
| $Q$ | heat transfer rate for entire surface |
| $R$ | radius of disc |
| $\Delta T$ | steam-to-silver temperature difference |
| $x$ | horizontal axis |
| $y$ | vertical axis. |
| Greek symbols | |
| $\theta$ | angle in Fig. A1 |
| $\lambda$ | latent heat of condensation |
| $\mu$ | viscosity of liquid |
| $\rho$ | density of liquid. |

## EXPERIMENTAL

### *Test piece preparation*

Condensation tests were made on the 25.4 mm diameter, circular, vertical condensing surface of a silver-plated copper test piece, see Fig. 1. The disc was 6.4 mm thick. A thermocouple was located 4.8 mm from the condensing face of the test piece to allow monitoring of the temperature at that point.

Two different test piece preparations were used prior to electroplating. The first preparation was similar to that of earlier studies [2, 18]. The test piece was first smoothed using 320 and 600 grit silicon carbide paper. This was followed by polishing with 9.5 and 1.0 $\mu$m alumina, suspended in water, on Buehler microcloth on a brass polishing wheel. Between each of the smoothing and polishing steps, the test piece was cleaned in an ultrasonic cleaner filled with deionized water. Because some organic materials are known promoters of dropwise condensation, the next step was a thorough degreasing of the test piece. It was soaked in trichloroethylene, methanol and, finally, in a boiling alkaline solution. Next came a thorough rinse with deionized water. From this point on, through the entire preparation, plating and loading into the equipment, the test piece was handled with cotton gloves. This was done to avoid finger oil contamination of the test piece. The test piece was next polished with 0.3 and 0.05 $\mu$m alumina. The latter size corresponds to 50 nm and is about one-tenth of the wavelength of light. Once again the test piece was cleaned in the ultrasonic cleaner after each polishing step. The final polishing produced visually similar surfaces with a mirror finish. The final step of this surface preparation technique was a dip in a 5% sulfuric acid solution followed by a thorough rinsing with deionized water.

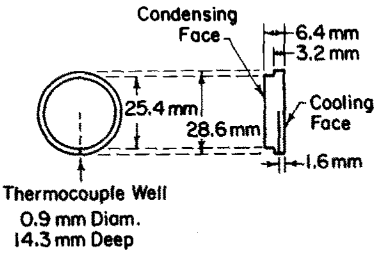

FIG. 1. Sketch of the copper test piece, the condensing face was silver-coated.

The second surface preparation technique for the substrate began as for the first, by smoothing the condensing surface with 320 and 600 grit silicon carbide paper. At this point the test piece underwent the same degreasing procedure as described above. The degreasing was followed by polishing with 9.5 $\mu$m alumina and a thorough rinsing. The test piece was then electropolished in a solution of 530 $\mathrm{g\,l^{-1}}$ of phosphoric acid in water. A copper cathode was spaced 38 mm above the horizontally mounted test piece which was the anode. The test piece was electropolished for 4 min at 2.4 V, thoroughly rinsed, and removed from the electropolishing apparatus. As with the first surface preparation technique, the final step was a sulfuric acid dip and a rinse with deionized water. A more in-depth description of these surface preparations is contained in ref. [28].

While the test piece was still thoroughly wetted from the final surface preparation, it was transferred to the electroplating cell. The electroplating cell was made of Teflon and contained a Teflon electrode spacer which kept the silver anode and the test piece parallel at a distance of 203.2 mm apart. The electrical connection to the test piece was at the back of the piece. Two Teflon-coated stirring bars, one at each end of the plating cell, provided vigorous agitation. A 5 V power supply was used to provide the plating current of 55 or 110 mA, depending on the plating solution. The plating thickness was controlled by measuring the coulombs passed through the circuit and using the known plating efficiency of 95% (Bath A) or 100% (Bath B). The coulombs were determined by means of a current integrator coupled with a voltage comparator. When the voltage across a capacitor in the current integrator reached the preselected value, the voltage comparator interrupted the current to the plating cell. The actual voltage across the capacitor at that time was read from a digital multimeter. This method kept the plating thicknesses to within 0.2 nm of the desired thickness.

Two plating baths were used in this study, both were supplied by Technic, Inc. Providence, Rhode Island. Bath A, with the trade name Techni-Silver Cy$^{(-)}$Less, was a cyanide-free solution which claimed to produce a 99.99% pure silver plate.

Plating Bath B, with the trade name Techni-Silver E, was a potassium cyanide based silver plating bath. It is claimed to produce an electroplate which had a hardness greater than that of pure silver and that the hardness did not change with time. Bath B was a high silver content alloy. Chemical analyses at the University of Illinois showed that the other metal was chromium. Following the suggestion of the plating bath supplier, a silver strike was deposited on the copper test piece before plating with Bath B. A silver strike consists of a 2 s electroplating of silver at an increased current from a bath high in cyanide and low in silver content. The strike was used to prevent immersion deposition of silver when the test piece was placed in Bath B. The silver strike was performed in the same plating cell, with a stainless steel anode substituted for the silver anode. The thickness of the silver strike was about 7.3 nm, and this was taken into account when reporting the plating thickness.

*Heat transfer equipment*

The condensation tests were made in the condensing cell shown in Fig. 2(a). A window was mounted on the cell so that visual and photographic observations of the condensing surface could be made. A copper–constantan thermocouple was used to monitor the steam temperature.

Cooling water was supplied to the back of the test piece by a gear pump. The coolant entered the cooling chamber, impinged on the back of the test piece and exited at the top of the cooling chamber. Thermo-

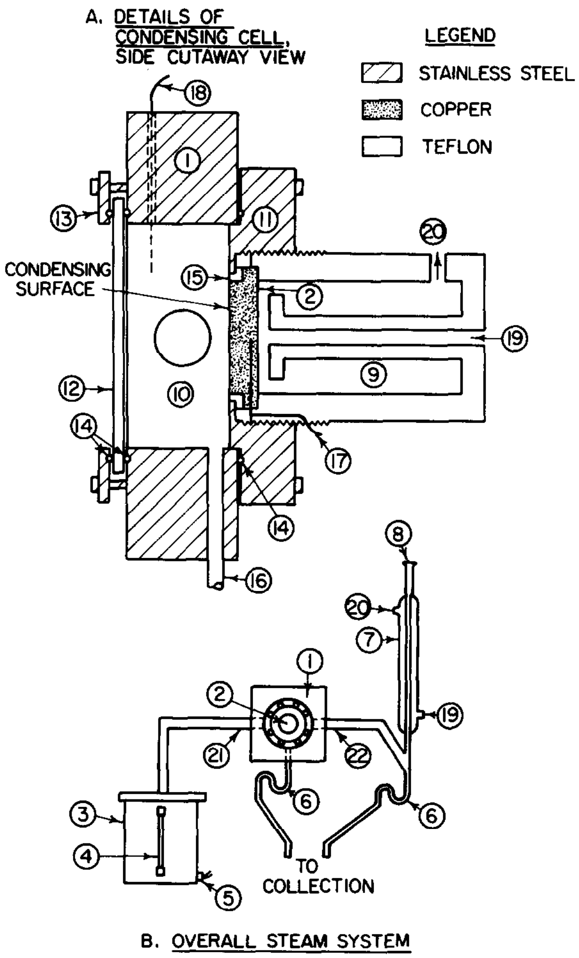

FIG. 2. Sketch of the condensing test equipment. (a) Details of condensing cell (side cutaway view). (b) Overall steam system. (1) condensing cell; (2) test piece; (3) boiler; (4) sight glass; (5) heaters; (6) U-tube trap; (7) auxiliary condenser; (8) open to atmosphere; (9) cooling chamber; (10) steam chamber; (11) stainless steel cap; (12) Pyrex window; (13) stainless steel flange; (14) Teflon O-ring; (15) Teflon gasket; (16) condensate drain; (17) test piece thermocouple; (18) steam thermocouple; (19) coolant inlet; (20) coolant outlet; (21) steam inlet; (22) steam outlet.

couples in the cooling water flow measured its inlet and outlet temperatures. The test piece thermocouple wires fitted into a groove cut in the threads of the cooling chamber. All the thermocouple temperatures were monitored using a digital multimeter.

Steam at atmospheric pressure was generated by two 750 W immersion heaters mounted in a 4 liter stainless steel boiler. As shown in Fig. 2(b), the steam flowed through stainless steel tubing, entered the LHS of the steam chamber, and condensed on the cooling surface. Excess steam was always used. The excess exited the steam chamber and flowed through stainless steel tubing to a glass auxiliary condenser. Both the main and auxiliary condensates flowed into U-tube traps and were metered. The equipment was a once-through steam flow system. That is, after the condensate was collected it was sent to the drain. Through the entire steam system, steam and condensate contacted only stainless steel, glass, Teflon and the condensing surface. To avoid organic contamination, the steam system underwent a rigorous degreasing procedure similar to that used in the test piece preparation. This procedure included cleaning with a hot alkaline bath.

To start a heat transfer run, the test piece was removed from the electroplating cell, thoroughly rinsed, and mounted into the steam chamber while steam was flowing through the system. The cooling water flow, which was measured using rotameters, was then started. Before heat transfer data were taken, the equipment ran for 3.5–4 h under continuous condensation conditions. At intervals, boiling makeup water was added to the boiler at the rate of approximately 1100 ml $h^{-1}$. The water used was taken from a Barnstead Nanopure purification system which included ion exchange resins, activated carbon and a particle filter. The resistivity of the water was greater than $12 \times 10^6$ Ω cm. The Illinois State Water Survey found the total organic carbon content of this water to be below their detection limit of 0.5 mg $l^{-1}$. The makeup water was preboiled at least 10 min before being added to the boiler.

After the warmup period, the window was covered with insulation and heat transfer data were taken. Most runs consisted of ten data points taken at various cooling water flow rates. By measuring the condensation rate from the test piece and monitoring the cooling water inlet and outlet temperatures, two independent calculations of the heat flux through the condensing surface were made. They usually agreed within 5%. From a knowledge of the heat flux and the temperature at the known position in the test piece, the condensing surface temperature was calculated. This allowed calculation of the surface subcooling $\Delta T$ and the steam-side heat transfer coefficient $h$.

After the last data were recorded, the cooling water was turned off, and the test piece was removed from the steam chamber while steam was still flowing. The piece was once again handled only while cotton gloves were worn. It was stored in a covered culture dish for a period of time ranging from hours to weeks before being analyzed by Auger electron spectroscopy.

### *Lifetime equipment*

A second set of heat transfer equipment, nearly identical to that used for the daily runs, was used to make lifetime studies. The cooling water to the lifetime equipment was supplied by a constant head tank located near the ceiling of the laboratory. This allowed cooling water to run 24 h a day without the fear of an electrical power failure. The main and auxiliary condensate streams were both recycled by gravity to the boiler. Three-way stainless steel valves in the system allowed collection of the condensate when heat transfer data were taken. During a lifetime run, both the steam flow rate and the cooling water rate were kept as constant as possible.

### *Surface examination*

The glass window in the steam chamber of each heat transfer equipment allowed photographs to be taken. During the 3.5–4 h warmup period of a daily run, photographs of the condensing surface were taken to record the progression of dropwise condensation. In addition, before the cooling water was turned off at the end of each run, another photograph was taken. During lifetime runs, photographs and heat transfer data were recorded daily.

Many of the test pieces used for condensation tests were subsequently analyzed using Auger electron spectroscopy. Auger analysis is an ultrahigh vacuum technique which uses an electron source to excite surface atoms. This method allowed elemental analyses of the condensing surfaces. A more in-depth discussion of the Auger electron spectroscopy technique is given in ref. [2, 29].

## RESULTS

### *Effect of silver thickness*

The effect of silver plating thickness on the ability of the condensing surface to promote dropwise condensation was studied for the various combinations of plating bath and surface preparation. Figure 3(a) contains the heat flux curves for 13 heat transfer runs with silver plating thicknesses ranging from zero to 3000 nm. All of these electroplates were from Bath A and the test pieces had been mechanically polished to 0.05 μm (50 nm) for their final surface preparation prior to plating. All electroplates of 150 nm and thicker produced dropwise condensation. The data for the six thicknesses which produced dropwise condensation are so close together that one line is used to define them.

The line shown corresponding to equation (A8) is derived from a Nusselt type analysis for filmwise condensation on a vertical disc. The derivation of this equation is contained in the Appendix. The agreement between this theoretical line and the observed data for filmwise condensation on the disc is very good.

The heat transfer advantage of dropwise conden-

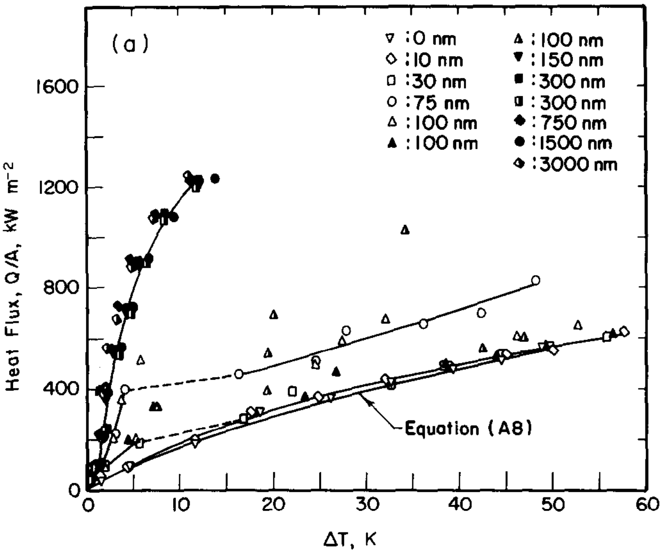

Fig. 3(a). Effect of silver plating thickness on the heat transfer during steam condensation. The plating bath contained no cyanide or alloying ingredients (Bath A).

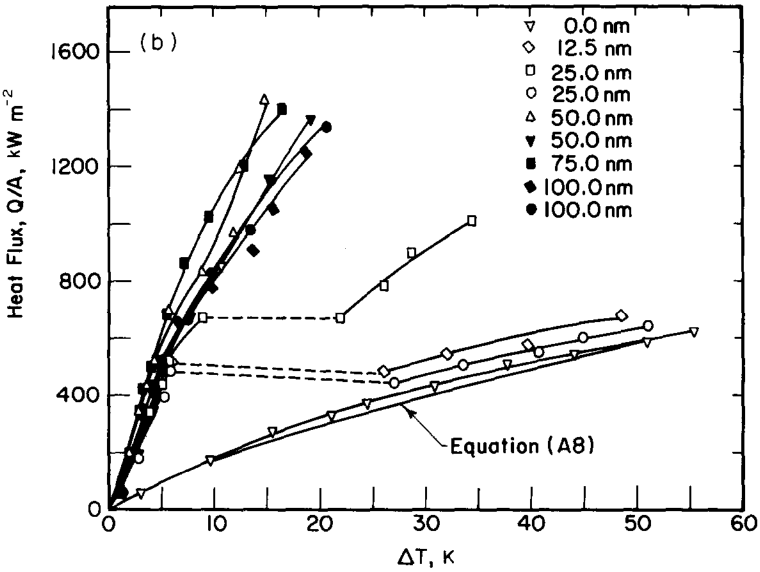

Fig. 3(b). Effect of silver plating thickness. The plating bath contained cyanide and chromium (Bath B). The base metal was electropolished before plating.

sation can be seen in this plot. A $\Delta T$ of 5 K produced a heat flux of approximately 800 kW $m^{-2}$ for dropwise condensation. At the same $\Delta T$ the heat flux for filmwise condensation was about 100 kW $m^{-2}$. Plates thinner than 30 nm did not promote dropwise condensation. Plating thicknesses between 30 and 100 nm produced partial (mixed) condensation. The data for these mixed condensation cases did not fall on a smooth line and were not reproducible.

The effect of plating thickness for Bath B over an electropolished substrate was also studied. The nine heat transfer runs had plating thicknesses ranging from zero to 100 nm and are shown in Fig. 3(b). All electroplates of 50 nm or more produced dropwise condensation, although the data are not as closely packed as for Bath A and do not fall on a single line. Also, the heat transfer characteristics from these runs were not as good as for Bath A. At a $\Delta T$ of 5 K, the heat flux was between 500 and 600 kW $m^{-2}$. However, all plating thicknesses provided an advantage over filmwise condensation. Even a 12.5 nm plate from Bath B had good heat transfer characteristics below a $\Delta T$ of 5 K. Once again the middle thicknesses, in this case 12.5 and 25 nm, did not produce consistent heat transfer results.

The lower two lines in Fig. 3(b) show data for filmwise condensation obtained on the smooth unplated copper and the theoretical prediction, equation (A8) for filmwise condensation on a vertical disc. The agreement was very good.

Table 1. Lifetime studies

| Run | Plating bath | Plating thickness (nm) | Final substrate preparation |
|---|---|---|---|
| 501 | A | 300 | Mechanical polishing |
| 502 | A | 3000 | Mechanical polishing |
| 503 | B | 300 | Electropolishing |

A third set of similar data, for plates deposited from Bath B on a mechanically polished substrate, was collected but are not included in the graphs. Those data show that approximately 75 nm of silver from Bath B over a mechanically polished substrate was required to fully promote dropwise condensation. This thickness is greater than the critical value for plating on electropolished substrates. Thus the method of surface preparation before plating is an important parameter.

The highest heat flux obtained in this study was slightly less than 1.5 MW $m^{-2}$. The steam generation rate and the cooling capacity of the equipment were the factors which limited this value. Using experimental data to calculate constants for a condensation model, Stylianou and Rose [30] developed an equation which predicts a peak heat flux of 11.9 MW $m^{-2}$ for dropwise condensation of steam at atmospheric pressure. Thus, even higher heat fluxes than reported here should be possible during dropwise condensation of steam.

*Lifetime tests*

Three lifetime studies were made using different combinations of plating bath, plating thickness and final surface preparation of the substrate prior to plating. Table 1 summarizes these combinations. At the constant cooling water flow rate used, the heat flux during dropwise condensation was approximately 950 kW $m^{-2}$.

Figure 4 is a graphical representation of the heat transfer performance for each of the lifetime runs. Because the maximum heat transfer coefficient for each run was slightly different, the data for each run have been normalized using the maximum heat transfer coefficient for that run.

The solid data points in Fig. 4 correspond to the photographs in Fig. 5. All of the runs had perfect dropwise condensates at the start; Fig. 5(a) is typical of this. Although the 300 nm plate of Run 501 did promote dropwise condensation, the heat transfer rate began to decay almost immediately. After approximately 300 h of continuous condensation, a major catastrophe occurred, and the condensation changed almost completely to filmwise. Near the end of the run the condensing surface looked as though the silver electroplate had simply worn off. Figure 5(b) shows the condensing surface of Run 501 after 357 h of condensation. Note that where the silver has worn off the condensation has become filmwise.

Lifetime Run 502 had a silver electroplate 10 times thicker than that for Run 501. As can be seen in Fig. 4, this surface promoted consistent, nearly perfect, dropwise condensation for approximately 1050 h. Beyond this time the heat transfer coefficient gradually decayed with time. Clearly, a thick silver plate gives a longer life than a thin one.

Figure 5(a) is a photograph of Run 501 at nearly the same time in the run as Fig. 5(b) is for Run 502. The dramatic visual difference between these two condensing surfaces coincides with their very different position in Fig. 4. At the end of Run 502 the condensing surface looked very similar to that of Run 501; it appeared that the silver had simply worn off particularly during the time period 1050–2100 h. At the end, the condensation had become filmwise.

For lifetime Run 503 both the plating bath and the

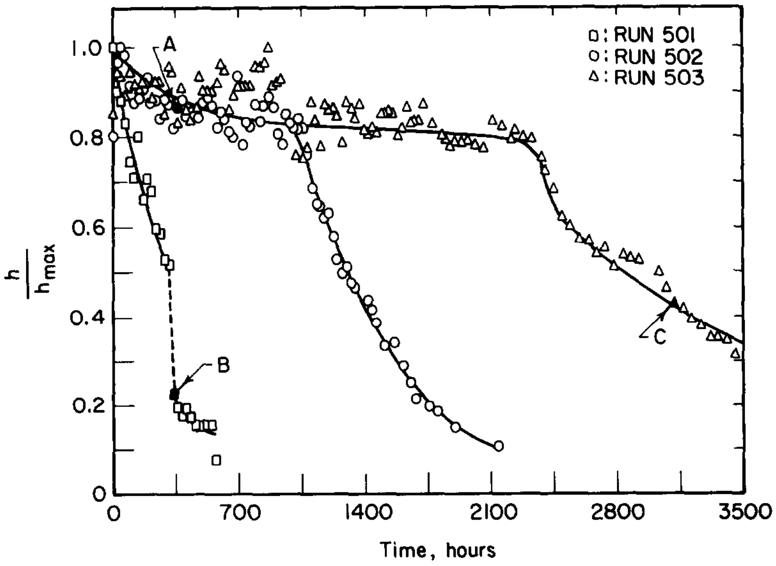

FIG. 4. Three lifetime tests for steam condensation on electroplated silver. The runs are identified in Table 1. The letters A, B, C refer to the photographs in Fig. 5.

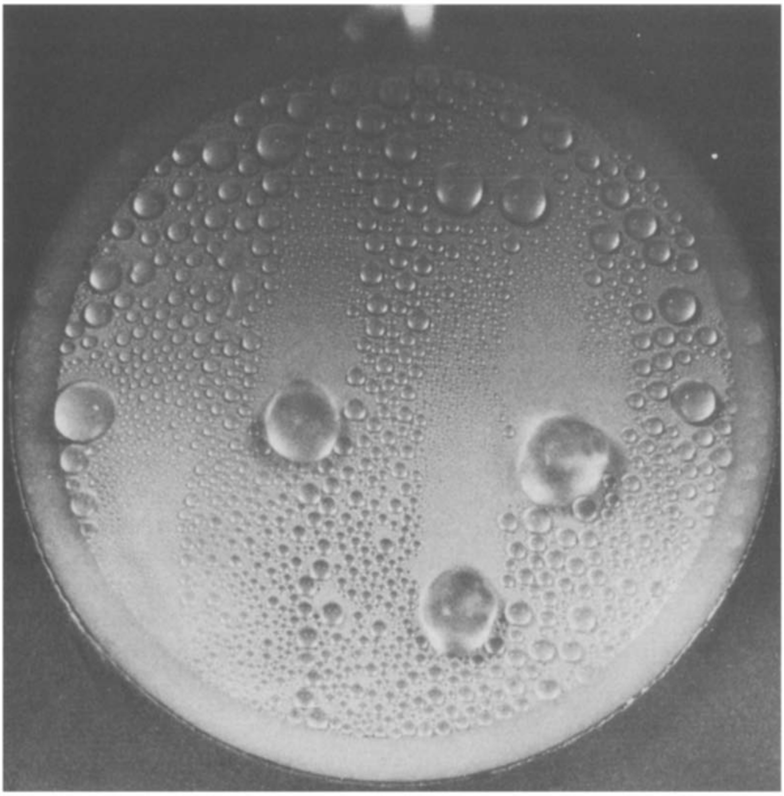

Fig. 5(a). Perfect dropwise condensation, Point A in Fig. 4.

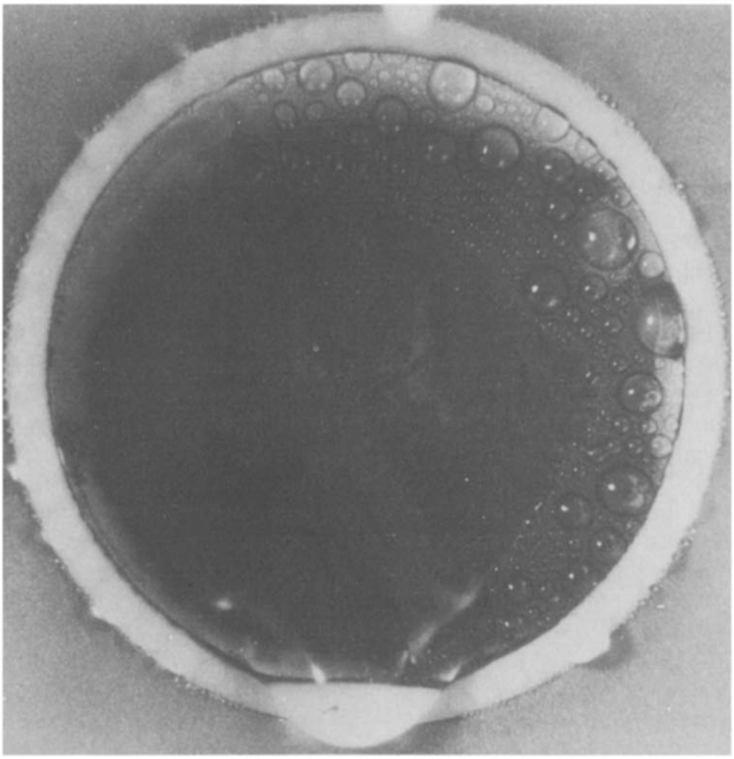

Fig. 5(b). Silver plate showing dropwise condensation on thicker surface (right side) and filmwise condensation on eroded area (left side), Point B in Fig. 4.

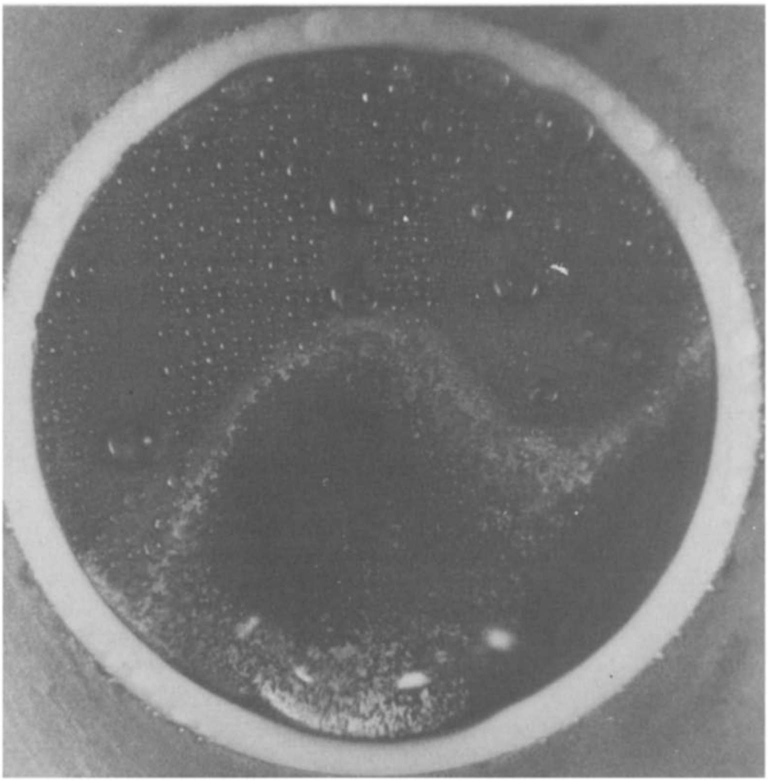

FIG. 5(c). Silver plate showing dropwise condensation on intact surface (upper part) and filmwise condensation below the wavy white boundary of the mechanically failed coating. Point C in Fig. 4.

final surface preparation prior to plating were changed. A 300 nm plate from Bath B was deposited over an electropolished surface. This condensing surface provided consistent dropwise condensation for approximately 2400 h before the heat transfer coefficient began to decay. A major difference in this run was that visual observations and photographs showed that the silver condensing surface was not simply washing away. In fact, after about 500 h of continuous condensation, the condensing surface developed a faint red discoloration. Color photographs are available [28]. This discoloration, which Auger analysis later showed to contain sulfur, in no way degraded the mode of condensation or the heat transfer. At present, the origin of the sulfur is not known. The eventual failure of this run was accompanied by the appearance of a mechanical defect near the bottom part of the condensing surface. Figure 5(c) shows this surface after 3070 h of condensation. It can be seen that, while the condensation on the bottom of the surface was suffering from the mechanical defect in the plate, on the upper portion the discolored silver plate had not worn off. Good dropwise condensation was still occurring there. In fact this upper portion still had good dropwise condensation after 3500 h.

### *Auger analysis*

A number of the condensing surfaces were analyzed using Auger electron spectroscopy. All data reported here are for runs using Bath A. However, similar data were obtained for plates from Bath B. Each data point is the average of at least three spectra taken at different positions on the condensing surface. Each spectrum corresponded to an area of approximately 1 × 1 mm.

Certain elemental signals, those of chlorine, nitrogen and sulfur were very small (usually less than 1%) and almost constant on all samples. Other elemental signals, those of silver, copper, carbon and oxygen were very dependent on the thickness of the silver electroplate. Figure 6 shows how these elemental percentages and the steam-side heat transfer coefficient *h* were affected by the thickness of the electroplate. An increase in plating thickness resulted in larger percentages of silver and carbon on the surface and also in an increase in the heat transfer coefficient. Thicker electroplates also showed lower percentages of copper and oxygen. Also seen was a very strong correlation between the steam-side heat transfer coefficient and the percentage of carbon on the condensing surface. A dramatic change in surface chemistry occurred between 75 and 150 nm of silver plate. This is the same thickness range in which both photographic and heat transfer data showed a transition from filmwise to dropwise condensation. The same elemental trends were seen on surfaces which exhibited mixed condensation. The areas on the test piece which were dropwise had larger amounts of silver and carbon, and smaller amounts of copper and oxygen, than those areas where filmwise condensation was occurring. Similar elemental trends were reported on gold surfaces by Woodruff and

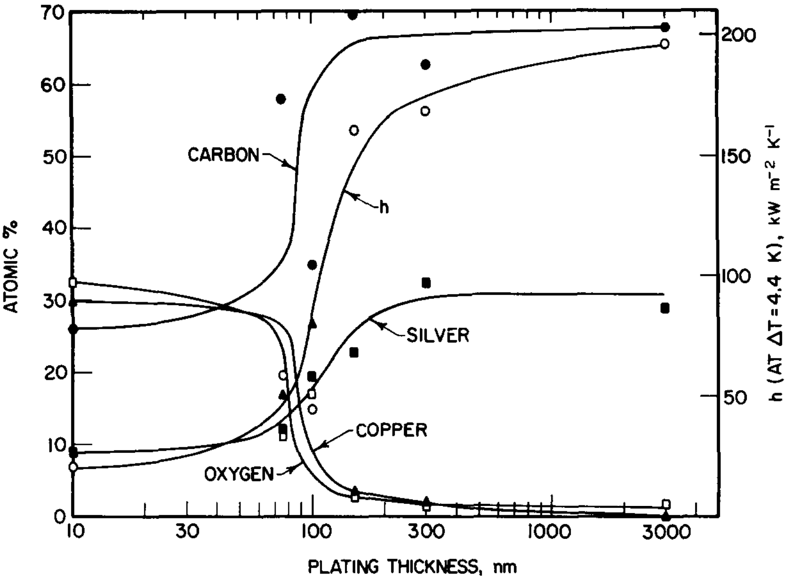

FIG. 6. Effect of thickness of silver plating on the surface composition and the condensing heat transfer coefficient. Tests at a $\Delta T$ of 4.4 K. Runs with Bath A.

Westwater [2] with the dramatic surface chemistry change occurring between 60 and 100 nm.

The relationship between carbon and oxygen on the condensing surface can be seen in Fig. 7. These two elemental signals had a very strong negative correlation. An important conclusion is that the carbon on the surface is not in an oxygen-containing form such as carbon monoxide or carbon dioxide.

The fact that surfaces which were good promoters of dropwise condensation had lower amounts of oxygen on them is consistent with the theory of Erb and Thelen [3] that the role of noble metal plates in dropwise condensation is to provide an oxide-free condensing surface. However, the higher levels of carbon on surfaces which were dropwise indicates the existence of an unknown organic contaminant promoting dropwise condensation. The boiler makeup water and the Teflon gasket surrounding the condensing surface have been considered as possible sources of the carbon on the surface. Because of the extremely low organic content of the boiler water, it seems unlikely that this is the source of the carbon. Because no Auger spectra to date has ever had a flourine signal, it appears that the carbon on the condensing surface is not from the Teflon gasket. The remaining possible sources for carbon are the stainless steel and the copper. These should be evaluated in the future.

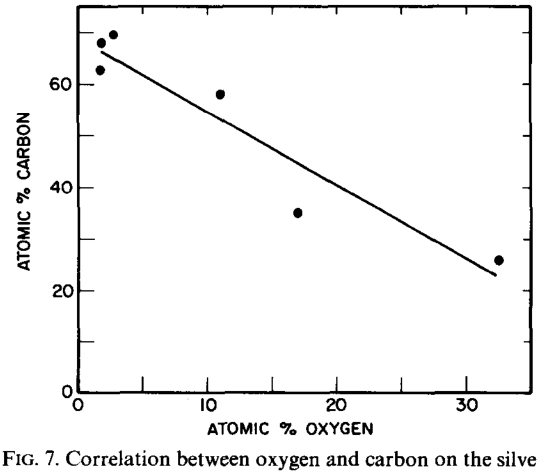

FIG. 7. Correlation between oxygen and carbon on the silver plated surfaces.

Regardless of the source of the carbon contaminant, it functions as a promoter of dropwise condensation only for thicker silver coatings. The carbon on the surface is tenaciously bound to the silver electroplate. In the case of lifetime Run 503, dropwise condensation was still being promoted on the top of the condensing surface even after 3500 h of continuous condensation. There is every reason to believe that longer lifetimes can be achieved with thicker coatings.

## CONCLUSIONS

Electroplated silver surfaces promote dropwise condensation of steam without intentional introduction of any additional promoter. The minimum thickness of silver required depends on the surface preparation of the base metal and the composition of the plating bath. The minimum value is about 50 nm.

The lifetime of silver as a promoter depends strongly on the plate thickness, the plate composition, and the base metal preparation. Continuous dropwise condensation occurred for 2400 h on a 300 nm plate over electropolished copper.

Auger electron spectroscopy showed that the composition of a silver coating is strongly dependent on its thickness. Coatings thick enough to produce dropwise condensation show significant amounts of silver and carbon and small amounts of oxygen and copper. Coatings thin enough to produce filmwise condensation show relatively small amounts of silver and carbon and large amounts of oxygen and copper. These trends are similar to those found previously for electroplated gold. The carbon is believed to be in the form of an unknown organic material, adsorbed tenaciously in trace amounts. It is probably the true promoter of dropwise condensation.

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## APPENDIX

### DERIVATION OF THE NUSSELT TYPE EQUATION FOR FILMWISE CONDENSATION ON A VERTICAL DISC

The same assumptions are used here that were used in the original derivation of an infinitely wide, vertical wall of constant height. In addition, it is assumed that condensate flow is in the vertical direction only, even though the film thickness at a fixed elevation is not constant across the width of the disc.

Figure A1 shows a vertical disc of radius $R$. For the shaded area, the average heat transfer coefficient is given by the well-known equation

$$h_x = \frac{4}{3}\left[\frac{k^3\rho^2 g\lambda}{4\mu L\Delta T}\right]^{1/4}. \tag{A1}$$

For the entire disc, the total heat transfer rate is

$$Q = 2\int_0^R h_x \Delta T L \,\mathrm{d}x. \tag{A2}$$

Substituting $L = 2R\sin\theta$, $x = R\cos\theta$, $\mathrm{d}x = -R\sin\theta\,\mathrm{d}\theta$, and fixing the integration limits: from $\theta = 0$ to $\pi/2$, we get

$$Q = \left(\frac{16}{3}\right)R^{7/4}\left[\frac{k^3\rho^2 g\lambda}{8\mu}\right]^{1/4}\Delta T^{3/4}\int_0^{\pi/2}\sin^{7/4}\theta\,\mathrm{d}\theta. \tag{A3}$$

The integral is given in terms of gamma functions

$$\int_0^{\pi/2}\sin^{7/4}\theta\,\mathrm{d}\theta = \frac{\sqrt{\pi}\,\Gamma(11/8)}{2\Gamma(15/8)}. \tag{A4}$$

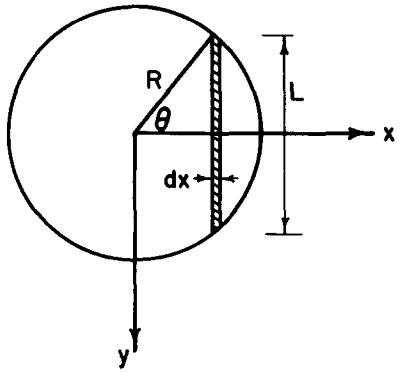

FIG. A1. Vertical circular condensing surface.

We substitute equation (A4) in equation (A3) to get $Q$. The average heat transfer coefficient for the entire disc is given by

$$h = Q/(\pi R^2 \Delta T). \tag{A5}$$

Thus

$$h = \frac{8\Gamma(11/8)}{3\sqrt{\pi}\Gamma(15/8)}\left[\frac{k^3\rho^2 g\lambda}{8\mu R\Delta T}\right]^{1/4} \tag{A6}$$

or

$$h = 0.83404\left[\frac{k^3\rho^2 g\lambda}{\mu R\Delta T}\right]^{1/4}. \tag{A7}$$

Note that this is the same as Nusselt's equation for the average $h$ for a vertical wall of constant height, except that Nusselt's case has a coefficient of 0.943 instead of 0.83404, and Nusselt's case has the constant height instead of $R$. It is easy to modify equation (A7) so that we can use the standard Nusselt coefficient along with an effective or 'average' height $L_e$. The result is

$$h = 0.943\left[\frac{k^3\rho^2 g\lambda}{\mu L_e\Delta T}\right]^{1/4} \tag{A8}$$

(average $h$ for a vertical disc)

where $L_e = 0.817D$, and $D$ is the disc diameter.

Equation (A8) was used to calculate the theoretical curves for filmwise condensation in this paper.

## CONDENSATION EN GOUTTES D'UNE VAPEUR D'EAU SUR DES SURFACES ARGENTEES ELECTROLYTIQUEMENT

**Résumé**—Des surfaces argentées électrolytiquement sont expérimentées comme promoteurs de la condensation en gouttes de vapeur d'eau à la pression atmosphérique. L'épaisseur de la couche varie de zéro à 3000 nm. Le $\Delta T$ vapeur–argent varie de 1 à 58 K. Le flux de chaleur surfacique atteint 1,5 MW m$^{-2}$, une valeur très supérieure à celle observée pour la condensation en film avec le même $\Delta T$. Deux solutions de recouvrement de surface sont utilisées. La plus grande durée de vie, 2400 h, pour la condensation continue en gouttes, s'obtient avec un recouvrement de 300 nm à partir d'une solution cyanide appliquée sur du cuivre électropoli. Une argenture plus épaisse donne une vie plus longue. La spectroscopie Auger indique que l'argenture donne une surface à faible taux d'oxygène qui adsorbe des traces organiques de l'environnement. Ceci améliore la condensation en goutte. Pour la première fois, une formulation du type Nusselt pour la condensation en film sur un disque vertical est présentée. La longueur verticale moyenne correcte est 0,817 fois le diamètre.

## TROPFENKODENSATION VON DAMPF AUF ELEKTROPLATTIERTEN SILBEROBERFLÄCHEN

**Zusammenfassung**—Elektroplattierte Silberoberflächen wurden als Hilfsmittel zur Tropfenkondensation von Dampf unter Atmosphärendruck untersucht. Die Plattierungsdicke bewegte sich im Bereich von null bis 3000 nm. Die Temperaturdifferenz $\Delta T$ zwischen Dampf und Silberoberfläche wurde von 1 bis 58 K variiert. Die Wärmestromdichte betrug bis zu 1,5 MW m$^{-2}$, ein viel größerer Wert als bei Filmkondensation mit gleicher Temperaturdifferenz $\Delta T$ beobachtet wird. Zwei Lösungen wurden zum Oberflächenplattieren benutzt. Die längste Standzeit für kontinuierliche Tropfenkondensation von 2400 Stunden wurde mit einer Schicht von 300 nm erreicht, die aus einer Zyanidlösung auf elektropoliertes Kupfer abgeschieden wurde. Eine dickere Silberschicht würde eine längere Standzeit ergeben. Mittels Auger-Elektrospektroskopie wurde festgestellt, daß Silber eine Oberfläche mit niedrigem Sauerstoffgehalt ergibt, die Spuren organischer Stoffe aus der Umgebung adsorbiert. Genau diese verursachen die Tropfenkondensation. Außerdem wurde zum ersten Mal eine Herleitung vom Nusseltschen Typ für Filmkondensation auf einer senkrechten Scheibe angegeben. Die wirksame mittlere senkrechte Länge beträgt 81,7% des Durchmessers.

## КАПЕЛЬНАЯ КОНДЕНСАЦИЯ ПАРА НА ПОВЕРХНОСТЯХ С СЕРЕБРЯНЫМ ГАЛЬВАНОПОКРЫТИЕМ

**Аннотация**—Проведено исследование серебряных гальванопокрытий как промоторов капельной конденсации пара при атмосферном давлении. Толщина покрытия изменялась от 0 до 3000 Нм. Разность температур между паром и серебряным покрытием изменялась от 1 до 58 K. Величина плотности теплового потока равнялась примерно 1,5 МВт/м$^{-2}$, что намного превышало значение для пленочной конденсации при той же разности температур $\Delta T$. Для покрытий использовались два вида растворов. Наиболее продолжительная непрерывная капельная конденсация в течение 2400 часов наблюдалась с покрытием толщиной 300 Нм из раствора цианида, нанесенного на электрополированную медь. Чем больше была толщина серебряного покрытия, тем более длительней был процесс. Методом оже-спектроскопии показано, что поверхность с серебряным покрытием содержит небольшое количество кислорода, а поэтому поглощает органические вещества из окружающей среды, что и вызывает капельную конденсацию. Впервые дан вывод зависимости нуссельтовского типа для пленочной конденсации на вертикально расположенном диске. Точное усредненное значение длины по вертикали равняется 0,817 диаметра диска.