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Dropwise condensation of steam at low pressures

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Abstract—The heat transfer coefficient was measured very carefully and repeatedly for dropwise condensation of steam in a pressure range from atmospheric pressure down to 1 kPa using five condenser surfaces. The experimental heat transfer coefficient at 1 kPa was between 30 and 35 $\mathrm{kW\,m^{-2}\,K^{-1}}$, being about one-sixth that at atmospheric pressure. A gold-plated copper block, an ultra-finished gold disk, a silicon disk vapor-deposited with gold, and two chromium-plated copper blocks were employed as the condenser surface. The magnitude of the surface roughness of the gold and the silicon disks was smaller than the radius of the smallest droplet that can exist thermodynamically on the condenser surface under the experimental surface subcoolings. Contrary to expectation, the nucleation-site density was not directly related to the surface roughness but seemed to be affected by subtle physico-chemical conditions of the surface.

1. INTRODUCTION

IN DROPWISE condensation, the vapor condenses at the surface of each droplet that lies on the condenser surface, and then the latent heat of liquefaction is transferred to the condenser surface by thermal conduction inside the droplet. Therefore, microscopic droplets which have a small thermal-conduction resistance make a major contribution to the heat transfer [1]. For those microscopic active droplets, the total temperature drop from the vapor to the condenser surface is mostly consumed by the temperature jump at the liquid–vapor interface due to mass transfer [2]. The interfacial heat transfer coefficient causing this temperature jump can be determined from the kinetic theory of gases, and it contains one important empirical constant, the condensation coefficient [3, 4]. This coefficient is defined as the ratio of the vapor molecules that will not be reflected but be captured by the liquid phase to the total number of vapor molecules that hit the liquid surface.

To date there exists a variety of reported values of the condensation coefficient of water [5–10]. This is due to the great experimental uncertainties involved in the experimental methods used so far for determining the condensation coefficient [11]. Here, it seems that recent advances in the theory of dropwise condensation, especially in the knowledge of the distribution of drops by sizes, permit the condensation coefficient to be correctly determined from the heat transfer data for dropwise condensation [12, 13].

In this respect, according as the vapor pressure decreases, the interfacial heat transfer coefficient decreases sharply, resulting in the rapid increase in the characteristic drop size at which the interfacial thermal resistance becomes equivalent to the thermal-conduction resistance through the drop. While at atmospheric pressure this characteristic drop size is estimated to be below 1 μm, it will amount to over 10 μm at 1 kPa. Thus, obtaining heat transfer data at pressures as low as possible is very desirable to catch accurately the interfacial thermal resistance, and thereby the condensation coefficient, without these being obscured by an assumed drop size distribution in the submicroscopic size range which is beyond the reach of an optical microscope [14].

Most experimental studies of dropwise condensation of steam, however, have been carried out at atmospheric pressure but only a few at lower pressures. Figure 1 shows available and reliable heat transfer data for dropwise condensation of steam at pressures below atmospheric [15–19]. Though Wilmshurst and Rose [16] and Graham [18] made measurements in a relatively wide pressure range, the data in the range of a few kilo-Pascals are scarce as well as scattered.

The purpose of the present work is to determine experimentally the heat transfer coefficient for dropwise condensation of steam in a pressure range from atmospheric down to 1 kPa, with special attention focused upon the region of the lowest possible pressure. At the same time, in order to investigate the effect of the surface roughness on the nucleation-site density, five different surfaces were used as the test condenser surface. For two of these, the magnitude of the surface roughness was smaller than the radius of the smallest droplet that can exist thermodynamically under the present experimental surface subcoolings.

2. EXPERIMENTAL APPARATUS AND PROCEDURE

2.1. *Apparatus*

Figure 2 shows a schematic drawing of the experimental apparatus. The main closed system consisted of a boiler, a test condenser, and a main condenser. The boiler was a cylinder of 155 mm i.d. and 700 mm high, of which the lower one-third contained water and the upper two-thirds was a steam chamber. The total volume of the closed system was $1.5 \times 10^4\ \mathrm{cm^3}$. Since the experiment was carried out

NOMENCLATURE

h	heat transfer coefficient, $q/\Delta T$	*Ts*	saturation temperature
Ps	steam pressure	*Tw*	condenser surface temperature
q	heat flux	ΔT	surface subcooling, *Ts*–*Tw*.

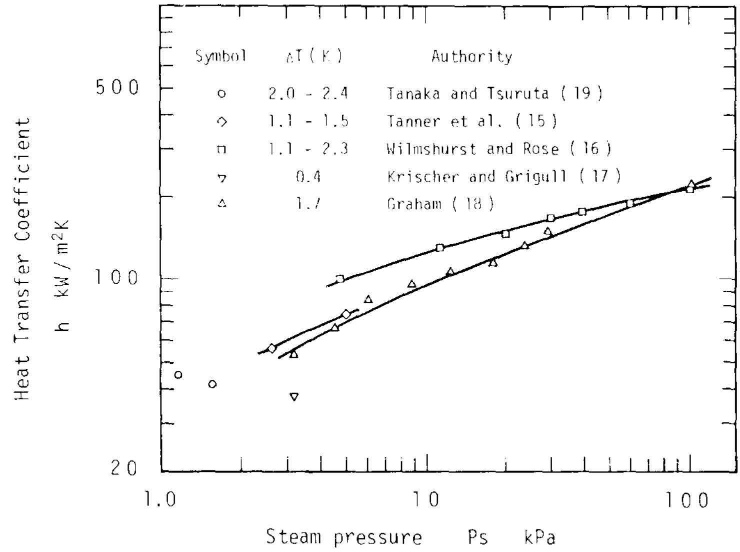

FIG. 1. Available heat transfer data for dropwise condensation of steam at pressures below atmospheric.

principally at 1 kPa, great care was taken to degas the system as well as to make it gastight. Namely, the closed system was all made of No. 304 stainless-steel and when the boiler was empty the system could be pulled to and maintained at a vacuum of 3×10^{-4} Pa by keeping a diffusion vacuum pump in motion.

Water purified with laboratory deionizing equipment was used. Its resistivity was greater than 2×10^6 Ωcm. The degassing procedure will be described later. The steam generated at the boiler was partly condensed in the test condenser and the remainder was completely condensed in the main condenser. Since the main condenser had a sufficiently large heat transfer area, the system pressure was effectively determined by the water temperature used as the main condenser coolant. As the coolant of the test condenser, on the other hand, either water or aqueous alcohol was employed, because the surface subcooling of the test condenser was adjusted by controlling this coolant temperature in the range between -15°C and 60°C.

At very low pressures, intermittent boiling with severe bumping would take place. Then a stirring impeller, driven indirectly from outside the container wall by a magnetic force, was installed in the boiler. In addition, the boiler was equipped with two kinds of heaters: a submerged sheath heater and a ribbon heater fastened on the outside surface of the container. Proper use of these devices permitted sufficient steam to be generated either by still evaporation from the water surface at low pressures, or by stable nucleate boiling on the heater surface at pressures near atmospheric.

Steam temperature *Ts* was measured by three thermocouples, of which two were installed in the steam chamber (see Fig. 2) and one was set a little downstream of the test condenser surface (Fig. 3). At 1 kPa, the saturation temperature became well below the room temperature. In this situation, in order to avoid the effect of radiation on the thermocouples, the upper half of the container wall, which was equipped with coolant piping, was made to work as an auxiliary condenser; besides, the steam chamber was separated from the container wall by another cylindrical wall (Fig. 2). Further, the thermocouple installed in the test condenser was arranged so that it was kept in the wet-bulb condition. The average steam temperature measured by the foregoing three thermocouples coincided to within an accuracy of 0.1 K with the saturation temperature corresponding to the pressure at the steam chamber that was measured in the range below 2 kPa by a manometer using di-butyl phthalate.

Figure 3 shows the setup of the test condenser. The condenser block was made of copper of purity 99.96% and its main part had the shape of a cylinder, 20 mm in diameter and 91 mm long (Fig. 4). The condensing surface was oriented vertically. Visual observation was possible through the 3-mm-thick glass window which was placed in front of the condenser surface

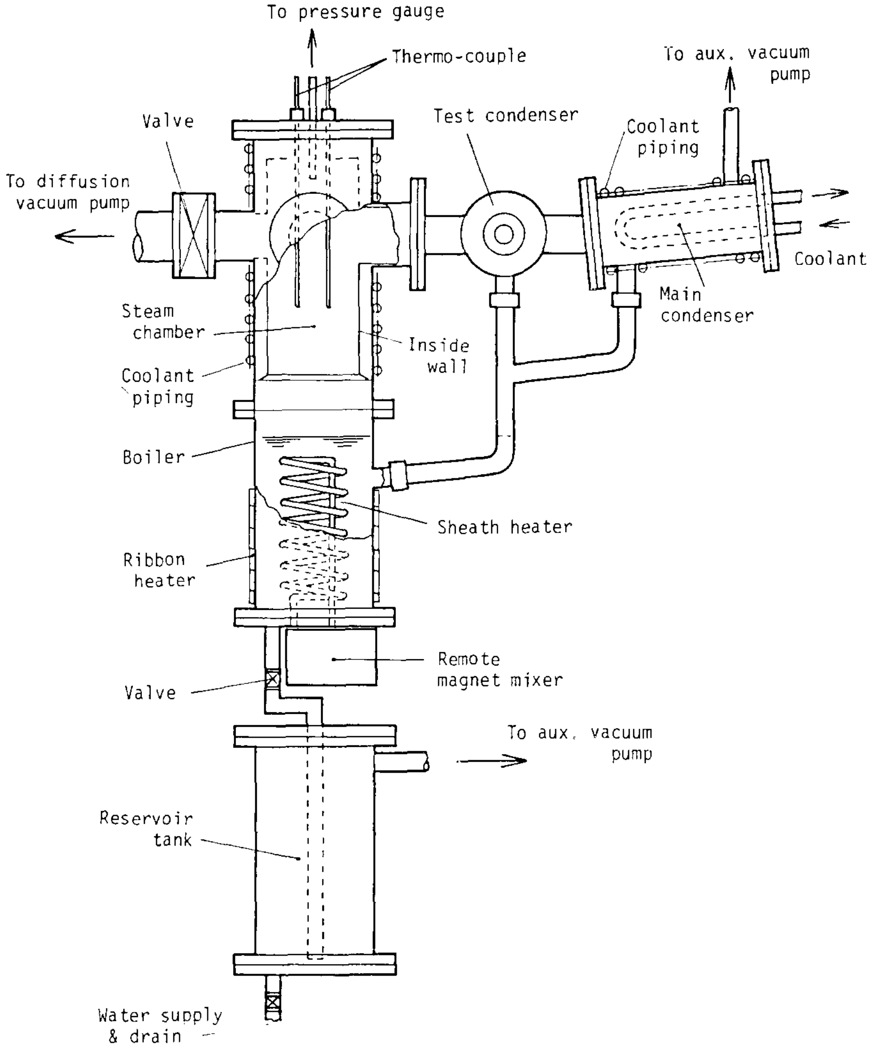

FIG. 2. Experimental apparatus.

with a space of 3 mm. Six thermocouple holes, 0.6 mm in diameter, were drilled radially to the axis of the condenser block (Fig. 4), and sheathed chromel–alumel thermocouples 0.5 mm in diameter were installed. By applying a least-square regression to the readings of these thermocouples, a linear temperature distribution in the copper condenser block was determined. The heat flux q and the surface temperature Tw were respectively obtained from the gradiant and from the extrapolation of the temperature distribution [taking account of the surface composition in case of surfaces (C) and (D)].

2.2. *Test surfaces*

Five test surfaces (A)–(E) were used in the present study. Figure 4 shows the shape of the condenser blocks and their surface compositions.

Surfaces (A) and (E) were prepared with the same process: the condensing-side end of the copper condenser block was polished first to a mirror finish using several grades of emery paper followed by alumina powder suspended in deionized water, and then it was electro-plated with chromium in the usual commercial manner.

Surface (B) was prepared in the way similar to surfaces (A) and (E) but it was plated with gold.

Surface (C) was a 0.3-mm-thick gold disk which was diffusion-welded to the end of a condenser block. This surface was finished by superprecision cutting with a diamond tool and its 10-point-average surface-roughness was 0.02 μm. This value is equivalent to the thermodynamic critical radius of a droplet under a subcooling of 1.0 K.

Surface (D) was a 0.4-mm-thick silicon disk which was soldered to a condenser block with its condensing surface being vapor-deposited with gold. This silicon disk was cut out of the same silicon wafer used as the substrate of an electronic LSI circuit, and its surface had been finished to an order of a few nanometers. Further, it must be noted that silicon has a high thermal conductivity of 84 W m^{-1} K^{-1}, a little larger than that of pure iron.

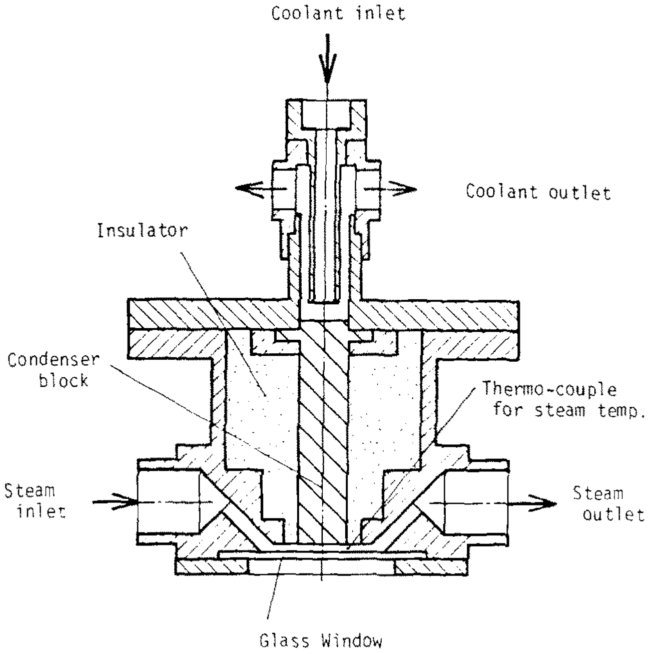

FIG. 3. Test condenser (plan view).

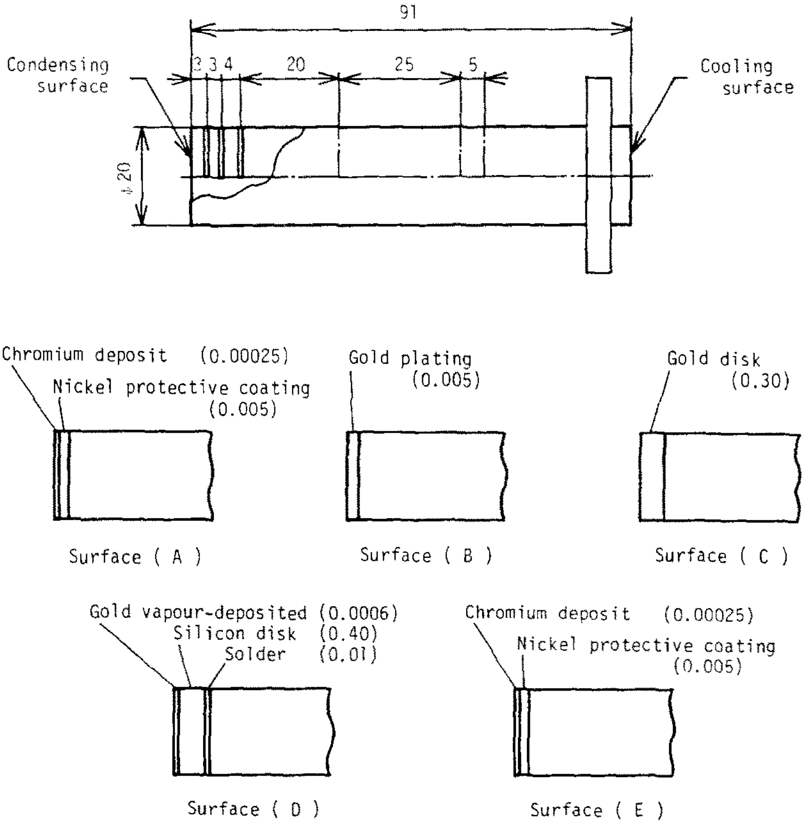

FIG. 4. Shape of condenser blocks and their surface compositions (numerals in parentheses denote thickness in millimeters).

These five surfaces needed no organic promoter to maintain dropwise condensation. The three gold surfaces (B), (C) and (D) could be made to support dropwise condensation by alkaline cleaning [20], i.e. cleaned with a 10% aqueous solution of potassium hydroxide, followed by rinsing with deionized water in an ultrasonic washer. Surface (A), on the other hand, was simply wiped with absorbent cotton soaked with ethyl alcohol. Cleaning or wiping the surface was done at intervals of 50–100 h of cumulative operation of the apparatus.

In the preliminary experiment, surface (E) was found to bear microscopic droplets very sparsely distributed at low pressures. Then this surface was used without cleaning throughout the cumulative experimental time of about 150 h, after which no difference in the surface conditions was recognized.

2.3. *Experimental procedure*

The test water was degassed as follows. Deionized water was supplied to the reservoir tank (Fig. 2). Setting the auxiliary vacuum pump in motion, the main system was evacuated, and the pressure in the reservoir tank was also decreased to the saturation pressure at the room temperature. Then, the water was transferred to the boiler by utilizing the difference in the saturation pressure between the two vessels. While the test loop was kept running at a high evaporation rate for several hours, the noncondensable gas, accumulated in the main condenser, was removed by opening the valve leading to the auxiliary vacuum pump for a short time at intervals.

The degassed water was restored to the reservoir tank. The dummy condenser block, which was installed in place of the test surface during the degassing operation, was removed from the test condenser, and then the test surface, cleaned and thoroughly rinsed, was mounted. After the system was evacuated to 3×10^{-3} Pa, the test water was returned to the boiler.

For a single heat transfer datum, the system was kept running for 3–4 h to attain a completely stationary condition. Microphotographs of the condenser surface were taken simultaneously with the heat transfer measurement.

Steam flow near the condensing surface not only prevents the buildup of enriched noncondensables but also reduces the departing drop size. In the present experiment, the steam flow rate was adjusted so that the dynamic pressure, based on the average steam velocity in the test condenser, amounted to 4 Pa. When the surface subcooling ΔT was taken as 1.5 K, the average steam velocity in the test condenser amounted to about 10 times the mean suction velocity toward the condenser surface caused by condensation, irrespective of the experimental pressure.

3. MICROSCOPIC OBSERVATION OF SMALL DROPS

It seems generally admitted that in dropwise condensation the primary drops originate at discrete nucleation sites on the surface, and that pits and grooves on the surface are the most probable nucleation sites [21]. This statement seems to be supported fairly well by our microphotograph in Fig. 5, which was taken during dropwise condensation on

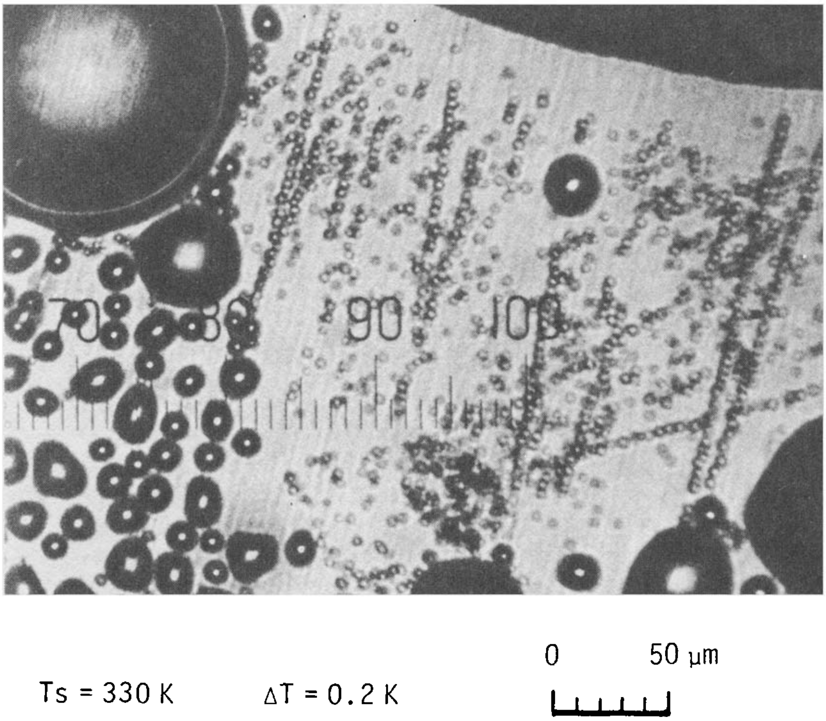

FIG. 5. Microphotograph of chromium-plated surface; droplets originating along scratches.

a chromium-plated surface of the same kind as surface (A). This picture clearly shows droplets originating along scratches. Then, if pits and grooves are completely removed from the surface, what will happen?

Figure 6 is an electron-microscope picture of surface (C) by means of a carbon replica. Two fairly conspicuous traces made by a diamond cutter are seen in the picture. Observation by an interference microscope revealed that pairs of those conspicuous traces were repeated at regular intervals of 15 μm, a value which turned out to correspond to the feed of cutting tool, and further that the maximum difference in height between fairly smooth ridges and valleys repeated at long intervals amounting to approximately the nominal 10-point-average surface-roughness of 0.02 μm. Thus, surface (C) was considered to have very few flaws that would function as nucleation sites having sizes over the thermodynamic critical drop radius [21].

Contrary to expectation, the ultra-flat surface (C) proved to bear small drops fairly densely. Actually, Fig. 7 compares distributions of small drops on three gold surfaces (B), (C) and (D), of which (B) is of commercial surface finish while (C) and (D) are ultra-flat. In this comparison, steam temperature Ts and the surface subcooling ΔT were respectively taken to be almost the same for the three surfaces. It can be seen that small drops having radii of 1–2 μm are distributed equally in three pictures in Fig. 7.

On the other hand, we found that the chromium surface (E), whose surface finish was of the commercial level, bore microscopic droplets very sparsely at low pressures. This seemed quite accidental among many similar chromium-plated surfaces used so far in our laboratory, but occurred to surface (E) constantly and repeatedly. Figure 8 demonstrates the situation by comparing microphotographs of surfaces (C) and (E) taken under the same experimental conditions. This peculiarity of surface (E) in the small drop population, however, was noted only at low pressures. With increasing steam pressure, small drops increased in number on surface (E), until at $Ts = 334$ K distinction could not be made between surfaces (C) and (E) as to the small drop distributions.

4. HEAT TRANSFER MEASUREMENTS

Heat transfer coefficients, $h = q/(Ts - Tw)$, measured with varying pressure for three gold surfaces (B), (C) and (D) are shown in Fig. 9. For surface (B), that was gold-plated in an ordinary manner, measurements were carried out carefully and repeatedly with the purpose of obtaining standard heat transfer data. The surface subcooling, $\Delta T = Ts - Tw$, was taken within a range of 1.1–1.5 K. While the heat transfer coefficient was 250 kW m^{-2} K^{-1} at atmospheric pressure, it decreased with decreasing pressure, becoming 35 kW m^{-2} K^{-1} at 1 kPa. The experimental results were very consistent as well as reproducible. More than 90% of the data were included in the range of ±10% deviation from the solid line drawn in Fig. 9.

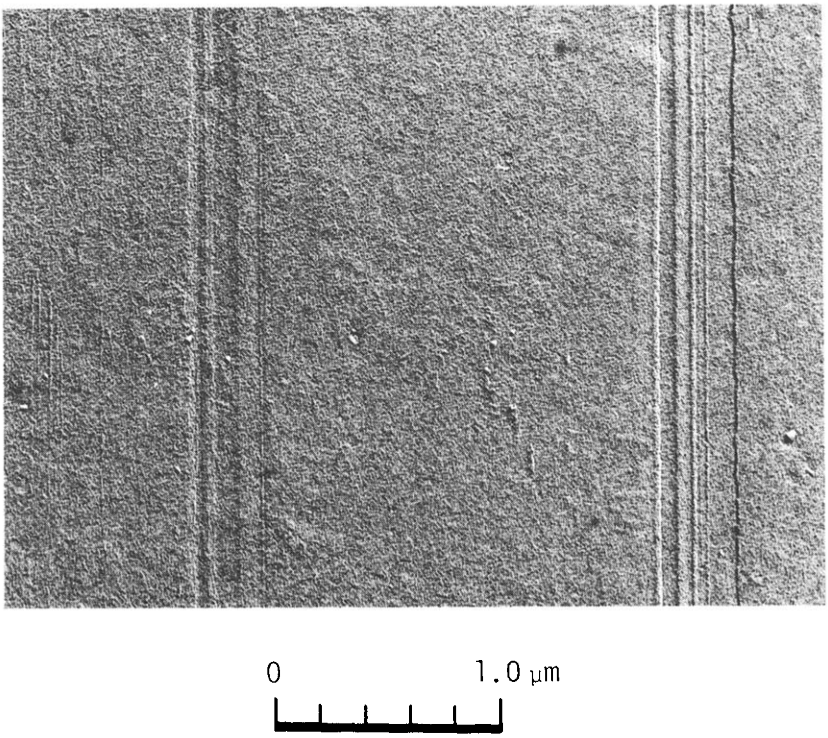

FIG. 6. Electron-microscope picture of surface (C).

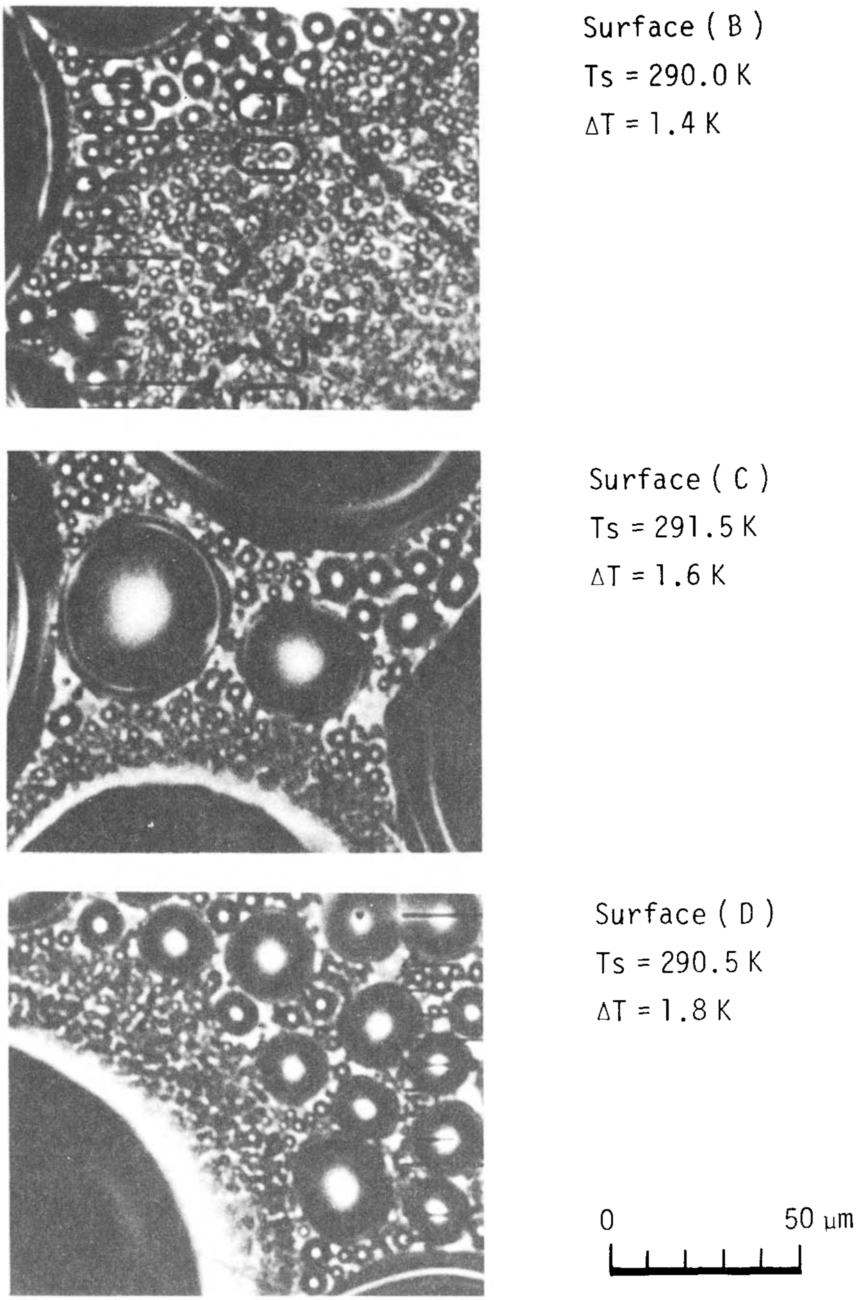

FIG. 7. Comparison of small drop populations between three gold surfaces (B), (C) and (D).

The heat transfer results for the ultra-flat gold surfaces (C) and (D) are also plotted in Fig. 9. Though the surface subcoolings ΔT for these surfaces were taken to be slightly greater than those for surface (B), the heat transfer coefficient under a constant pressure became almost independent of ΔT when $\Delta T > 1.0$ K, as is understood from Fig. 10. While the heat transfer coefficients of surfaces (C) and (D) are slightly lower than that of surface (B), the overall behavior of the heat transfer coefficients are similar between the three gold surfaces. This seems natural from the fact that the three surfaces bore microscopic droplets similarly well, as shown in Fig. 7. The departing drop radius *R*max was 1.5 mm at 1 kPa—for all the three gold surfaces.

The heat transfer data for chromium surfaces (A) and (E) are shown in Fig. 11. The heat-transfer coefficient of surface (A) was around 200 kW $\mathrm{m^{-2}\,K^{-1}}$ at atmospheric pressure, but it decreased to 32 kW $\mathrm{m^{-2}\,K^{-1}}$ at 1 kPa. The contact angle of water on surface (A) was about 90°, and the departing drop radius at 1 kPa was 1.3 mm.

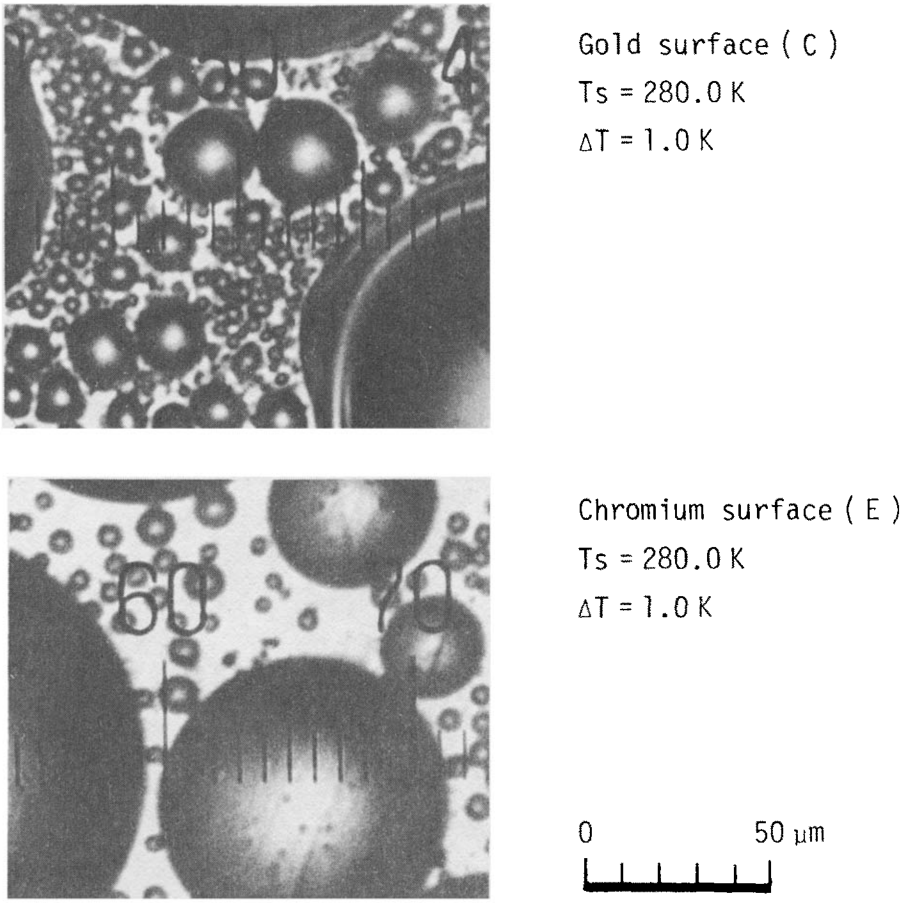

FIG. 8. Comparison of small drop populations between surfaces (C) and (E).

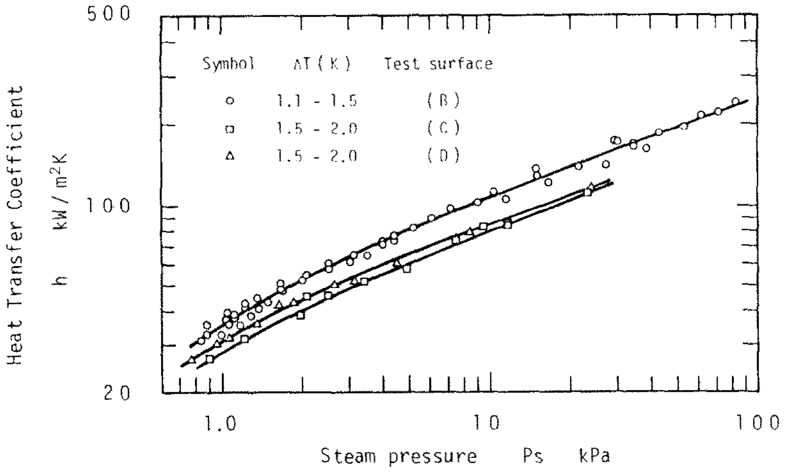

FIG. 9. Heat transfer data for gold surfaces (B), (C) and (D).

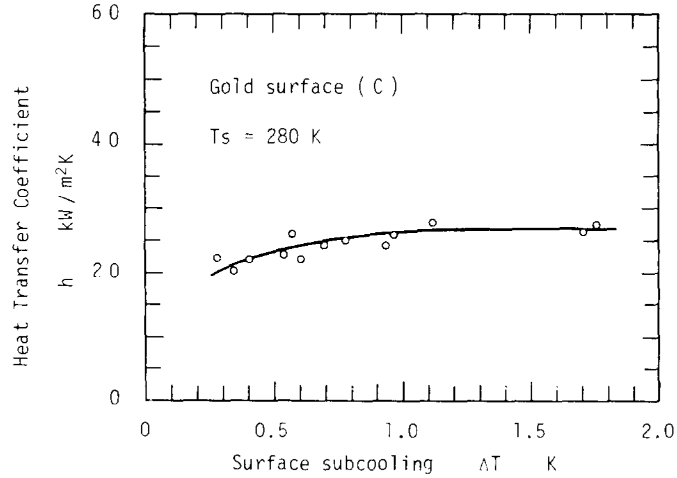

FIG. 10. Variation of heat transfer coefficient with surface subcooling.

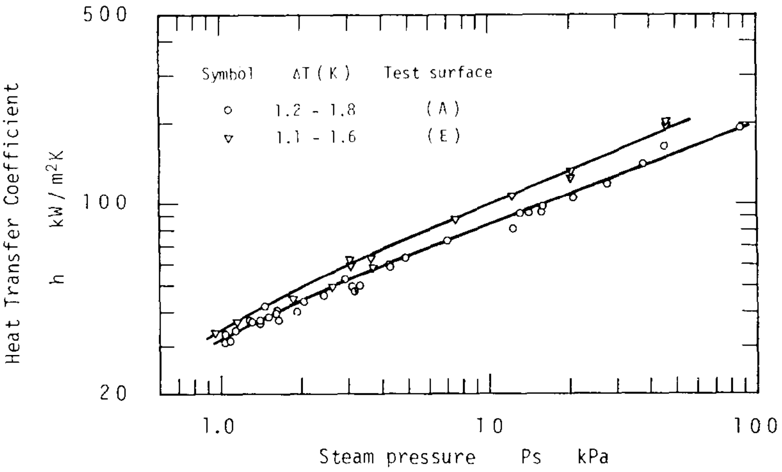

FIG. 11. Heat transfer data for chromium surfaces (A) and (E).

Surface (E) showed an extraordinarily small population density of microscopic droplets at low pressures, as mentioned previously. Then, since microscopic droplets were thought to play an important role in the heat transfer in dropwise condensation, we expected that the heat transfer coefficient of surface (E) would be moderately lower than those of the other surfaces. The results obtained for surface (E), however, merged indistinguishably with other data even at the low pressure range, as shown in Fig. 11. This seeming discrepancy has been resolved in ref. [14], in which distributions of drops by sizes down to 1 μm in radius were experimentally determined, and then the true contribution to heat transfer from each drop-size range was evaluated. In the end, the departing drop radius for surface (E) was a little smaller, being 1.0 mm at 1 kPa. In addition, the contact angle of drops in this case was estimated to be slightly over 100°, with small drops being partly concealed at the edge of a large drop.

5. CONCLUSIONS

1. The heat-transfer coefficient for dropwise condensation of steam decreased with decreasing steam pressure. It took a value between 30 and 35 $\mathrm{kW\,m^{-2}\,K^{-1}}$ at 1 kPa.
2. In the pressure range below a few kilo-Pascals, the heat transfer coefficient was not affected by an apparent difference in the population of microscopic droplets.
3. The nucleation-site density was not directly related to the microscopic surface roughness, but seemed to be affected by subtle physico-chemical conditions of the surface.

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CONDENSATION EN GOUTTES DE LA VAPEUR D'EAU A FAIBLE PRESSION

Résumé—Le coefficient de transfert de chaleur est mesuré avec soin pour la condensation en gouttes de la vapeur d'eau dans le domaine de pression compris entre la pression atmosphérique et 1 kPa, en utilisant cinq surfaces de condensation. Le coefficient de transfert à 1 kPa est entre 30 et 35 kW m^{-2} K^{-1}, soit à peu près le sixième de celui pour la pression atmosphérique. On emploie comme surface un bloc plaqué-or, un disque d'or de belle finition, un disque de silice avec dépôt de vapeur d'or et deux blocs de cuivre chromés. L'amplitude de la rugosité de surface de l'or et des disques de silice est plus faible que le rayon de la plus petite gouttelette qui peut exister thermodynamiquement sur la surface froide dans les conditions expérimentales de sous-refroidissement. Contrairement à ce qui était attendu, la densité des sites de nucléation n'est pas directement reliée à la rugosité de la surface mais semble être sensible à des conditions physico-chimiques de la surface.

TROPFENKONDENSATION VON WASSERDAMPF BEI KLEINEN DRÜCKEN

Zusammenfassung—Der Wärmeübergangs-Koeffizient bei der Tropfenkondensation von Wasserdampf wurde im Druckbereich zwischen Atmosphärendruck und 1 kPa an fünf Kondensator-Oberflächen gemessen—und zwar sehr sorgfältig und wiederholt. Der experimentell ermittelte Wärmeübergangs-Koeffizient betrug 30 bis 35 kW m^{-2} K^{-1} bei 1 kPa, was ungefähr ein Sechstel des Wertes bei Atmosphärendruck darstellt. Die Kondensator-Oberflächen waren: Ein gold-plattierter Kupferblock, eine sehr fein bearbeitete Goldscheibe, eine gold-bedampfte Silikonscheibe und zwei chrom-plattierte Kupferblöcke. Die Oberflächen-Rauhigkeit der Gold- bzw. der Silikonscheibe war geringer als der Radius des kleinsten Tröpfchens, das an der Kondensator-Oberfläche bewi der vorhandenen Oberflächen-Unterkühlung thermodynamisch existieren kann. Entgegen den Erwartungen ist die Kiemstellendichte nicht direkt mit der Oberflächen-Rauhigkeit verknüpft, sondern es scheint, daß jene von feinen Unterschieden der physikochemischen Oberflächenbedingungen beeinflußt wird.

КАПЕЛЬНАЯ КОНДЕНСАЦИЯ ВОДЯНОГО ПАРА ПРИ НИЗКИХ ДАВЛЕНИЯХ

Аннотация—Проведено тщательное и многократное измерение коэффициента теплообмена при капельной конденсации водяного пара в диапазоне давлений от атмосферного до 1 кПа на пяти поверхностях конденсации. Экспериментально измеренная величина коэффициента теплообмена при давлении 1 кПа находится в диапазоне от 30 до 35 кВт/м^2 К, что примерно в шесть раз меньше значения, полученного при атмосферном давлении. В качестве поверхностей конденсации использовались позолоченный медный брусок, тщательно отполированный золотой диск, кремниевый диск, позолоченный методом вакуумной металлизации, и два медных хромированных бруска. Величина шероховатости золотого и кремниевого дисков была меньше радиуса самой маленькой термодинамически возможной капли на поверхности конденсации при используемых в эксперименте недогревах поверхности. Вопреки предположениям оказалось, что число центров конденсации не находится в прямой зависимости от шероховатости поверхности, а скорее зависит от неустановленных физико-химических условий, имеющих место на поверхности.