Int. J. Heat Mass Transfer. Vol. 34, No. 12, pp. 3047–3054, 1991
Printed in Great Britain

0017–9310/91 $3.00+0.00

The effect of polyvinylidene chloride coating thickness on promotion of dropwise steam condensation

T. HARAGUCHI
Technical College of Ibaraki University, Hitachi, Japan

R. SHIMADA
Faculty of Science and Engineering, Ishinomaki Senshu University, Ishinomaki, Japan

S. KUMAGAI
Faculty of Engineering, Tohoku University, Sendai, Japan

and

T. TAKEYAMA
Faculty of Science and Engineering, Ishinomaki Senshu University, Ishinomaki, Japan

(*Received* 4 *June* 1990 *and in final form* 6 *February* 1991)

Abstract—Polyvinylidene chloride coating is proposed as a promoter of dropwise steam condensation. The effect of coating thickness is investigated in regard to promotion of the condensation. Four thicknesses, 0.05, 0.10, 0.25 or 0.50 μm, are coated on a copper heat transfer block. Each coating surface is heat-set for 83 h, after which it is evaluated. The 0.05 μm coating provides heat transfer performance comparable to that of gold or oleic acid promoter coatings on surfaces. The 10 μm coating retains fair dropwise condensation over a 21 568 h period.

1. INTRODUCTION

BOILING phenomena are explained by using a boiling curve, in which the horizontal axis shows wall superheat temperature and the vertical axis shows the heat flux. Takeyama and Shimizu [1] measured a condensation curve which is considered to be the counterpart of the boiling curve.

Dropwise condensation results in heat transfer coefficients much greater than for filmwise condensation, so that many studies have been made on the former. The primary experimental research was done by Utaka and Tanasawa [2] who showed that steam velocity had an effect on the condensation curve. Continuing from the work of Tanner *et al.* [3], Citakoglu and Rose [4] showed that noncondensable gas included in steam caused the heat transfer coefficient to decrease. Izumi *et al.* [5] reported on the hysteresis phenomenon of steam including noncondensable gas in a high subcooling temperature region. Kaino *et al.* [6] measured the heat transfer coefficient of dropwise condensation at a low subcooling temperature, $\Delta T_{sub} = 0.03$–2 K. With a view to more practical use, Izumi *et al.* [7] investigated the effect of surface roughness on the heat transfer coefficient.

On the other hand, from the viewpoint of producing a permanent dropwise condensation surface, Woodruff and Westwater [8] found that an electroplated gold surface could provide permanent dropwise condensation, while Erb and co-workers [9–11] showed that an electroplated silver surface gave good dropwise condensation.

Nonmetal coating surfaces, particularly PTFE, have also been found to produce permanent dropwise condensation. A number of investigations have looked at this [12–16], however, none achieved the high subcooling temperature region of glacial condensation, because the films were too thick, and a high heat flux could not be obtained.

Utaka *et al.* [17] used propylene glycol for dropwise condensation and showed its condensation curve. With a view to practical use, Holden *et al.* [18] carried out endurance tests for dropwise condensation using several kinds of polymer films.

Using noble metals is more expensive than using polymers for producing permanent dropwise condensation surfaces. But as polymers have a relatively low thermal conductivity, if they are too thick the heat transfer is reduced. However, we expected that the dropwise condensation heat transfer coefficient, including the resistance of the film, was even greater than the filmwise condensation heat transfer coefficient. In laboratory tests, we looked at the use of polyvinylidene chloride to provide permanent

NOMENCLATURE

a	diameter of condensation surface [m]	v	steam velocity [m s^{-1}]
D	departure diameter [m]	Wt	temperature fluctuation.
q	heat flux [W m^{-2}]		
t	time [s]	Greek symbol	
ΔT_{sub}	subcooling [K]	δ	coating thickness [m].

dropwise condensation. We wanted to find the optimum thickness that could realize a heat transfer coefficient equivalent to that of an oleic acid coated copper surface, an electroplated gold surface or a gold deposited surface. Various thicknesses of polyvinylidene chloride film on a copper surface were exposed to steam at atmospheric pressure and observations were made on dropwise condensation.

2. EXPERIMENTAL APPARATUS AND PROCEDURE

2.1. *Heat flux measurement apparatus and method to produce dropwise condensation surface*

The experimental apparatus is outlined in Fig. 1. Steam was generated from distilled water in a large glass boiler. Watermist particles were eliminated, by their inertia, while flowing in the pipe from the boiler to the condensation surface. Steam was blown vertically against the condensation surface, through a nozzle (16.3 mm i.d.), and its velocity was calculated.

Figure 2 shows the heat transfer block and steam chamber. The heat transfer block was made of copper, shaped in a truncated cone, and its vertical surface was set at a right-angle so as to absorb a high heat flux. The top was the heat transfer surface which was cooled by water or LN_2 from behind to produce a large temperature difference between the steam and the cooled surface. The surroundings of the heat transfer surface were insulated using PTFE. Furthermore, a thin aluminum foil was put around the surface to eliminate the boundary effect, and to ensure the condensing droplets and film flowed smoothly. The copper surface was polished to a mirror finish with a metallurgical polishing cloth soaked in a 0.06 μm aluminum oxide polishing compound. Next, the polished surface was carefully washed with a cotton swab, previously dipped into distilled water. This was followed by another washing with a cotton swab, this time dipped into ethanol. After air drying, the surface was coated with polyvinylidene chloride. The coating film thicknesses were 0.05, 0.10, 0.25 or 0.50 μm. These thicknesses were measured using an interference microscope.

Four C–A sheath thermocouples were located 1, 2, 3 and 4 mm from the surface along the block axis. They measured the temperature distribution in the block.

Heat flux was obtained with a thermal conduction equation. The surface subcooling was calculated from the copper surface temperature, steam saturation temperature, heat flux and coating film thickness. The thermal conductivity of polyvinylidene chloride used in the above calculation was 0.13 W m^{-1} K^{-1} [20].

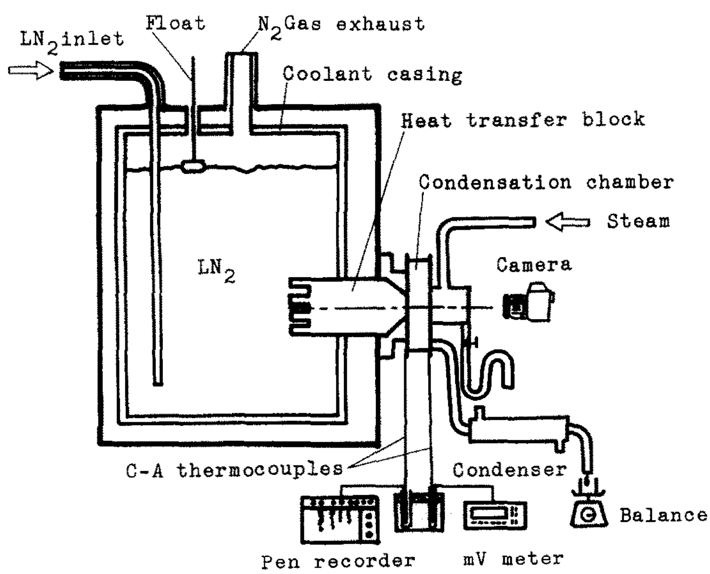

FIG. 1. Schematic of experimental apparatus.

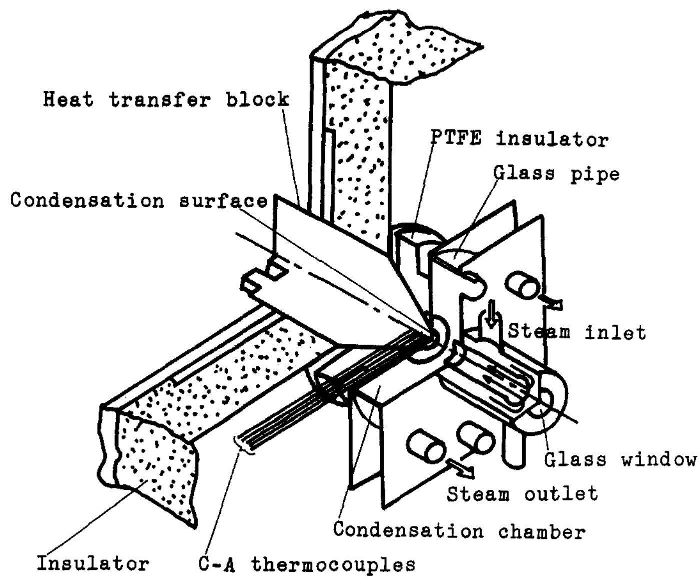

FIG. 2. Steam chamber and heat transfer block.

The measurement accuracy of the heat transfer of dropwise condensation was confirmed by comparing the obtained condensation curve for the same heat transfer surface, when gold electroplated, with literature curves.

2.2. *Endurance test apparatus*

Figure 3 shows the apparatus for the endurance test. Steam was produced from distilled water boiled in a flask and the steam was condensed on the heat transfer surface. The working fluid was allowed to circulate inside the loop. The coolant used was tap water. The heat transfer surface was a 40 × 80 mm copper surface coated with a 10 μm thick polyvinylidene chloride film.

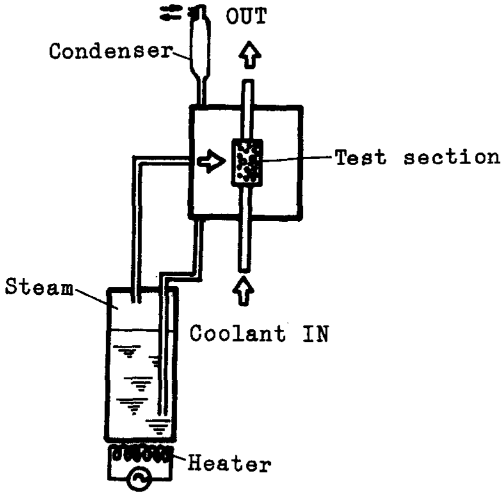

FIG. 3. Schematic of endurance test apparatus.

3. EXPERIMENTAL RESULTS AND INTERPRETATION

3.1. *Condensation curve and observation at surface subcooling*

(i) *Measurement accuracy.* The measurement accuracy of the heat transfer for the dropwise condensation apparatus was confirmed by comparing the condensation curve obtained for this apparatus with other reported condensation curves [1, 2, 19]. The comparison results are shown in Fig. 4. In the present investigation, the diameter of the electroplated condensation surface was 10 mm and its condensation curve was located between those for 5 and 15 mm diameter surfaces having similar steam velocities obtained by other researchers.

The difference reflected the effect of the diameter size and confirmed the accuracy of the measuring system.

(ii) *Heat-set treatment effect for dropwise condensation of a polyvinylidene chloride surface.* To eliminate internal stress in the film, the coated surface was heated to about 105°C for 83 h. This process is called the heat-set treatment. Figure 5 shows the condensation curves for the 0.50 μm thick film before and after the heat-set. If heat-set treatment was not carried out, the film peeled or cracked in the region of small surface subcooling, allowing water to condense between the copper surface and film and decreasing the heat flux in the curve. Finally, the film was broken.

However, if the heat-set treatment was used, the data showed fairly good dropwise condensation was provided. Holden *et al.* [18] reported that the coating film was peeled and cracked after their heat transfer test, but in the present test no peeling or cracking occurred.

The heat-set treatment time required was shorter

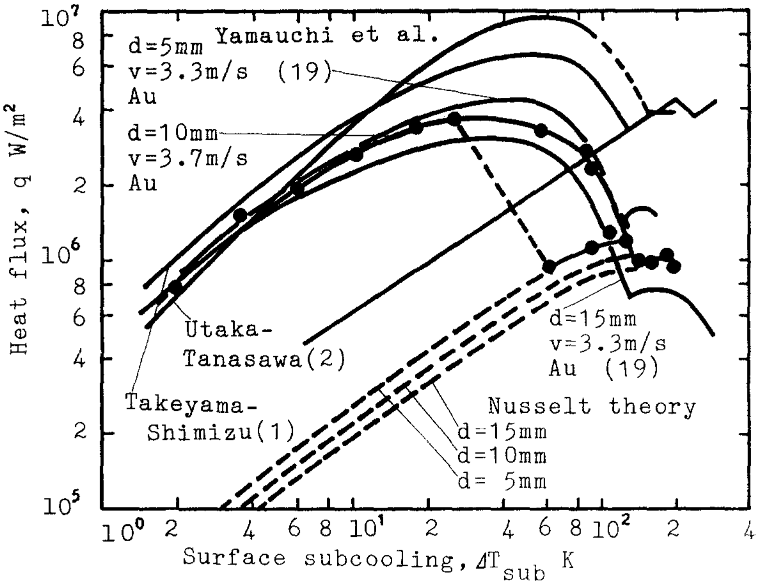

FIG. 4. Condensation curve (comparison with other experiments).

for thinner films than thicker ones. If the film thickness was 0.05 μm, the treatment time was about 17 h at 100°C. The film's mechanical strength has been suggested to increase, if the heat treatment temperature is increased [21], but we found that a satisfactory heat-set temperature was that equal to the highest temperature used during the condensing tests.

Figure 6 shows the photographs of the condensation at each surface subcooling temperature, where the film thickness was 0.50 μm. The dropwise condensation for a polyvinylidene chloride coated surface showed the same transition character, dropwise–filmwise–glacial–filmwise–dropwise as other chemical promoters, gold deposited surface and electroplated gold surface show.

(iii) *The effect of polyvinylidene chloride thickness on promotion of the dropwise condensation curve of steam.* Figure 7 shows the effect of the thickness of polyvinylidene chloride coatings for promotion of dropwise condensation of steam, in which four thicknesses, 0.05, 0.10, 0.25 and 0.50 μm, were examined. The coating thickness of 0.05 μm showed a dropwise condensation heat transfer performance as high as gold or oleic acid promoting surfaces in the large surface subcooling region. However, the other thicknesses did not have such a high heat transfer performance, because of their large thermal resistance. The 0.05 μm coating showed heat transfer performance much higher than the gold or oleic acid promoting surface for surface subcooling of up to 8 K. The 0.1 μm thick coating also gave good results.

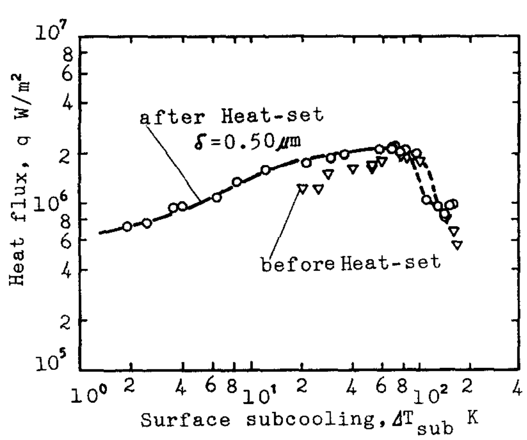

FIG. 5. Effect of heat-set treatment for condensing curve.

These could be attributed to the lowered surface energy of the coated condensing surface, which is mentioned in the next section. Holden *et al.* [18] reported that a 0.5 μm parylene-*N* coating increased the heat transfer coefficient 6–7.5 times, but with a 1.0 μm coating, the thicker film increased the coefficient only 4.5–6 times. Transition from the filmwise to dropwise condensation had a tendency to occur at larger surface subcooling with greater thickness. Close inspection of the 0.5 μm coating surface after the heat transfer tests revealed small areas in which the coating layer showed signs of peeling or crack initiation.

Heat flux decreased in the region of surface subcooling above the maximum heat flux point. Therefore, that maximum point should be one of the upper limits in designing condensers.

The maximum heat flux vs coating thickness is shown in Fig. 8. An almost linear relationship with negative slope was seen between heat flux and the coating thickness.

Figure 9 shows the temperature fluctuations 1.00 mm below the condensation surface. The coating thickness and the surface subcooling are shown in the figure. These temperature fluctuations were similar to those obtained by Takeyama and Shimizu [1]. The fluctuations increased with a decrease in the coating

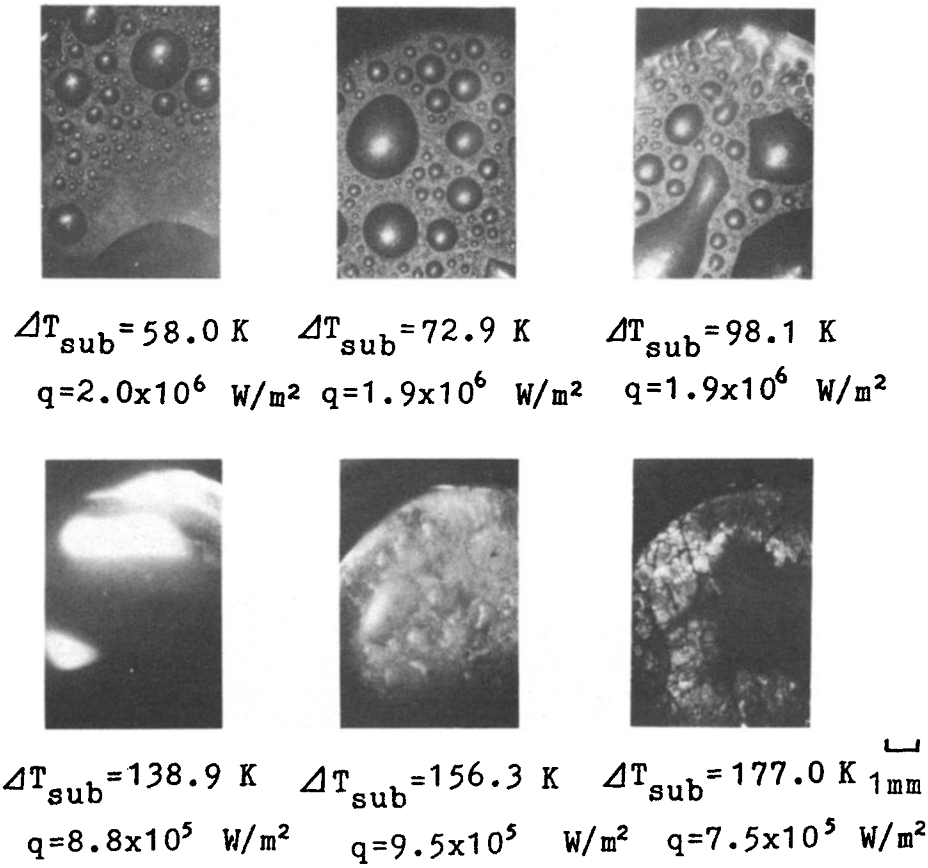

FIG. 6. Appearance changes of dropwise condensation with subcooling (film thickness = 0.50 μm).

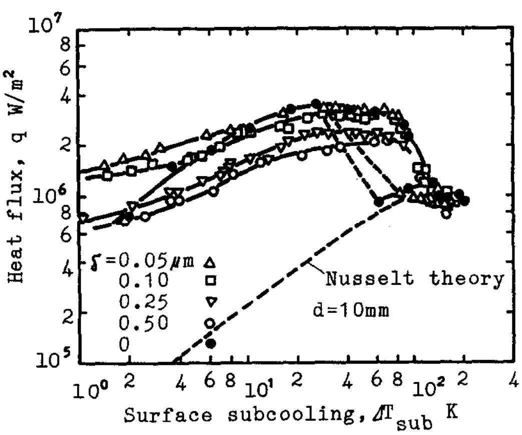

FIG. 7. Effect of coating thickness on heat flux.

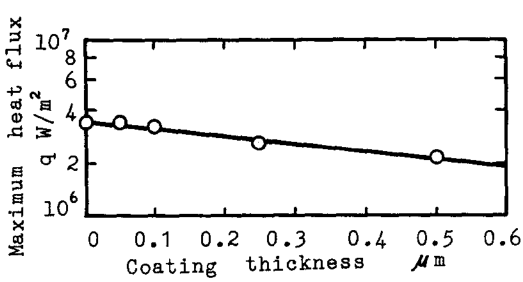

FIG. 8. Maximum heat flux dependence on coating film thickness.

thickness, and the fluctuation interval was shortened in the small subcooling region. In addition, if compared at surface subcooling $\Delta T_{sub} = 2$ K, the temperature fluctuation of the surface of coating thickness $\delta = 0.05$ μm was much larger than that of $\delta = 0$ μm (gold electroplated surface), which might have some relationship with the higher heat flux of the coated surface seen in Fig. 8.

Figure 10 shows the maximum temperature fluctuation $\Delta T_{sub} = 34$ K vs the coating thickness. The magnitude of the fluctuation decreased as the coating thickness increased and it was very large when the film was thinner than 0.10 μm.

3.2. *Drop departure diameter and heat transfer*

It has been reported by Tanasawa *et al.* [22] that the heat transfer coefficient increased with a decrease in the departure diameter.

Data in Fig. 7 showed that the surface with a film thickness $\delta = 0.05$ μm, had a larger heat flux enhancement than the case of $\delta = 0$ μm (gold electroplated surface). This could be attributed to the departure

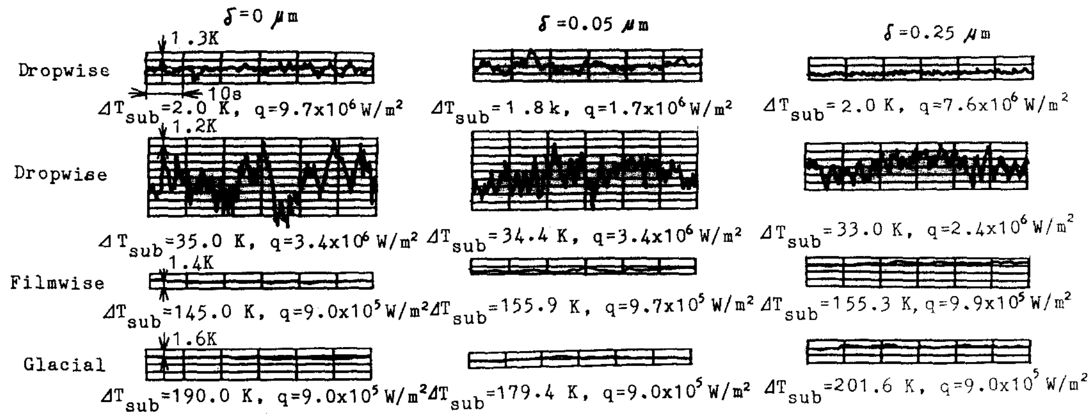

FIG. 9. Temperature fluctuation change with subcooling and coating film thickness.

diameter on the surface of $\delta = 0.05$ μm being smaller than that on the gold electroplated surface at the same subcooling temperature.

Figure 11 shows that as the departure diameter decreased, heat transfer was enhanced. Additionally, the experimental data fell on a straight line. In examining dropwise condensation of propylene glycol vapor on the PTFE surface Utaka *et al.* [23] found the same tendency. Departure droplet size of dropwise condensation on the gold electroplated surface was about two times larger than that on the surface with a film thickness of $\delta = 0.05$ μm. This would explain the lower heat flux of the gold electroplated surface.

3.3. *Endurance tests of polyvinylidene chloride*

There have been many investigations on the dropwise condensation surface regarding its ability to promote dropwise condensation for a long period of time. For example Holden *et al.* [18] reported on endurance tests of a polymer coating surface under dropwise condensation. We observed how a 10 μm thick film was able to promote and sustain dropwise condensation of steam for a long period of time while being exposed to steam at atmospheric pressure. Figure 12 shows the condensation after a period of 8076 h (about 11 months).

Figure 13 shows the appearance after 21 568 h (about 2 years and 5 months).

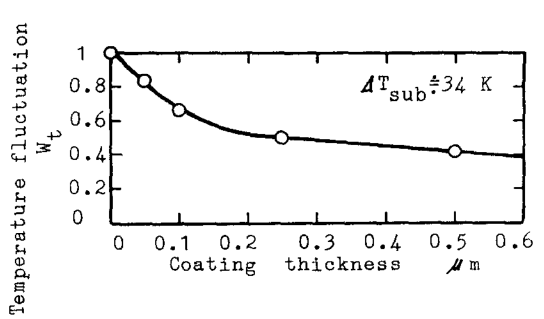

FIG. 10. Temperature fluctuation change with coating film thickness.

Polyvinylidene chloride is a stable polymer material and its monolayer thickness is about 1 Å. If PTFE is used, the coating thickness by sputtering or deposition is generally thicker than 1.5 μm. Furthermore, it does not promote or sustain dropwise condensation of steam for a very long time [18]. There are a number of advantages to the polyvinylidene chloride coating. Its thickness can be controlled easily by changing its concentration in the coating solution. Adhesion of the material on the substrate is achieved simply. Its material cost is also less than the PTFE coating surface. Only a bath of sufficient size for the heat transfer surface and a heating device for the heat setting are needed.

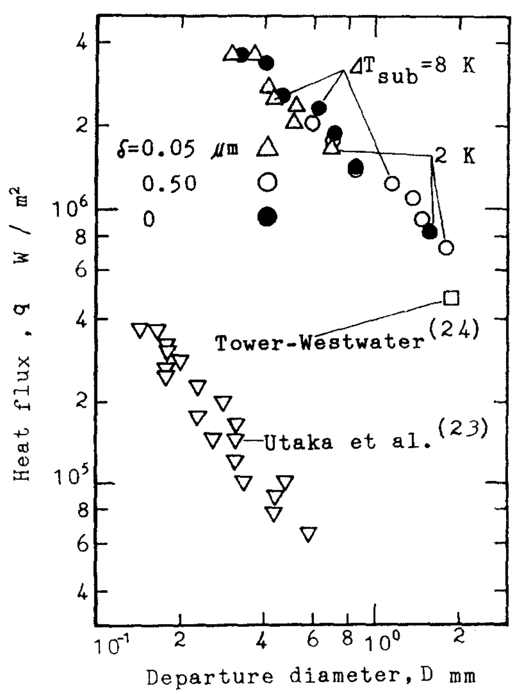

FIG. 11. Heat flux dependence on departure diameter.

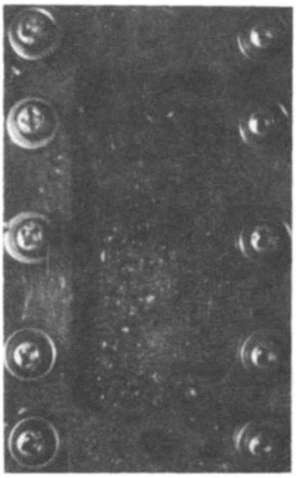

FIG. 12. Endurance test photographs of polyvinylidene chloride.

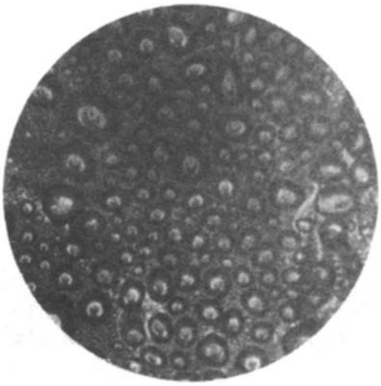

FIG. 13. Endurance test photographs of polyvinylidene chloride.

4. CONCLUSION

Noble metals of gold or silver, etc., as electroplated or deposited surfaces, are very expensive to use for producing dropwise condensation, especially in the case of sputtering or deposition on large heat transfer surfaces or large inner surfaces of pipes.

We found a thin coating layer of polyvinylidene chloride provided excellent dropwise condensation and its cost was much cheaper even when coating a large dropwise condensation surface. The heat transfer coefficient was more than 20 times that obtained for filmwise condensation. In addition, it was found that use of polyvinylidene chloride films in industrial condensers was possible, based on endurance tests.

REFERENCES

1. T. Takeyama and S. Shimizu, On the transition of dropwise-film condensation, *Proc. 5th Int. Heat Transfer Conf.*, Vol. 3, pp. 274–278 (1974).
2. Y. Utaka and I. Tanasawa, Measurement of dropwise condensation curve of steam, *Trans. Jap. Soc. Mech. Engng* **46B**(409), 131–140 (1980).
3. D. W. Tanner, C. J. Potter, D. Pope and D. West, Heat transfer in dropwise condensation—II. Surface chemistry, *Int. J. Heat Mass Transfer* **8**, 427–436 (1965).
4. E. Citakoglu and J. W. Rose, Dropwise condensation—some factors influencing the validity of heat-transfer measurements, *Int. J. Heat Mass Transfer* **11**, 523–537 (1968).
5. M. Izumi, S. Susuki and T. Takeyama, The effect of two hysteresis phenomena and non-condensable gas for condensing curve, *Trans. Jap. Soc. Mech. Engng* **50B**(454), 1600–1607 (1984).
6. K. Kaino, M. Izumi, S. Shimizu and T. Takeyama, Heat transfer coefficient of initial dropwise condensation, *Trans. Jap. Soc. Mech. Engng* **48B**(431), 1339–1347 (1982).
7. M. Izumi, T. Shinmura, N. Yamakawa, S. Ohtani and J. W. Westwater, Drop and filmwise condensation on a horizontally scratched rough surface, *Trans. Jap. Soc. Chem. Engng* **6**(12), 647–653 (1986).
8. D. W. Woodruff and J. W. Westwater, Steam condensation on various gold surfaces, *Trans. ASME J. Heat Transfer* **103**, 685–692 (1981).
9. R. A. Erb and E. Thelen, Promoting permanent dropwise condensation, *Ind. Engng Chem.* **57**(10), 49–52 (1965).
10. R. A. Erb, Wettability of metals under continuous condensing conditions, *J. Phys. Chem.* **69**, 1306–1309 (1965).

11. R. A. Erb, T. I. Haigh and T. M. Dowing, Permanent systems for dropwise condensation for distillation plants, *Symp. Enhanced Tubes for Desalination Plants*, Department of Interior, Washington, DC, pp. 177–201 (1970).
12. L. Topper and E. Bear, Dropwise condensation of vapors and heat-transfer rates, *J. Colloid Sci.* **10,** 225–227 (1955).
13. R. Wilmshurst and J. W. Rose, Dropwise and filmwise condensation of aniline, ethanediol and nitrobenzene, *Proc. Fifth Int. Heat Transfer Conf.*, Vol. 3, pp. 259–264 (1974).
14. A. C. Peterson and J. W. Westwater, Dropwise condensation of ethylene glycol, *Chem. Engng Prog. Symp. Ser.* **62**(64), 135–142 (1966).
15. T. Mizushina, H. Kamimura and Y. Kuriwaki, Tetrafluoroethylene coatings on condenser tubes, *Int. J. Heat Mass Transfer* **10,** 1015–1016 (1967).
16. P. G. Kosky, Tetrafluoroethylene coating on condenser tubes, *Int. J. Heat Mass Transfer* **11,** 374–375 (1968).
17. Y. Utaka, A. Saito, H. Ishikawa and H. Yanagida, Study on dropwise condensation curves (dropwise to filmwise transition of propylene glycol, ethylene glycol and glycerol vapors on a copper surface using a monolayer type promoter—Part II), *Trans. Jap. Soc. Mech. Engng* **53B,** 3100–3106 (1987).
18. K. M. Holden, A. S. Wanniarachchi, P. J. Marto, D. H. Boone and J. W. Rose, The use of organic coatings to promote dropwise condensation of steam, *Trans. ASME J. Heat Transfer* **109,** 768–774 (1987).
19. A. Yamauchi, S. Kumagai and T. Takeyama, Condensation heat transfer on various dropwise–filmwise coexistent surface, *Trans. Jap. Soc. Mech. Engng* **51B,** 2606–2613 (1985).
20. The Society of Polymer Science (Jap. Edn), *Data Handbook of Polymers*, p. 69. Baifuukan, Tokyo, Japan (1986).
21. Kinki Chemical Society (Jap. Edn), *Maku* (*Membrane*). Kagaku-Doujin, Kyoto, Japan (1980).
22. I. Tanasawa, J. Ochiai, Y. Utaka and S. Shioji, Experimental study on dropwise condensation (effect of maximum drop size), *Trans. Jap. Soc. Mech. Engng* **42B,** 2846–2853 (1976).
23. Y. Utaka, A. Saito, T. Tani, H. Shibuya and K. Katayama, Condensation curves in dropwise condensation of propylene glycol on PTFE coated surface, *Trans. Jap. Soc. Mech. Engng* **50B,** 2418–2426 (1984).
24. R. E. Tower and J. W. Westwater, Effect of plate inclination on heat transfer during dropwise condensation of steam, *Chem. Engng Prog. Symp. Ser.* **66,** 21–25 (1970).

EFFET DE L'EPAISSEUR DU REVETEMENT DE CHLORURE DE POLYVINYLIDENE SUR LA PROMOTION DE LA CONDENSATION DE VAPEUR D'EAU EN GOUTTES

Résumé—Le revêtement de polyvinylidene est proposé comme promoteur de la condensation de la vapeur d'eau en gouttes. On étudie l'effet de l'épaisseur de la couche sur la condensation. Quatre épaisseurs 0,05, 0,10, 0,25 et 0,50 μm sont déposées sur un bloc de cuivre. Chaque recouvrement est chauffé pendant 83 heures, après quoi elle est évaluée. La couche de 0,05 μm donne des performances thermiques comparables à celles des recouvrements d'or ou d'acide oléique. La couche de 0,10 μm réalise une bonne condensation en gouttes pendant une période de 21 568 heures.

DER EINFLUSS EINER PVC-BESCHICHTUNG UND DEREN DICKE AUF DIE TROPFENKONDENSATION VON WASSERDAMPF

Zusammenfassung—Es wird eine PVC-Beschichtung als Promotor für die Tropfenkondensation von Wasserdampf vorgeschlagen. Der Einfluß der Schichtdicke wird im Hinblick auf das Verhalten der Kondensation untersucht. Hierbei wird ein Kupferblock verwendet, der mit vier unterschiedlichen Dicken beschichtet wurde: 0,05; 0,1; 0,25 und 0,5 μm. Jede beschichtete Oberfläche wurde 83 Stunden lang betrieben. Die Beschichtung mit einer Dicke von 0,05 μm zeigte ein Wärmeübergangsverhalten ähnlich dem, das man von Oberflächenbeschichtungen mit Gold oder Ölsäure kennt. Auf der 10 μm Beschichtung blieb die Tropfenkondensation über einen Zeitraum von 21 568 Stunden erhalten.

ВЛИЯНИЕ ТОЛЩИНЫ ПОКРЫТИЯ ИЗ ПОЛИВИНИЛИДЕНХЛОРИДА НА АКТИВИЗАЦИЮ КАПЕЛЬНОЙ КОНДЕНСАЦИИ ВОДЯНОГО ПАРА

Аннотация—В качестве активатора капельной конденсации водяного пара предложено покрытие из поливинилиденхлорида. Исследовалось влияние толщины покрытия на активизацию процесса. На медный теплообменный блок наносились покрытия четырех процесса. На медный теплообменный блок наносились покрытия четырех толщин, равных 0,05; 0,10; 0,25 и 0,50 мкм. На каждой поверхности процесс протекал в течение 83 часов, после чего проводились соответствующие оценки, которые показали, что при толщине покытия, составляющей 0,05 мкм, характеристики переноса сопоставимы с полученными для покрытий из золота или олеиновой кислоты. При толщине покрытия, равной 10 мкм, капельная конденсация происходила достаточно интенсивно в течение 21 568 часов.