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Heat Transfer Characteristics of Dropwise Condensation of Steam on Vertical Polymer Coated Plates*

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Abstract The plasma polymerization method and dynamic ion-beam mixed implantation method were employed to coat ultra-thin polymer films on copper plates. Experiments indicated that steady dropwise condensation of steam at atmospheric pressure occurred. The condensation heat transfer coefficients increased by approximately 3 and 5—7 times for the polytrimethylvinylsilane film and polytetrafluoroethylene film respectively, compared with the value for film condensation under the same experimental conditions. The temperatures on the condensing surface and inside the test block were found to be rapidly and randomly fluctuated. The properties of the coated films and advantages of the methods used in this investigation were discussed briefly.

Keywords dropwise condensation heat transfer, polymer film, temperature fluctuation

1 INTRODUCTION

Dropwise condensation has a significantly higher heat transfer coefficient than film condensation, but this perspective condensation mode has not been widely used in commercial equipment because of its special requirements for condensation surfaces[1,2]. Dropwise condensation can be promoted by (1) applying a suitable organic promoter to the condensing surface or the bulk vapor, (2) using a thin layer of special metal (such as gold, chromium, *etc.*) or metal compounds, and (3) coating the condensing surface with a polymer film. In the past several decades, some organic promoters were used in laboratory to investigate the mechanism of dropwise condensation heat transfer. However, metal compound films are currently of considerable interest due to its successful application in a small-scale industrial condenser[3], although, hitherto, there is no firm theoretical basis to explain why this surface can promote dropwise condensation.

As an alternative to the special metal and organic compounds, polymer film with lower surface free energy than metal can achieve dropwise condensation mode for many vapors. However, two problems must be solved before this film might be used in industrial condensers. The first one is that the adhesion between metal substrate and its coating must be strong enough to assure the dropwise condensation sustaining for a sufficiently long period of time. Secondly, the film thickness must be thin enough (for example, less than $1\,\mu$m). Otherwise, the benefits of dropwise condensation are retarded by the increase of thermal resistance of the coating itself because of its low thermal conductivity. From the practical viewpoint, using polymer coating to maintain long-term dropwise condensation seems to be very promising. Particularly, this might be the only approach to achieve dropwise condensation of organic vapors that are very commonly used in petrochemical processes. Holden *et al.*[4] and Marto *et al.*[5] examined several organic coatings for promoting dropwise condensation. Their results indicated that the heat transfer coefficients of steam dropwise condensation for surfaces coating with organic films are as large as 3—8 times that of film condensation for smooth surface. The organic coatings were successful in promoting good quality of dropwise condensation for about 22000 hours (with film thickness of $60\,\mu$m). Haraguchi *et al.*[6] found that a thin film of polyvinylidene chloride provided excellent dropwise condensation of steam and its processing cost was much cheaper than other methods used previously even for a large area coating surface. The condensation heat transfer coefficient was more than 20 times that for film condensation. Endurance test showed that a film with $10\,\mu$m thick retained dropwise condensation over 21586 hours.

In the present study, the plasma polymerization (PP) method and the dynamic ion-beam mixed implantation (DIMI) method are employed to coat ultra-thin polymer films on copper plates. The condensation heat transfer characteristics of steam are tested under atmospheric pressure. The fluctuation of the temperatures at points below and on the condensa-

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tion surface is investigated as well.

2 PREPARATION OF DROPWISE CONDENSATION SURFACES

Polytrimethylvinylsilane (PTMVS) and polytetrafluoroethylene (PTFE) were coated on copper plates by PP method and DIMI method respectively. Preliminary surface treatment was as follows: First, removing the fouling and oxide film on the copper plates with carbide-paper No. 1000 and rinsing them with acetone and distilled water; Secondly, using 0.05 μm alumina to polish the surface to a mirror finish and then, activating and cleaning the surface with argon ion beam sputtering in vacuum; Finally, PTMVS and PTFE films were prepared in the separate apparatus under the selected processing conditions.

3 EXPERIMENTAL EQUIPMENT AND HEAT TRANSFER CALCULATION

Fig. 1 shows the schematic drawing of the experimental apparatus. An observation window was mounted at the condensing cell so that the visual observation and photographic recordings of the condensation mode could be conducted. Steam at a little above atmospheric pressure was generated by two electrically heating boilers (with the power of 15 kW and 3 kW respectively).

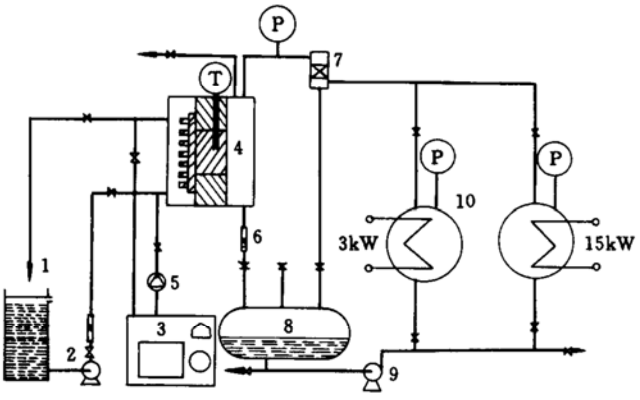

Figure 1 Experimental loop
1—water thank; 2,5,9—pump; 3—bath tub;
4—condensing chamber; 6—measuring pipe;
7—separator; 8—condensate tank; 10—boiler

A copper-constantan thermocouple was used to monitor the steam temperature. The steam flowed through a stainless steel tube, entered the condensing chamber and condensed on coated plates. In order to prevent accumulation of non-condensable gases in the condensing chamber, steam with higher flow rate flowed rapidly through the condensing chamber for 10 min, and then the experiment under normal operation conditions was kept running for at least 30 min before the data were collected. The cooling water was supplied to the rear side of the condensation plate by a centrifugal pump. The heat transfer surface on the cooling side was extended by 15 rectangular fins, as shown in Fig. 2, to augment the heat transfer of cooling water.

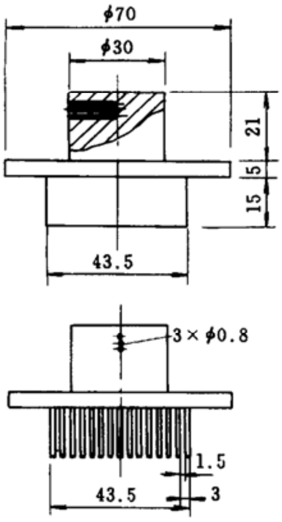

Figure 2 Condensing block

A cylindrical condensing surface, 30 mm in diameter and 410 mm long, was made from a high purity copper block to allow precise measurement of the surface temperature and heat flux. The condensation surface was oriented vertically. Three 0.8 mm diameter holes were drilled into the block on the same vertical plane, perpendicular to the axis, with copper-constantan thermocouple inserted into the bottom of each hole. The thermocouple arrangement is shown in detail in Fig. 2. All thermocouples were calibrated in a bath at same constant temperature with an accuracy of 0.1℃. The temperature signals were collected by a HP3852A data acquisition/control unit and transmitted to a personal computer for data reduction.

During experiments, the temperature variations in the condensing block and condensing chamber were shown on the computer screen to check if the condensation condition was steady. The measurement time interval was 0.01 second.

The heat flux, q, was determined using the least square method from the readings of the three thermocouples in the condensing block. The surface temperature was then calculated by extrapolating the temperature gradient within the condensing block to the surface. Accordingly, the surface subcooling degree, ΔT, and the condensation heat transfer coefficient, h, were obtained.

4 RESULTS AND DISCUSSION

4.1 Contact angle and surface free energy

A JY-82 type contact angle measurement apparatus (with an accuracy of ±5′) was used to measure the contact angles of liquids on coated surfaces at room temperature. The surface free energy was calculated by measured contact angles based on the formula for low-free-energy surfaces given by Owens and Wendt[7]

$$\gamma_{\mathrm{S}}^{\mathrm{p}}=\left(\frac{137.5+256.1\cos\theta_{\mathrm{H_2O}}-118.6\cos\theta_{\mathrm{CH_2I_2}}}{44.92}\right)^2 \tag{1}$$

$$\gamma_{\mathrm{S}}^{\mathrm{d}}=\left(\frac{139.9+181.4\cos\theta_{\mathrm{CH_2I_2}}-41.5\cos\theta_{\mathrm{H_2O}}}{44.92}\right)^2 \tag{2}$$

$$\gamma_{\mathrm{S}}=\gamma_{\mathrm{S}}^{\mathrm{d}}+\gamma_{\mathrm{S}}^{\mathrm{p}} \tag{3}$$

As shown in Table 1, the contact angles of water on coated surfaces are greater than 90°, therefore we can preliminarily conclude that dropwise condensation of steam may occur on these films. However, the contact angle measured at room temperature and in equilibrium with an air atmosphere has been proven to be useless for determining the wettability of systems in which mass transfer takes place[8]. Ma[9] proposed a criterion to predict whether film or dropwise condensation of a vapor will occur on a solid surface by the surface free energy difference between condensate liquid at the condensation temperature and solid surface on which condensation takes place, defined as $\Delta\gamma=\gamma_{\mathrm{l}}-\gamma_{\mathrm{s}}$. Generally speaking, if the solid surface free energy is less than the liquid subdue free energy (or surface tension) at a certain temperature, the solid can not be wetted by the liquid so that dropwise condensation mode could be anticipated. Otherwise, filmwise condensation will occur on the solid surface. Since the surface free energy of present coated surfaces is much less than that of the condensate, $5.858\times10^{-2}\,\mathrm{J\cdot m^{-2}}$, good dropwise steam condensation is expected to occur.

4.2 Measurement accuracy

The accuracy of the heat transfer coefficients measured in the dropwise condensation apparatus was determined by comparing the heat transfer results for filmwise condensation on the mirror-finish uncoated copper plate measured in this apparatus with that of modified Nusselt's correlation for filmwise condensation on a vertical disc[10]

$$q=0.83404\left[\frac{\lambda_{\mathrm{L}}^3\rho^2 g h_{\mathrm{fg}}}{\mu R}\right]^{1/4}\Delta T^{3/4} \tag{4}$$

As shown in Fig. 3, the experimental results agree well with those predicted using modified Nusselt's correlation, Eq. (4). The relative deviation between the two series of data was less than 5%.

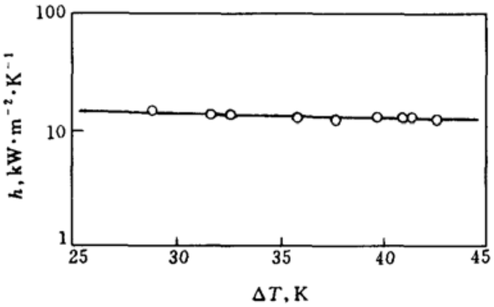

Figure 3 Comparison of experimental data of film condensation with calculated results
○ experimental data; —— Eq. (4)

4.3 Observation and heat transfer results

For PTMVS film, steady dropwise condensation was observed at the startup of running. The surface became noticeably dark in color after 2 days operating, and then film condensation occurred. It might be the oxidation of the substrate that led the polymer film to peel off. Although the plasma polymerization has been recognized as a unique method to prepare uniform, pinhole-free and ultra-thin polymer films on various substrates, few reports on directly polymerizing organic films on metal substrates have been found up to now. As a result, inappropriate processing conditions used in the present investigation gave rise to the poor adhesion between metal substrate and polymer film, and hence to a very short period of dropwise condensation. Therefore, it is more crucial to improve the adhesion between polymer film and metal substrate. This adhesive intensity is influenced by some factors: the film aging in the steam-water moist environment, the corrosion and oxidation of the substrate, *et al.*[11]. We conduct research work to explore an effective approach to form a passivated organic sublayer on the metal surface before the plasma-polymerized film is coated. Fig. 4 illustrates the experimental results of heat transfer coefficient of dropwise condensation on PTMVS film. The heat transfer coefficient of film

Table 1 Contact angles and free surface energy

Film	Contact angle, (°)		Free surface energy, $\mathrm{J\cdot m^{-2}}$		
	H_2O	CH_2I_2	$\gamma_s^d\times10^3$	$\gamma_s^p\times10^3$	$\gamma_s\times10^3$
PTFE	92	53	31.1	1.6	32.7
PTMVS	100	57	30	0.4	30.4

condensation for the bare plate calculated by Eq. (4) is also included in the figure for comparison. It is found that the condensation heat transfer coefficients of steam on the present PTMVS film were approximately 4 times that of film condensation.

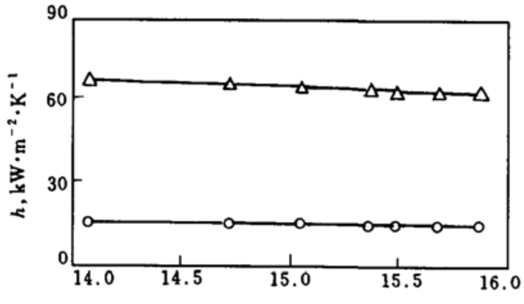

Figure 4 **Condensation heat transfer coefficient *vs.* surface subcooling for PTMVS film**
△ PTMVS film; ○ Eq. (4)

The PTFE film did not promote steam dropwise mode in the early operating period. The condensation mode gradually changed from mixing condensation mode to dropwise condensation within the next 25 hours. And then excellent dropwise condensation was sustained for 3 weeks. For the DIMI method, the component distribution analysis revealed that good adhesion of the coating with metal substrate resulted from the interfacial transition sublayer formed by ion-beam mixing during the preparation of the film. However, the processing conditions had a great impact on the adhesion and the chemical components of the film[12], consequently on the heat transfer performance. Fig. 5 illustrated the experimental results of heat transfer coefficient of dropwise condensation on PTFE film. The condensation heat transfer coefficients increased by a factor of 5—7 compared to film condensation value.

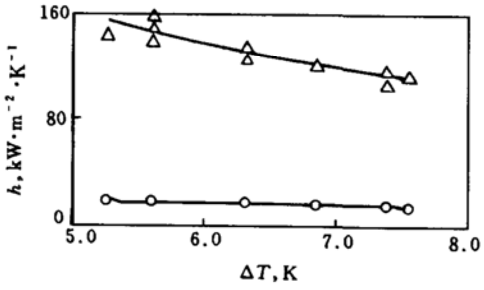

Figure 5 **Condensation heat transfer coefficient *vs.* surface subcooling for PFTE film**
△ PTFE film; ○ Eq. (4)

Fig. 6 shows a comparison of heat fluxes of present films with those of the organic promoter[11], coated Teflon films on horizontal aluminum tube[13] and copper tube[14], electroplated silver[10], electroplated gold[15] and ion plated chromium[16]. It can be found that the present PTFE film and PTMVS film demonstrates higher heat transfer coefficients than coated Teflon films reported in literature. This may be contributed to the effect of the film thickness.

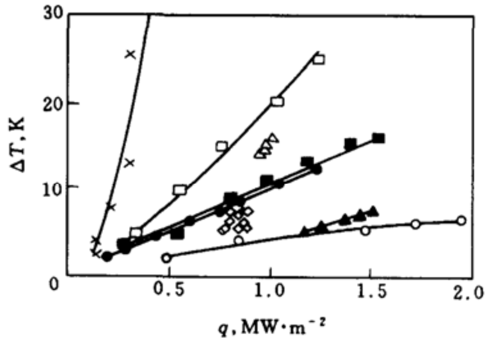

Figure 6 **Comparison of the present films with other surfaces for heat transfer performance**
○ promoter; × Al-Teflon; □ Cu-Teflon; ● plated silver; ■ plated gold; ▲ ion-plated chromium; △ Present PTMVS film; ◇ present PTFE film

4.4 Temperature fluctuation

Fig. 7 shows a transient history of temperatures at three points 3.5 mm (P_1), 5.5 mm (P_2), and 7.5 mm (P_3) below the condensation surface of PTFE film. A good linear relationship is shown between the three temperatures, but with somewhat fluctuation for everyone. The condensation condition is shown in the figure. Fig. 8 shows the fluctuation of surface temperature on PTFE film with time. The rapid surface temperature fluctuations occurred randomly unlike the results obtained by Truruta *et al.*[17] on surfaces with very low thermal conductivity. This might result from the different thermal conductivities of the substrates. Similar results have been obtained for PTMVS film. Fig. 9 shows the variation of temperatures inside the condensation block for PTMVS film.

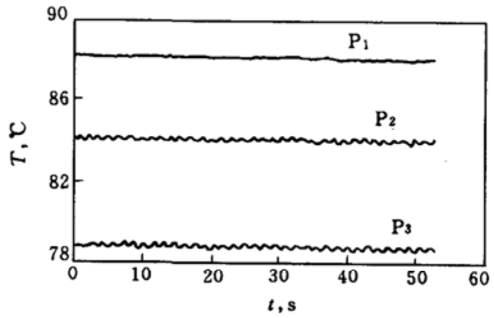

Figure 7 **Variation of temperatures inside the condensing block for PTFE film**
($q = 0.836$ MW·m^{-2})

5 CONCLUSIONS

Dropwise condensation of steam at atmospheric pressure was attained on plates coated with thin

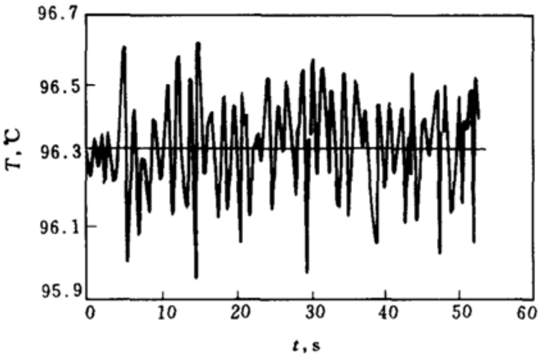

Figure 8 Surface temperature fluctuation for PTFE film ($q = 0.836\,\mathrm{MW{\cdot}m^{-2}}$)

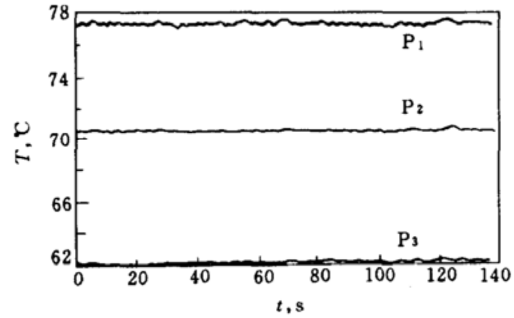

Figure 9 Variation of temperatures inside the condensing block for PTMVS film ($q = 0.94\,\mathrm{MW{\cdot}m^{-2}}$)

PTFE film and PTMVS film, respectively. The condensation heat transfer coefficients increased by approximately 3 and 5—7 times for PTMVS film and PTFE film respectively, compared with the film condensation value under the same experimental conditions. The high thermal conductivity of the copper substrate and the thin polymer film resulted in rapid, random fluctuation of the surface temperature.

NOMENCLATURE

g	gravitational acceleration, $\mathrm{m{\cdot}s^{-2}}$
h	condensation heat transfer coefficient, $\mathrm{W{\cdot}m^{-2}{\cdot}K^{-1}}$
h_{fg}	latent heat of condensation, $\mathrm{J{\cdot}kg^{-1}}$
q	heat flux, $\mathrm{W{\cdot}m^{-2}}$
R	radius of condensation surface, m
t	time, s
T	temperature, ℃
ΔT	surface subcooling degree, K
γ	surface free energy, $\mathrm{J{\cdot}m^{-2}}$
θ	contact angle, (°)
λ	thermal conductivity, $\mathrm{W{\cdot}m^{-1}{\cdot}K^{-1}}$
μ	viscosity, $\mathrm{N{\cdot}s{\cdot}m^{-2}}$
ρ	density, $\mathrm{kg{\cdot}m^{-3}}$

Superscripts

d	dispersion component
p	polarity component

Subscripts

L	liquid
s	solid

REFERENCES

1 Tanasawa, I., "Advances in condensation heat transfer", Advances in Heat Transfer, **21**, 55—139 (1991).
2 Rose, J. W., "Interphase matter transfer, the condensation coefficient and dropwise condensation", In: Proceedings of the 11th International Heat Transfer Conference, Lee, J. S. ed., Taylor & Francis Publishing Corp., New York, **1**, 89—104 (1998).
3 Zhao, Q., Zhang, D. C., Zhu, X. B., *et al.*, "Industrial application of dropwise condensation", In: Proceedings of the 9th International Heat Transfer Conference, Hetsroni, G., ed., Taylor & Francis Publishing Corp., New York, **4**, 391—394 (1990).
4 Holden, K. M., Wanniarchchi, A. S., Marto, P. J., *et al.*, "The use of organic coatings to promote dropwise condensation of steam", *Trans. ASME, J. Heat Transfer*, **109** (3), 768—774 (1987).
5 Marto, P. J., Looney, D. J., Rose, J. W., *et al.*, "Evaluation of organic coating for the promotion of dropwise condensation of steam", *Int. J. Heat Mass Transfer*, **29** (8), 1109—1117 (1986).
6 Haraguchi, H., Shimada, R., Kumagai, S., *et al.*, "The effect of polyvinylidene chloride coating thickness on promotion of dropwise steam condensation", *Int. J. Heat Mass Transfer*, **34** (12), 3047—3054 (1991).
7 Owens, D. K., Wendt, R. C., "Estimation of the surface free energy of polymers", *J. Applied polymer Sci.*, **13** (8), 1741—1747 (1967).
8 Ponter, A. B., "Contact angles on metal and polymer surfaces in mass transfer environments", *Adv. Colloid Interface Sci.*, **39** (6), 383—395 (1992).
9 Ma, X. H., "Dropwise condensation on PTFE coated surfaces and the catastrophe transition mechanism between dropwise and film condensation", Ph. D. Thesis, Dalian University of Technology, Dalian (1994). (in Chinese)
10 O'Neill, G. A., Westwater, J. W., "Dropwise condensation of steam on electroplated silver surfaces", *Int. J. Heat Mass Transfer*, **27** (9), 1539—1549 (1984).
11 Stylianou, S. A., Rose, J. W., "Dropwise condensation on surfaces having different thermal conductivities", *Trans. ASME, J. Heat Transfer*, **102** (3), 477—482 (1980).
12 Ma, X. H., Xu, D. Q., Lin, J. F., "A study of dropwise condensation on the ultrathin polymer surfaces", In: Proceedings of the 10th International Heat Transfer Conference, Hewitt, G. F., ed., Taylor & Francis Publishing Corp., New York, **3**, 359—364 (1994).
13 Depew, C. A., Reisbig, R. L., "Vapor condensation on a horizontal tube Teflon to promote dropwise condensation", *Ind. Eng. Chem. Process Des. Dev.*, **3** (4), 365—369 (1964).
14 Guo, X. F., Bai, L., Cai, Z. Y., *et al.*, "Dropwise condensation on a horizontal tube", *J. Engineering Thermophysics*, **11** (1), 72—75 (1991). (in Chinese)
15 Woodruff, D. W., Westwater, J. W., "Steam condensation on electroplated gold: effect of plating thickness", *Int. J. Heat Mass Transfer*, **22** (4), 629—632 (1979).
16 Song, Y. J., Ma, X. H., Lin, J. F., "Condensation of steam on chromium", In: Proceedings of China-Japan Chemical Engineering Conference, Tianjin University Press, Tianjin, 688—695 (1991).
17 Truruta, T., Tanaka, H., Togashi, S., "Experimental verification of constriction resistance theory in dropwise condensation", *Int. J. Heat Mass Transfer*, **34** (11), 2787—2796 (1991).