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Influence of processing conditions of polymer film on dropwise condensation heat transfer

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Abstract

The effect of processing conditions of polymer film on dropwise condensation heat transfer of steam under atmospheric pressure is investigated to find an effective technique to prepare a viable polymer film sustaining long-term dropwise condensation pattern state. The polytetrafluoroethylene (PTFE) films were coated on the external surfaces of brass tubes, copper tube, stainless steel tube and carbon steel tube by means of the dynamic ion-beam mixed implantation technique, with a variety of surface processing conditions. The experimental results indicated that heat flux is increased by 0.3–4.6 times and condensation heat transfer coefficient by 1.6–28.6 times of film condensation values for the brass tubes treated with various conditions. The surface processing condition is crucial to the adhesion between polymer film and metal substrate, different substrate material requires different optimal processing condition, and leads to different condensation heat transfer characteristic. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Dropwise condensation heat transfer; PTFE (polytetrafluoroethylene) film; Film processing conditions

1. Introduction

Dropwise condensation (DWC) has a significantly higher heat transfer coefficient than filmwise condensation. A substantial amount of material and space could be saved if the presupposition of filmwise condensation, which is normally the basis for condenser design calculations, could be changed to DWC. Up to now, there have still few literature reports on the industrial application of dropwise condensation [1,2]. The reason is that filmwise condensation is a very common situation, whereas DWC requires special long-life surfaces. DWC can be promoted by:

(1) applying a suitable organic promoter to the condensation surface;
(2) using a thin layer of special metal (such as gold, chromium, etc.) or metal compounds; or
(3) applying a coating of low-surface-energy polymeric films on the condensation surface.

The first method does not produce a permanent hydrophobic coating. The second method has been the subject of considerable interests of many investigators.

The use of polymer coatings to maintain DWC seems to be a very promising method in industrial applications. In particular, a polymer coating may be the only approach to yield DWC of organic vapor. However, several difficulties have to be overcome before the polymer coating approach can be widely used. The first problem is to form a film that adheres well to the substrate with few voids and sufficiently high-mechanical strength. The second problem is to make the film thin enough to not excessively increase the conduction heat transfer resistance or the constrict resistance in the film. Holden et al. [3] and Marto et al. [4] evaluated several organic coatings for their ability to promote DWC of steam. Their results indicated that the heat transfer coefficients of

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Nomenclature

A_o	outside area of the test tube (m^2)
c_p	specific heat (J/kg K)
D	implanting dosage (ions/cm^2)
D_i	inside diameter of tube (m)
D_o	outside diameter of tube (m)
E_1	energy for the low-energy ion beam (keV)
E_2	energy for the high-energy ion beam (keV)
h	heat transfer coefficient (W/m^2 K)
h_{fg}	latent heat of evaporation (J/kg)
I	current intensity (A)
K	overall heat transfer coefficient (kW/m^2 K)
L	length of tube (m)
Nu	Nusselt number hL/λ
Pr	Prandtl number $c_p\mu/\lambda$
Q	heat transfer rate (W)
q	heat flux (W/m^2)
Re	Reynolds number uL/v
ΔT	surface subcooling degree (K)
u	coolant velocity (m/s)

Greek symbols

δ	wall thickness (m)
λ	thermal conductivity (W/m K)
μ	viscosity (N s/m^2)
v	kinematic viscosity (m^2/s)

Subscripts

c	cooling water side
i	inlet of cooling water
LMDT	log mean temperature difference
m	mean
o	exit of cooling water
w	cooling water side tube wall
s	saturation state

steam DWC 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 22 000 h (with film thickness of 60 μm). Haraguchi et al. [5] found that a thin film of polyvinylidene chloride provided excellent DWC 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 μm thick retained DWC over 21 586 h. Liu and Xu [6] prepared a metal–organic compound film on a copper tube maintaining dropwise condensation of steam for about 2000 h. They also found that this surface enhanced filmwise condensation heat transfer of ethanol and ethylene glycol vapors to a somewhat extent. Ma et al. [7,8] employed a plasma polymerization method to polymerize the polymer film with the thickness of less than 0.1 μm directly on the metal substrates from monomers promoting DWC of steam. However, DWC was maintained for only 700 h [9]. Afterwards, Ma et al. [10] used dynamic ion-beam mixing implantation technique to coat the polytetrafluoroethylene (PTFE) film on the metal substrates, and test the impact of ion implantation dosage on the dropwise condensation heat transfer property. Recently, Das et al. [11] attempted to use an organic self-assembled monolayer coating to promote dropwise condensation of steam on various tube substrates, indicating larger increase of condensation heat transfer coefficient compared with the film condensation case.

In present paper, the dynamic ion-beam mixed implantation (DIMI) technique was applied to prepare an ultra-thin PTFE film on various substrates under different processing conditions. The characteristics of steam condensation on these surfaces were tested experimentally at atmospheric pressure.

2. Condensation surface preparation

A PTFE film was deposited by using a low-energy argon ion beam to sputter the PTFE target and a high-energy nitrogen ion beam simultaneously to implant the sample. The component distribution analysis [12] revealed that a transition layer is formed at the interface between the coated film and the substrate, so that the adhesion of the film with the substrate is greatly enhanced.

The tube that was used as the heat transfer surface was 400 mm long, 14 mm inner diameter and 16 mm outer diameter. The active test section was 265 mm long. The surface was prepared as follows: first, remove the fouling and oxide film on the metallic surface with No. 600 and 800 carbide-paper, then rinse with acetone and distilled water. Next, clean the surface using argon ion beam sputtering in a vacuum. Finally, the PTFE films were applied using the different processing conditions for various substrates shown in Table 1.

3. Experimental apparatus and data reduction

The experimental setup is shown schematically in Fig. 1. The shell of the condensing chamber was made of Plexiglas tube with 83 mm I.D. and 265 mm long to

Table 1
Film processing conditions for various substrate materials

Surface no.	Low-energy ion beam (Ar^+)		High-energy ion beam (N^+)		Condensation mode
	E_1 (keV)	I (mA)	E_2 (keV)	D (ions/cm^2)	
B-1	2.7	25	50	4.6×10^{15}	45% DWC
B-2	2.7	17	50	1.7×10^{16}	100% FWC
B-3	2.7	10	70	3.8×10^{14}	100% FWC
B-4	16	33	16	4.7×10^{13}	50% DWC
B-5	11	9	11	9.9×10^{15}	100% FWC
B-6	10	7	10	5.3×10^{10}	90% DWC
B-7	1.3	80	–	–	100% FWC
B-8	1.3	26	32	1.4×10^{14}	100% DWC
B-9	1.2	30	60	1.3×10^{14}	60% DWC
B-10	1.2	31	60	4.7×10^{14}	50% DWC
SS-1	1.2	30	60	1.3×10^{15}	40% DWC
C-1	1.2	30	60	1.3×10^{15}	75% DWC
CS-1	1.2	30	60	1.3×10^{15}	100% FWC

B – brass, SS – stainless steel, CS – carbon steel, C – copper.

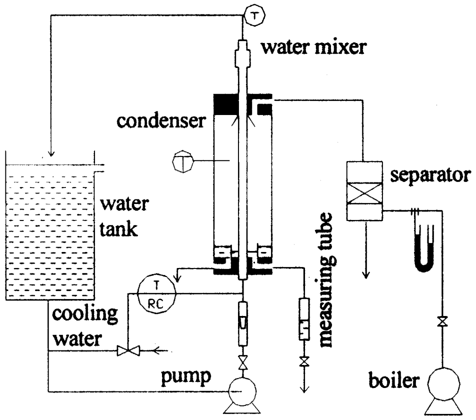

Fig. 1. Schematic diagram of experimental setup.

allow visual observation of the condensation modes. Steam was generated in a producer gas fired boiler and condensed on the outside of test tube at atmospheric pressure. Tap water flowing through the inside of test tube was used as the coolant. The temperatures were measured with calibrated copper–constantan thermocouple of 0.1 °C accuracy. The coolant inlet temperature was maintained at about 28 °C. The coolant velocity in the tube was varied from 0.50 to 6.0 m/s, corresponding to Reynolds numbers ranging from 14 000 to 174 000. Throughout the system, steam and condensate were exposed only to stainless-steel surfaces, Teflon seals and the condensation surface. The steam system was cleaned to remove organic and dirt contamination with detergent, hot alkaline solution, acetone and deionized water until steady film condensation was observed on the bare metal surface.

The heat transfer rate to the condensation tube was determined from (1) the mass flow rate and the temperature rise of the coolant in the tube as

$$Q_w = m_w c_p (T_o - T_i) \tag{1}$$

and (2) the condensation rate on the condensation surface as

$$Q_c = m_c h_{fg}. \tag{2}$$

The heat balances obtained from these two methods agreed to within 10%.

The average value of heat transfer rate Q_w and Q_c, Q, was used to calculate the overall heat transfer coefficient, K, with the log mean temperature difference:

$$K = Q/(A_o \Delta T_{LMTD}), \tag{3}$$

$$\Delta T_{LMTD} = \frac{T_o - T_i}{\ln\left(\frac{T_s - T_i}{T_s - T_o}\right)}. \tag{4}$$

The convective heat transfer coefficient for cooling water inside the tube was determined by the following experimental correlation, reported earlier for relatively short tubes [13]:

$$Nu = 0.062\, Re^{0.75}\, Pr^{0.353}. \tag{5}$$

The mean condensation heat transfer coefficient, h, on the outside of the tube was determined by subtracting the inside and wall thermal resistances from the overall thermal resistance, or

$$h = 1/(1/K - A_o/(A_i h_w) - A_o \delta/(A_m \lambda_s)). \tag{6}$$

It should be noted that the mean tube-side condensation heat transfer coefficient in the present situation includes the contribution of both the thermal resistance of liquid condensate and that of the coated PTFE film.

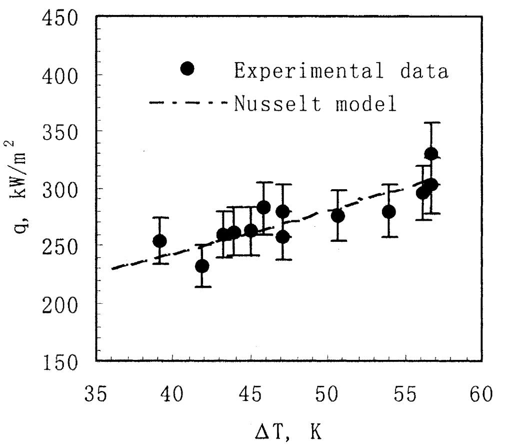

Fig. 2. Comparison of film condensation heat flux between experimental data and the results calculated by Nusselt's model.

The surface subcooling temperature, ΔT, was hence obtained from dividing of the mean heat transfer rate, q, by the average condensation heat transfer coefficient

$$q = Q/A_o, \qquad \Delta T = q/h. \tag{7}$$

As a check, experimentally determined heat flux and condensation heat transfer coefficients measured with this apparatus for pure filmwise condensation on a bare tube compared well with the well-known Nusselt's correlation [14], as shown in Fig. 2.

4. Experimental results

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 the PTFE coated plate at room temperature. The surface free energy of the polymer films is calculated in terms of the measured contact angles, as given by Owens and Wendt [15] for low-surface-free-energy film. The measured contact angles and the surface free energies are shown in Table 2. The contact angles of water on films prepared under various processing conditions are greater than 90°. Therefore, dropwise steam condensation would be expected on all these films. The result also implies that the physical–chemical property of the polymer film is considerably dependent on its processing conditions.

The steam condensation mode at atmospheric pressure on various surfaces is indicated by "DWC" area in Table 1.

4.2. Condensation heat transfer on coated brass tubes

Careful precaution was taken to get rid of the non-condensable gas from the condensing chamber. Every run of experiments was kept operating more than 30 min with a higher vapor velocity than usual, and consequently adjusted the experimental conditions as expected. All tests were repeated at least once on a different day. Excellent dropwise condensation was obtained on the B-8 surface during periodic operation for over 1000 h. The B-4 surface sustained DWC for only 1 h. The B-7 surface deteriorated rapidly because the film was deposited by argon ion beam sputtering only, so that no transition sublayer was formed at the interface between the coated film and the substrate, leading to poor adhesion. Other surfaces demonstrated the dropwise–filmwise coexisting condensation phenomena. The coexistence of the two modes may result from inappropriate processing methods.

Figs. 3–6 show the variation of condensation heat flux and heat transfer coefficient with the Reynolds number of the cooling water and the surface subcooling degree for coated brass tubes. Compared to the values for film condensation on bare brass tube, the condensation heat flux is increased by 0.3–4.6 times, while the heat transfer coefficient by a factor of 1.6–28.6. The experimental results also indicated that the increased condensation heat transfer coefficient is not proportional to the DWC area on the dropwise–filmwise co-

Table 2
Contact angles and surface free energy

Surface no.	Contact angle (deg)		Surface free energy (J/m^2)		
	H_2O	CH_2I_2	$\gamma_s^d \times 10^3$	$\gamma_s^p \times 10^3$	$\gamma_s \times 10^3$
B-1	100	45	37.6	0.1	37.7
B-4	109	50	36.1	0.2	36.3
B-6	110	60	29.7	0	29.7
B-8	114	63	28.3	0.2	28.5
B-9	104	62	27.4	0.2	27.6
B-10	99	50	34.3	0.2	34.5
SS-1	96	47	35.6	0.4	36.0
C-1	103	57	30.5	0.1	30.6

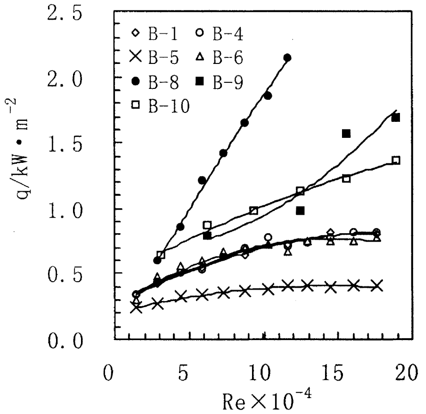

Fig. 3. Heat flux vs cooling water *Re*.

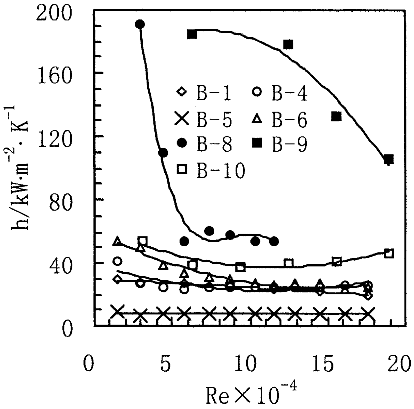

Fig. 4. Condensation heat transfer coefficient vs cooling water *Re*.

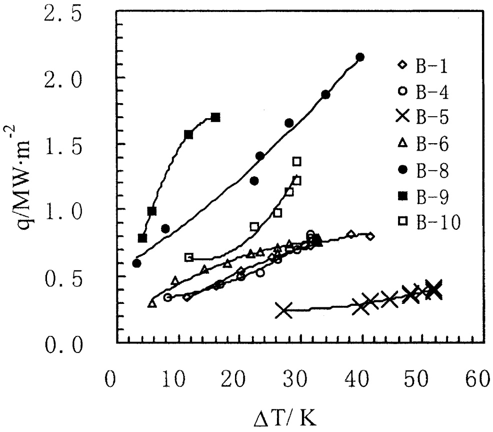

Fig. 5. Heat flux vs surface subcooling degree.

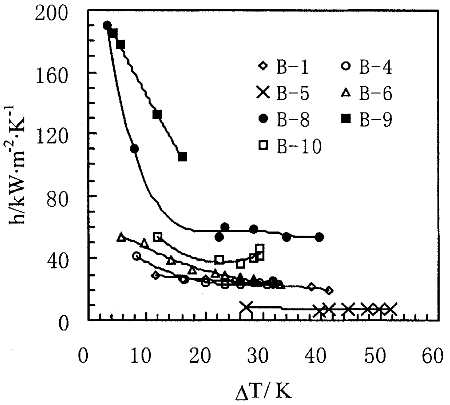

Fig. 6. Condensation heat transfer coefficient vs surface subcooling degree.

existing surface. Condensation heat transfer enhancement on a dropwise–filmwise coexisting surface depends on many factors such as surface division patterns, relative position between the dropwise part and the filmwise part, and so on [16,17].

4.3. Condensation heat transfer for different substrates

PTFE films were deposited on copper, brass, stainless steel, and carbon steel tubes using identical processing methods. The experimental observations indicated that the first three surfaces (C, B, SS) had dropwise–filmwise coexisting condensation patterns, while the CS-1 surface had filmwise condensation from the beginning of the condensation. Figs. 7 and 8 illustrate the condensation heat flux and heat transfer coefficient for various coated surfaces. It can be found that the substrate material greatly affects the condensation heat transfer characteristics. So, different optimum processing conditions should be chosen for different substrates.

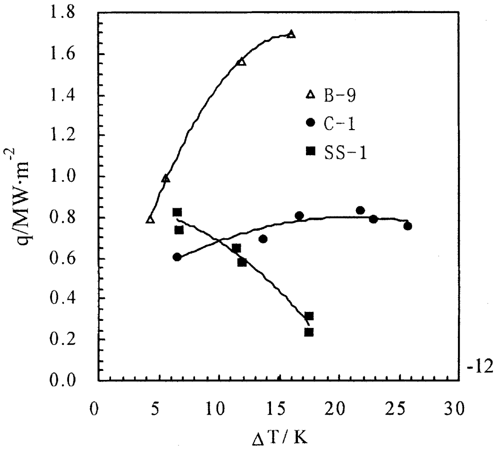

Fig. 7. Heat flux vs surface subcooling degree for various substrate materials.

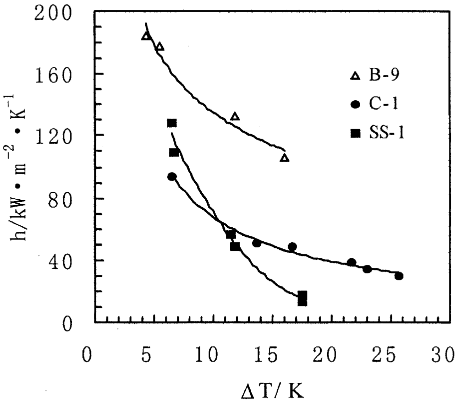

Fig. 8. Condensation heat transfer coefficient vs surface subcooling degree for various substrate.

5. Discussion

The experimental results reported in the present paper indicated that the surface processing conditions have significant effect on the DWC heat transfer characteristics and on the adhesion of the polymer film with the metal substrate. For the DIMI technique, the Ar^+ ion beam was employed to sputter a PTFE plate for the purposed film deposited on substrate, while the N^+ ion beam to implant or tail the coated film and substrate to improve the adhesion of film with the metallic surface. Therefore, the energy and implanting dosage of the ion beams directly influence the structure, components, and as a result, leading to different physico-chemical properties and purity of the polymer film for various conditions of surface processing. At the same time, interaction of groups of target material, N^+ and Ar^+ with the substrate plays a very important role in the adhesion between the deposited film and substrate. For instance, if the energy of Ar^+ is too high, the covalent bond of polymer will be broken down, resulting in the change of structure and component of the coated film. Similarly, the secondary sputtering for the deposited film would change not only the film's structure and component, but also the deterioration of the adhesion of the film and substrate. All those factors mentioned, of course, will affect the behavior of the droplets and DWC heat transfer, as well as the life-span for the film sustaining DWC mode.

In short, the optimum surface processing conditions for different systems of polymer film and metal substrate remains a key problem for the DWC on polymer film can be realized in practical applications. But, from the objective reality of the material science and the surface processing technology, it will need long time further to develop an effective surface processing technology including a special preliminary treatment for metal surface to enhance the adhesion of the polymer film with the metal substrate without significant increase of thermal resistance. Consequently, more interests should be focused on the adhesion between metal and polymer film in the future, other than heat transfer performance of DWC. It might be more feasible to enhance the adhesion of the coated polymer film with the metal substrate with a little loss of enhancing heat transfer performance. For example, the polymer film can be coated slightly thicker (a slight reduction of heat transfer performance) to ensure enough adhesion of the polymer film with the metal substrate as long as the total heat transfer coefficient being increased to certain extent. As an alternative, a metal organic or inorganic compound sublayer was preliminarily deposited to tailor the metal substrate and the polymer film, and then the expected polymer film was coated on finally.

6. Conclusions

The effects of surface processing conditions on the condensation heat transfer characteristics were investigated experimentally. Excellent dropwise condensation was obtained on one of the PTFE coated surfaces at atmospheric pressure. Dropwise–filmwise coexisting condensation occurred on other surfaces prepared using inappropriate processing conditions. Conclusions can be drawn as below:

(1) The surface processing conditions greatly affect the distribution of chemical components on the coated films, and hence resulting in the variation of the physiochemical characteristics of the subsequent films and the condensation heat transfer properties. Meanwhile, the surface processing condition plays a decisive role to the adhesion between film and substrate.
(2) Compared to the data of steam film condensation, the condensation heat fluxes were increased by a factor of 0.3–4.6, while the heat transfer coefficient only 1.6–28.6, for the coated PTFE films on brass tube processed with different processing conditions.
(3) The condensation heat flux and heat transfer coefficient differ from each other for the coated PTFE films on copper, brass, stainless steel, and carbon steel tubes using identical processing methods. So different optimum processing conditions should be chosen for different substrates.
(4) Although the dynamic ion-beam mixed implantation (DIMI) method is an effective technique for improving the adhesion of coated films with the substrate, further work should be conducted to assess the chemical purity and anti-corrosion properties of the coated film.

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