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Advances in dropwise condensation heat transfer: Chinese research

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Abstract

A brief state-of-the-art review is presented on research progress on dropwise condensation heat transfer in China. During the past 10 years, Chinese researchers have put forward some new proposals on the mechanism of dropwise condensation, and developed some new surface materials for promoting dropwise condensation. In particular, successful applications of dropwise condensation heat transfer surfaces in industrial condensers have provoked interest around the world and inspired the further investigation on the dropwise condensation. Since much of the work had been published in Chinese, it was considered appropriate to give a review in English. This review includes: (1) micro mechanisms and heat transfer characteristics for dropwise condensation; (2) methods for promoting dropwise condensation and (3) industrial applications of dropwise condensation.

Keywords: Dropwise condensation; Heat transfer; Chinese research

1. Introduction

The higher heat transfer performance due to dropwise condensation as compared with filmwise condensation has been of considerable interest to many researchers around the world since the first paper on dropwise condensation heat transfer was published by Schmidt et al. [1] in 1930. Much progress has subsequently been made in understanding the mechanisms for the dropwise condensation process. However, the dropwise condensation mode has not been widely applied to practical industrial condensers because of the problem of maintaining dropwise condensation for sufficiently long periods to meet the requirements of the industrial applications. Therefore, the most important aspect for dropwise condensation heat transfer research at the present time is to explore techniques for preparing effective surfaces or surface films, which prolong the dropwise condensation for lifetimes appropriate for industry.

During the past 10 years, researchers in China have studied various aspects of dropwise condensation heat transfer, have put forward new proposals on the mechanism, and have developed new surface materials for promoting dropwise condensation. The practical successful applications of dropwise condensation heat transfer surfaces in industrial condensers have provoked the interest of counterparts round the world and inspired the further investigation of dropwise condensation [2,3].

This paper briefly reviews the research activities in China on dropwise condensation heat transfer during the past 10 years. Most of the papers cited here were published by Chinese researchers. More general reviews on dropwise condensation heat transfer have been provided by Tanasawa [2] and Rose [3]. The present review will introduce the Chinese results on micro mechanisms of dropwise condensation, heat transfer characteristics for various condensation surfaces, methods for promoting dropwise condensation and industrial applications for dropwise condensation. Finally, comments on the future trends of dropwise condensation research are summarised.

2. Mechanism and heat transfer characteristics for the dropwise condensation process

2.1. Micro-mechanism for dropwise condensation process

Historically, there are two opposite hypotheses on the mechanism of the formation of the initial droplet: the film fracture hypothesis and the nucleation hypothesis. The latter one has been supported by most of people since microscopic

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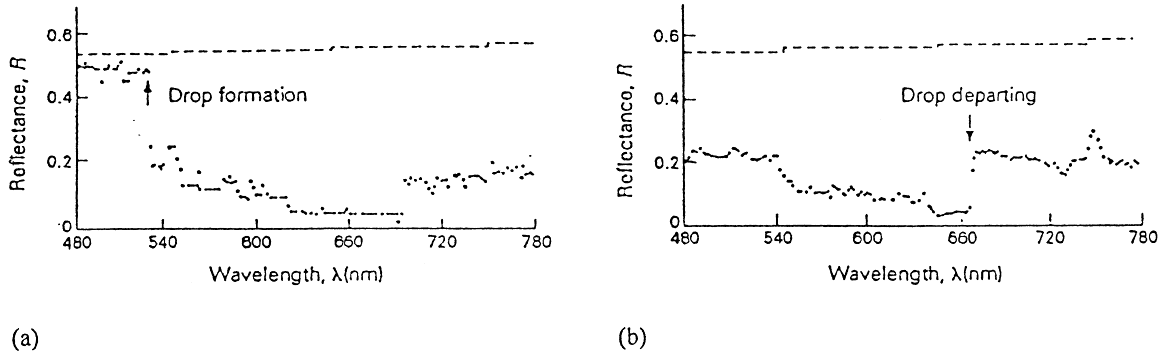

Fig. 1. Reflectance spectrum for very slow steam rate (after Song et al. [5]): (a) location between two drops and (b) spot of the departing drop.

observations provided by McCormic and Westwater [4] indicated that there was no visible condensate liquid film existing among droplets. However, Song et al. [5] have put forward a droplet and condensate film coexisting mechanism of the formation of droplets during dropwise condensation, from the viewpoint of adsorption theory. They proposed that a thin condensate film exists on the area among the droplets and also that a condensate film exists at the spots from which the droplets departed. The condensate on the liquid film moves towards drop sites due to surface tension. They also experimentally demonstrate the existence of condensate film by qualitatively comparing the measured reflectance spectra of certain locations on the condensation surface in the condensation environment with the standard reflectance spectrum, i.e. the reflectance spectrum on the plain surface without contacting with steam or condensate liquid (the dashed line at the top area in Figs. 1 and 2), as shown in Figs. 1 and 2. The reflectance can be expressed as a function of film thickness and the wavelength of the incident light λ. Consequently, using this technique, the film thickness can be measured during dropwise condensation. The experiments were conducted at the atmospheric pressure with surface subcooling temperature difference ranging from 1 to 5 K. In the case of low steam flow rate, it can be seen from Fig. 1 that the reflectance spectra at locations before the droplet was formed (on the left-hand side of the arrow in Fig. 1a) or after the droplet departed (the arrow position in Fig. 1b), were below the standard reflectance spectrum. This indicated that condensate film exists on the condensation surface all along. From Fig. 2, similar results were also found for the case of normal steam flow rate except that the frequency of droplet formation was much faster than that of the situation in Fig. 1.

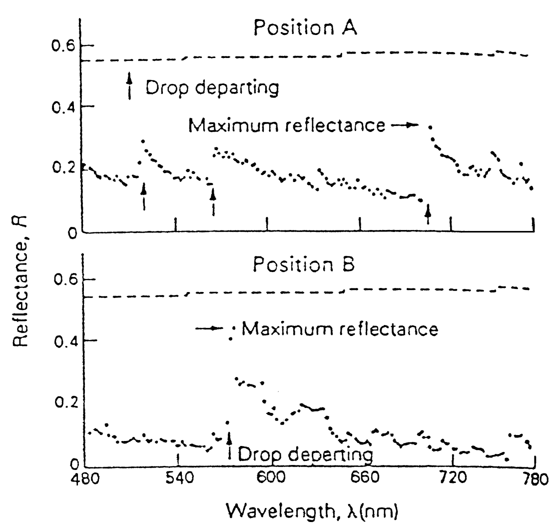

Fig. 2. Reflectance spectrum of the position between two drops for very slow steam rate (after Song et al. [5]).

The drop departure diameter, the drop growth rate and the drop size distribution are of significance for the dropwise condensation heat transfer characteristics. Guo et al. [6] derived the drop departure diameter and its dependence on the inclination angle of the condensation surface based on the balance of the forces acting on the droplet. Good agreements had been obtained between the theoretical prediction and the experimental results. Song et al. [7–9] experimentally investigated the drop-size distributions, drop growth rates and drop departure diameters for various ion-implanted surfaces under different operating conditions by means of high-speed photographs. The drop diameter ranged from 0.1 to 3 mm. They found that the drop-size distribution was dependent on the surface properties and little on steam pressure and surface subcooling temperature difference.

Contact angle has sometimes been used to predetermine the condensation mode on a specific solid surface. However, the contact angle measured at room temperature and in equilibrium with an air environment has been proven not to be useful for determining the wettability of systems where mass transfer takes place. For example, the contact angle of water on a polytetrafluoroethylene (PTFE) surface is 88° under the condensation condition at atmospheric pressure but 108° at room temperature with an air environment [10]. The difference was caused mainly by the difference of the condensate surface free energies at different measurement temperatures. Ma [11] put forward a surface free energy criterion, i.e. the surface free energy difference between the condensate liquid at the condensation temperature and the solid surface, defined as $\Delta\gamma=\gamma_l-\gamma_s$ (γ_l and γ_s denote the

Table 1
Condensation mode criteria (after Ma [11])

Surface free energy difference criterion	Contact angle method	Condensation mode
$\Delta\gamma \leq 0$	–	Filmwise
$0 \leq \Delta\gamma < 0.0333$	$0° \leq \theta < 90°$	Mixed condensation
$\Delta\gamma \geq 0.0333$	$\theta \geq 90°$	Dropwise

surface free energies of liquid and solid, respectively) to predict whether filmwise or dropwise condensation of a vapour will occur on a solid surface. In a conservative manner, the critical surface free energy difference was considered to be $0.0333\,J/m^2$ according to an empirical correlation between contact angle and above surface free energy difference [12]. The surface free energy of a solid depends only on its composition and chemical structure and can be calculated from the measured contact angles at room temperature [13] for low surface-free-energy solid surfaces like polymer films. Consequently, it is more convenient and accurate to use the surface free energy rather than the contact angle to predict condensation mode because the surface free energy criterion is not affected by the measuring temperature of the contact angles. The new surface free energy difference criteria and comparison with contact angle method are shown in Table 1.

Zhao and Lin [14] computed the liquid cohesive energy due to the intermolecular attraction and the adhesive energy between solid and liquid by using the quantum chemistry method. Accordingly, the condensation mode of the vapour on the solid would be determined by comparing the above two energies. Dropwise condensation will occur when the adhesive energy is less than the cohesive energy. Otherwise, filmwise condensation will take place. As an example, they tested four systems with two solid surfaces (a nitrogen-ion implanted copper plate and a barium stearate monolayer on copper plate) and two liquids (water and ethanol).

Dropwise condensation can only be maintained for surface subcooling up to a certain amount. At large surface subcoolings, so many active nuclei are present that a relatively thin continuous liquid film tries to form, thus, a maximum heat flux occurs, and then the heat flux decreases and approaches the filmwise condensation curve with a continued increase in surface subcooling. Further increase in surface subcooling may result in a portion of the condensate actually freezing on the cold surface, and a pseudo-film condensation condition will exist. Ma et al. [15] have attempted to elucidate this complex phenomena of the transitions of condensation pattern states by means of catastrophe theory. They considered the transitions among the condensation pattern states as a discontinuous process and supposed as a cusp-type catastrophe, as shown in Fig. 3, where Parts A, B and C represent the dropwise condensation region, the pseudo-film condensation region and the filmwise condensation region, respectively. The folding denotes the transition between the dropwise and pseudo-film condensation. They supposed the dropwise condensation

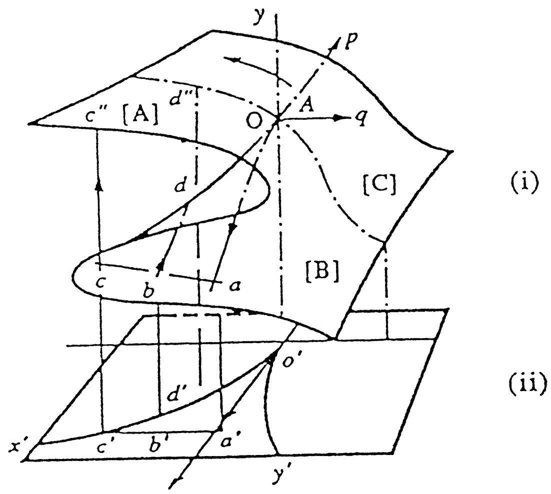

Fig. 3. The equilibrium curved surface (i) and the bifurcation set (ii) of cusp-type catastrophe (after Ma et al. [15]).

heat flux as a state variable (axis y in Fig. 3) and surface subcooling and the surface free energy difference between condensate and solid wall as the two control variables (axes p and q in Fig. 3). The surface free energy difference changing along the axis p leads to the transition between filmwise (Part C) and dropwise condensation mode (Parts A and B). This is consistent with the surface free energy difference criterion for prediction of condensation modes as mentioned before. Within the filmwise condensation area, Part A, the heat flux is continuously changed with the variation of surface subcoolings. However, within the dropwise condensation area, Parts B and C, the heat flux is discontinuously changed with the variation of surface subcooling. On the other hand, the heat flux is also dependent on the magnitude of the surface free energy difference. It is noticed that the condensation curve is very similar to the projecting curves in y–q plane of the equilibrium-curved surface. Further experiments and theoretical analysis should be carried out to get the relationship among the supposed variables.

2.2. Heat transfer characteristics

Song et al. [9] put forward a mathematical model for the dropwise condensation heat transfer, in accordance with the proposed mechanism of droplets and film coexisting during dropwise condensation. The total heat flux was composed of two parts, one through droplets and another through film among droplets. The results indicated that 90% of the total heat flux was transferred through the liquid film around the droplets and 10% through the droplets, to the coolant side. The effects of the vapour temperature and the surface thermal conductivity on the dropwise condensation heat transfer were investigated experimentally [16–18].

Ma et al. [19] prepared surfaces on which dropwise and filmwise simultaneously exist. The surfaces were vertically divided into many parts according to the designed dropwise and filmwise condensation area ratio. Dropwise condensation was promoted with a PTFE film. The experimental results showed that the appearance of condensation near the boundary region between the dropwise and filmwise regions was dependent on the relative positions of the two condensation regions, which was above and which was below. The condensate flowed smoothly across the boundary for dropwise condensation in the upper region. With filmwise condensation in the upper region, a condensate ring was formed at the interface and was retained at the interface for a short period of time before collapsing and then continued to flow downward through the dropwise condensation region. Kumagai et al. [20] also made observation on the partly dropwise condensation surface but did not report such phenomena. In the work of Ma et al. [19], the condensation heat transfer characteristics were highly influenced by the numbers of dropwise and filmwise regions into which the surface was divided and the relative area ratio of the dropwise and film condensation regions.

3. Surface materials for promoting dropwise condensation

Dropwise condensation can take place when the liquid condensate does not wet the solid surface, i.e. the solid surface should possess low surface free energy. Most vapours condense in filmwise condensation mode on most common metal surfaces. Therefore, a solid metal surface must be modified in order to promote the dropwise condensation mode. Generally speaking, dropwise condensation can be promoted by: (1) applying a suitable organic promoter to the condensation surface or the bulk vapour; (2) using a thin layer of metal organic compounds; (3) coating the condensation surface with a low-surface-free-energy polymer film. Most research work conducted in China can be included into the latter two [21].

3.1. Metal and its compound coating

Zhang et al. [22–25] used various surface processing methods including mechanical polish, ion plating, and ion plating and ion-beam mixing technology, to modify the micro structure of the metal surface layer in order to form a amorphous-state surface layer, which has low surface free energy. The Cu–Cr surface prepared by ion plating and ion-beam mixing combination technique maintained dropwise condensation for 8500 h. Zhao et al. [26] studied the effects of different ion-implanted elements and processing conditions on the dropwise condensation heat transfer characteristics. It was found that the processing condition for different implanted elements had considerably impact on the dropwise condensation heat transfer. Subsequently, many works have been conducted with various kinds of implanted elements and the ion implantation processing conditions [27–29].

Song et al. [30] investigated condensation heat transfer characteristics of steam on brass tubes having chromium surfaces prepared with three kinds of surface processing techniques, i.e. ion plating, electroplating, and ion plating with ion-beam mixing. The ion-plated tubes were sorted into three sets for experimental tests. The first set of tubes was used to conduct experiments in the laboratory immediately after the surface was treated. This kind of surface maintained dropwise condensation for 50 h. The tubes of the second set were installed in a large scale steam–water heat exchanger in a power station which operated for one and half years. Then, one of the tubes was taken from the heat exchanger and used in condensation experiments in the laboratory. Film condensation only was obtained. The third set of tubes which had been exposed to the air for about 2 years also failed to promote dropwise condensation. The chromium surfaces prepared by ion plating technique were of very high purity due to the vacuum operation for surface processing. The freshly treated surface gives rise to dropwise condensation of steam due to the organic substances adsorbed from the environment. One electroplated chromium surface maintained dropwise condensation in the laboratory even after the surface was exposed to the air for 1 year. As noted earlier by Finnicum and Westwater [31] dropwise condensation on electroplated chromium surfaces is due to impurities from the surface processing technique rather than the metal itself. The ion plating with ion-beam mixing technology transforms the chromium surface layer into an amorphous state which possesses low surface free energy, hence, resulting in dropwise condensation.

Some researchers also tried to prepare the metal organic compound film on the metal substrate in the laboratory. Liu and Xu [32] prepared a metal-organic compound film on a copper tube. The surface maintained dropwise condensation of steam for about 2000 h. They also found that this surface enhanced filmwise condensation heat transfer of ethanol and ethylene glycol vapours to some extent. Guo et al. [6] coated PTFE on an electrochemically eroded porous surface and tested steam dropwise condensation on the surface. Yang and Cheng [33] investigated dropwise condensation of steam on Ni-PTFE composite plated surfaces. Xin and Xia [34] experimentally studied the heat transfer performance of dropwise condensation in two-phase closed thermosiphones using the oleic acid as the promoter. Dropwise condensation of steam was maintained for 11,340 h.

3.2. Polymer film

For liquids with high surface free energy (or surface tension) such as water and ethanol, metal organic compound surface layers, which have good adhesion with the substrate, would be expected to maintain dropwise condensation mode for a long period of time to meet the requirements of industrial applications. However, for most organic vapours, which are widely used in petrochemical processes, a polymer film on the metal substrate may be the only approach for promoting dropwise condensation. The difficulties for the polymer lie in its much lower thermal conductivity and poor adhesion with metal substrates.

Ma et al. [35–38] employed a plasma polymerisation method to polymerise the polymer film with the thickness of less than 0.1 μm directly on the metal substrates from monomers. However, dropwise condensation of steam was only maintained for about 700 h [39]. The different thermal expansivities of metal and polymer film, and the weak binding effect between the two materials lead to the polymer film peeling after a period of time. In view of the disadvantage of the plasma polymerisation method, Ma et al. [18,29,40,41] used dynamic ion-beam mixing implantation technique to coat the PTFE film on the metal substrates. A polymer film was deposited by using a low energy argon ion beam to sputter the PTFE target and a high energy nitrogen ion beam to simultaneously implant the sample [20]. A component distribution analysis [11] revealed that a transition sublayer 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. In the laboratory test, dropwise condensation of steam on a copper tube with 10 mm o.d. and 100 mm long, which was coated with a PTFE polymer film has been maintained for about 1000 h so far [42]. Experimental investigations of the condensation heat transfer of steam indicated that the surface processing conditions have a significant effect on the dropwise condensation heat transfer characteristics and the adhesion of the polymer film with the metal substrate. This implied that the physico-chemical properties and the purity of the polymer film were dependent on the surface processing conditions. The optimum surface processing conditions for different systems of polymer film and metal substrate remains a key problem before the dropwise condensation on polymer film can be realised in practical applications.

Zhao et al. [43] prepared three layers of barium stearates monomolecular film on the copper plate (30 mm in diameter) using Langmuir–Blodgett (L–B) built-up film technology. Excellent of dropwise condensation of steam was formed on the surface in the laboratory.

4. Industrial applications

Practical applications of dropwise condensation heat transfer surface are restricted by surface processing technology and material science. For metal organic compound films, the main problems concerned are the cost for surface film preparation on an industrial scale and the durability of the dropwise promoting surface. Zhao et al. [44–48] have successfully applied one of this kind of surface film in a practical condenser in the integral heating system in Dalian Power Station in China. The surface film was prepared by the patented Actived Reactive-Magnetron Sputtering Ion Plating technique [49,50]. The condenser is 800 mm of diameter and 3500 mm high with 800 brass tubes each having 16 mm i.d. and 3000 mm long. An overall heat transfer coefficient between 6000 and 8000 $W/m^2 K$ with 2–3 m/s cooling water velocity has been maintained since its installation October 1989, to the present. The dropwise condenser was used to replace the old film one, which has 1600 brass tubes. The tubes used in the film condenser have the same dimensions with the treated ones. A similar application of the identical surface as described above also had been reported by Zhao et al. [51]. Recently, Xu [52] reported the practical application of dropwise condensation of steam on surfaces prepared by the Ion Beam Surface Modification technique.

Nevertheless, the polymer films for promoting dropwise condensation of a vapour are still tested in laboratory. At the best, the polymer film has as much as higher heat transfer coefficient than that of filmwise condensation and can maintain dropwise condensation for a long period of time for the practical application. But, from the objective reality of the material science and the surface processing technology, it will need long time 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 dropwise condensation. As a compromising proposal, it will be much more feasible to enhance the adhesion of the coated polymer film with the metal substrate with a little loss of heat transfer performance. For example, the polymer film thickness might to slightly increased (a slight reduction of heat transfer performance) in order to ensure the enough adhesion of the polymer film with the metal substrate as long as the total heat transfer coefficient can be 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.

5. Concluding remarks

The recent work in this field in China may be summarised as follows:

1. Various surfaces have been prepared to promote dropwise condensation of steam in laboratory. One surface has been successfully applied to an industrial condenser. A polymer film on the metal substrate may be the only feasible way for promoting dropwise condensation of organic vapours. Work on polymer films and organic compound films are currently being conducted to promote dropwise condensation of steam and organic vapours.
2. As far as the mechanism for dropwise condensation process is concerned, a drop-film coexisting mechanism has been proposed. A new surface free energy criterion has been put forward to predict whether filmwise or dropwise

condensation will occur. The critical surface free energy difference was considered to be 0.0333 J/m^2. It is considered more convenient and accurate to use the surface free energy than the contact angle to predict condensation mode because the surface free energy criterion is not affected by the temperature at which the contact angle is measured.

3. Transitions among condensation patterns have been considered as discontinuous processes and supposed as ‘cuspy-type’. Further experiments and theoretical analysis are needed to obtain the relationship among the supposed variables.

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