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A study on the mechanism of dropwise condensation

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Abstract—From the basic viewpoint of adsorption theory, the mechanism of the formation of droplets during dropwise condensation is analysed. It is proposed that a thin film of condensate exists on the area among the droplets and also a film of condensate still exists at the spots from which the droplets departed. Consequently, a mechanism of the dropwise condensation (droplets and film coexisting (DFC)) is presented. With the computerized thin film thickness measurement technology, the mechanism is proved.

INTRODUCTION

THE HIGH heat transfer coefficients of dropwise condensation are generally accepted, but the mechanism of this phenomenon has, not surprisingly, given rise to a variety of suggestions.

There are two completely different viewpoints about the mechanism of the formation of droplets during dropwise condensation. One idea that a thin unstable film first appears on the newly exposed area and subsequently breaks up into droplets, was proposed by Jakob [1].

The other idea that the drops appear to have the same arrangement on the surface and the existence of particular nucleation sites occurs on the surface, was proposed by Tammann and Boehme [2]. McCormick and Baer [3] suggested that condensation of the 'bare' areas took the form of numerous submicroscopic drops, growing from randomly distributed sites. This view has hereafter been strongly supported by Umur and Griffith [4]. It seems that this view is the same as that of Tammann and Boehme.

In the actual process of dropwise condensation, however, it might be possible for a very thin film of condensate to exist on the area among the drops and at the spots from which the droplets departed.

THE MECHANISM OF DROPLETS AND FILM COEXISTING (DFC) DURING DROPWISE CONDENSATION

Physical adsorption is a very general phenomenon and even common solids will adsorb gases and vapours at least to a certain extent. When a gas of vapour contacts with a solid surface, a certain amount of its molecules will continually collide with the surface and some molecules will condense upon the surface of a solid. The surface which is exposed to the gas or vapour can adsorb them everywhere. As for the physical adsorption [5], heat will be given up during the adsorption process. Therefore, equilibrium adsorptivity of the gas or vapour on the surface will increase at decreased temperature of the surface. Physical adsorption can be monolayer adsorption or multilayer adsorption. In multilayer adsorption, the adsorptive heat of a certain layer is less than the next one above it, and the more layers, the more the liquifying heat of the gas, or vapour, at this pressure is approached. Therefore, the condensation processes generally occur in the condition of the limitation of physical adsorption processes.

According to the adsorption theory, the adsorption sites are the higher surface energy positions on the surface. After the higher energy positions have been covered with some vapour molecules, the others will become the higher energy positions, relatively. Although there are some differences of surface energy in the solid surface, it is almost the same during condensation processes.

From this concept, the following physical model of dropwise condensation has been suggested. As shown in Fig. 1, there are numerous droplets on the surface which has been covered with a multilayer of vapour molecules. It means that there is a liquid film of certain thickness (it may be different in different plates) among the droplets during dropwise condensation and the main passage of heat flux (Fig. 1). The condensate on the liquid film moves toward drop sites due to surface tension. The same idea was mentioned by Eucken [6] and supported by Kast [7], but it does not offer any sufficient support for the existence of a film among the 'visible' drops.

NOMENCLATURE

h	thickness of condensate film
k	extinction coefficient
n	refraction index
R	refractance.

Greek symbols

θ	incident angle of light
λ	wavelength of incident light.

EXPERIMENTAL INVESTIGATION

Principle

The experiment has been carried out statically by Umur and Griffith [4]. It does not represent the dropwise condensation process, because it is a dynamic process. The classical method of measuring thin transparent films was the elliptically polarized light method. It was operated manually and could not perform the measurement of a dynamic process.

The reflectance spectrum method with computer imitation has been developed recently. It can detect the thin transparent film dynamically.

The principle of this method has been illustrated in detail in ref. [8].

According to the optic principle, when a ray of light projects on a transparent film adhered to the metal, the reflectance is

$$R = f(n_1, n_2, n_3, K_3, \theta_1, \lambda, h)$$

where n_1 is the index of refraction gas, n_2 the index of refraction of film, n_3 the index of refraction of metal (substrate), K_3 the extinction coefficient of substrate, θ_1 the angle of incident light, λ the wavelength of incident light, and h the film thickness. If n_1, n_2, n_3, K_3, and θ_1 are known, R will be a function of λ only for given h.

So imitation for the actual curve to be measured can be carried out with a computer for different values of h. Finally, the actual film thickness will be approached as in Fig. 2.

Experimental procedure and measurement system

The arrangement of the experimental apparatus is shown in Fig. 3. The right-hand side is the test chamber (i.e. the condenser, shown in Fig. 4) where the condensation processes occur, and the left-hand side is the measurement system. Saturated steam is generated from the electric boiler at atmospheric pressure and supplied to the condenser (i.e. the test chamber). The coolant is supplied by gravity with a tank at a higher level than the condenser. Measurements were carried out during the condensation process.

The polished surface of stainless steel or copper (i.e. the condensation surface), on which the dropwise condensation can occur, was obtained with a particular treatment. The surface was installed horizontally and adjusted to its proper position. The incident light is reflected from the surface. The beam of light incident upon and reflected from the surface passes through an electrically heated window to avoid condensation at its surface. The chamber is made of Teflon.

RESULTS AND DISCUSSION

Results of the static state

The purpose of the experiment carried out statically is to confirm whether there is a film of condensate among the drops. The standard reflectance spectrum of the stainless steel surface of no condensate is shown

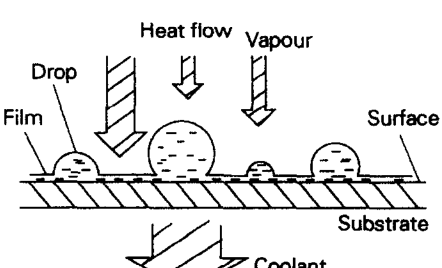

FIG. 1. Physical model of dropwise condensation.

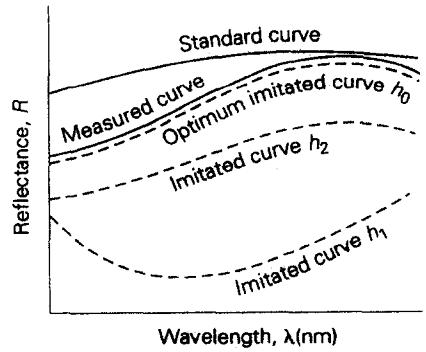

FIG. 2. Imitation of actual curve with computer.

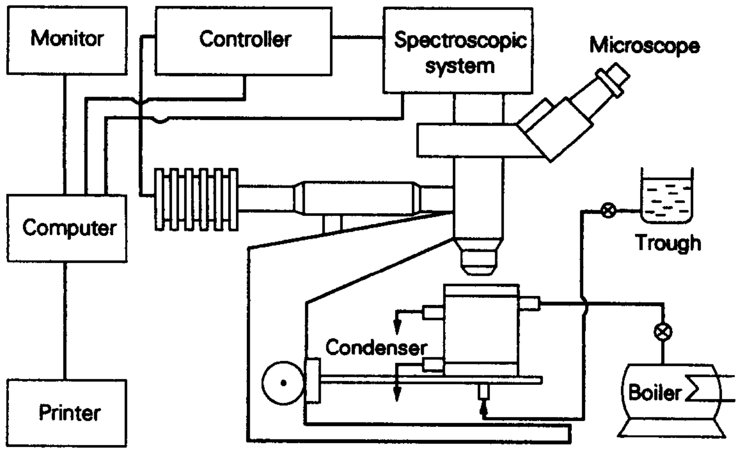

FIG. 3. Arrangement of experimental apparatus.

in Fig. 5, in which the dash line represents the theory values and the dot line represents the measured values. The two lines coincide with each other and prove that the measurement system is reliable and correct.

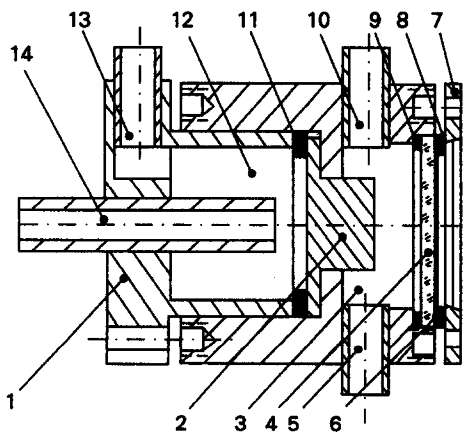

FIG. 4. Structure of the condenser: 1, back gland; 2, condensing block; 3, condensing chamber; 4, heated glass window; 5, condensate out; 6, electrode; 7, front gland; 8, sealing ring; 9, sealing ring; 10, steam in; 11, sealing ring; 12, cooling chamber; 13, water out; 14, water in.

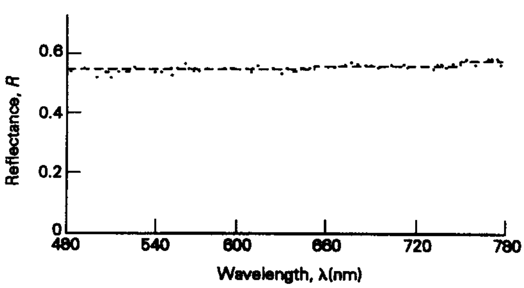

FIG. 5. Standard reflectance spectrum.

Figure 6 shows the reflectance spectrum of the static state of dropwise condensation. When the dropwise condensation is formed steadily, the steam supply is stopped and the static state is obtained. Comparing Fig. 5 with Fig. 6, no liquid film is observed, among the drops.

Results of the dynamic state

In Fig. 7 the momentary behaviour has been shown at the beginning of the steam condensation. When the

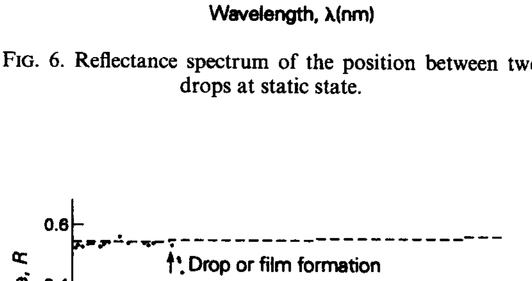

FIG. 6. Reflectance spectrum of the position between two drops at static state.

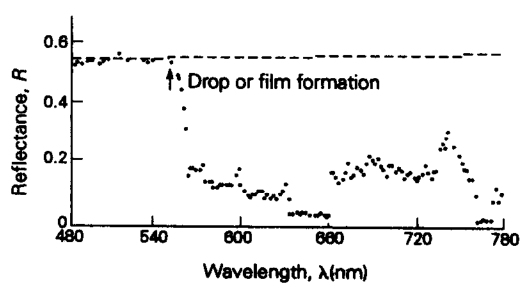

FIG. 7. The momentary behaviour of the beginning of steam condensation.

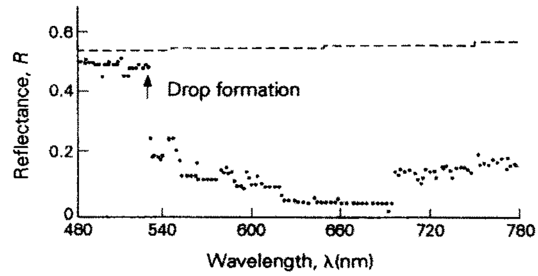

FIG. 8. Reflectance spectrum of the position between two drops at very slow vapour rate.

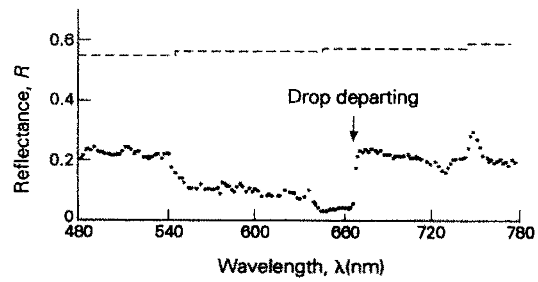

FIG. 9. Reflectance spectrum of the spot of the departing drop at very slow steam rate.

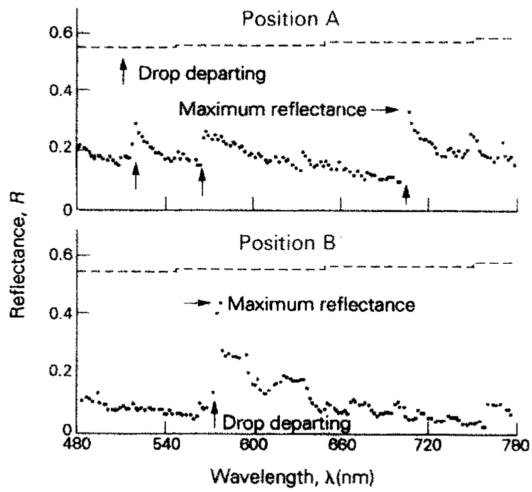

FIG. 10. Reflectance spectrum of different positions of departing drops at normal steam rate.

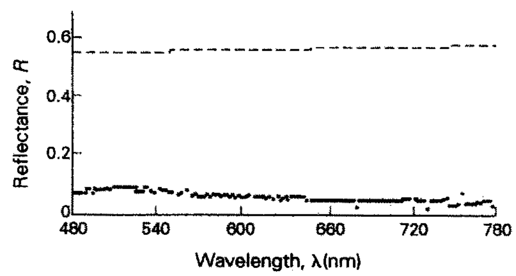

FIG. 11. The reflectance spectrum of a big drop at the normal condensing rate.

condensate was formed on the surface, the reflectance decreased. It indicated that there was a liquid film or drop on the cooling surface. In order to obtain the steady reflectance spectrum of the area between drops, the steam flow rate should be reduced to as slow as possible. The spectrum is shown in Fig. 8. On the left-hand side of the arrow, a condensate film has been formed on the cooling surface. On the right-hand side of the arrow, a liquid drop has been formed on the cooling surface, because the reflectance decreased rapidly. The reflectance spectrum of the spot of droplet departure is shown in Fig. 9. The position of the arrow in Fig. 9 indicates that a droplet departs from the surface and the reflectance does not rise to the standard position, obviously. It means that the liquid film still exists at this point.

The reflectance spectra of two different positions A and B are shown in Fig. 10 at the normal flow rate of steam. The frequency of droplet formation was faster than the situation in Fig. 9, but the reflectance does not rise to the standard. The peak points of the waves are different at different positions and vary with time. It means that the film thickness is different. For comparison the reflectance spectrum of a big drop at the normal condensing rate is shown in Fig. 11.

The experimental results mentioned above are obtained on a stainless steel surface. The results obtained on the copper surface (Cu–Ni alloy) are different from those on the stainless steel surface only in order of magnitude, but the conclusions are the same. They are shown in Figs. 12 and 13.

All of the experimental results indicate that the droplets and film coexist during the dropwise condensation process.

CONCLUSION

Conceptual and experimental results indicate that in dropwise condensation.

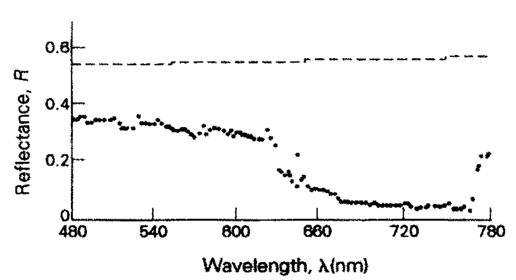

FIG. 12. Reflectance spectrum of the position between two drops at very slow vapour rate on the copper surface.

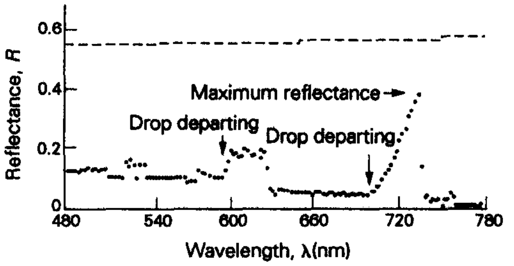

FIG. 13. Reflectance spectrum of the spot of the departing drop on the copper surface.

(1) A thin film of condensate exists on the area among the droplets and a thin film of condensate still exists at the spots of droplet departure.

(2) The reflectance spectrum method with computer imitation is an effective method to measure the thin film dynamically.

(3) Hitherto, the results obtained can describe the mechanism of dropwise condensation only qualitatively. So the improvement of the measurement system should be made in order to obtain the complete spectrum instantaneously and quantitatively.

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UNE ETUDE DU MECANISME DE LA CONDENSATION EN GOUTTES

Résumé—Sur la base de la théorie de l'adsorption, le mécanisme de la formation des gouttelettes pendant la condensation en gouttes est analysé. On propose qu'il existe un film mince de condensat sur la surface autour des gouttelettes et aussi lorsque les gouttelettes s'en vont. Par conséquent on présente un mécanisme de condensation en gouttes (avec coexistence de gouttelettes et de film). On prouve l'existence de ce mécanisme avec la technique informatique de la mesure de l'épaisseur du film.

UNTERSUCHUNG DER MECHANISMEN DER TROPFENKONDENSATION

Zusammenfassung—Der Mechanismus der Tropfenbildung bei der Tropfenkondensation wird auf der Grundlage der Adsorptionstheorie untersucht. Man geht davon aus, daß in der Umgebung der Tropfen ein dünner Kondensatfilm existiert und daß dieser Kondensatfilm auch noch an den Stellen fortbesteht, an denen sich die Tropfen gelöst haben. Auf dieser Grundlage wird eine Erklärung für den Mechanismus der Tropfenkondensation vorgeschlagen, deren wesentlicher Inhalt das gleichzeitige Bestehen von Tropfen und Film (DFC) ist. Die vorgeschlagene Erklärung wird mit Hilfe eines computergesteuerten Meßverfahrens für die Dicke dünner Filme überprüft.

ИССЛЕДОВАНИЕ МЕХАНИЗМА КАПЕЛЬНОЙ КОНДЕНСАЦИИ

Аннотация—С точки зрения теории поглощения анализируется механизм образования капель в процессе капельной конденсации. Предполагается, что тонкая пленка конденсата находится между каплями, а также в местах их отрыва. Описывается механизм капельной конденсации (при наличии как капель, так и пленки). Результаты подтверждаются использованием технологии измерения толщины тонкой пленки при помощи ЭВМ.