研 究 速 報

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Transient Heat Transfer Measurement in Dropwise Condensation

滴状凝縮過程における過渡的熱伝達測定

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1. Introduction

Transient heat transfer measurement in dropwise condensation was performed by removing instantly and periodically all the drops on the condensing surface using a wiper made of silicone rubber. The periodic changes in the temperatures of the condensing surface and the inside of the condensing block were measured, and the high speed motion pictures were taken at the same time of the process of drop growth. The relationship between the maximum drop size on the surface and the (instantaneous) heat transfer coefficient was derived.

Extremely high heat transfer coefficient observed in dropwise condensation is very likely caused by the transient heat transfer occurring on the bare parts of the condensing surface which appear due to coalescing of drops or sweeping by departing drops. Several investigators[1)2)3)] have measured the fluctuation of the temperature of the condensing surface attributed to the behavior of the drops, thus supporting the above-mentioned conjecture. However, since the drops behave quite randomly and unevenly during dropwise condensation, it is not easy to attain valuable results by such direct measurement.

As a part of the research program whose object is to make clear the relationship between the heat transfer coefficient and the drop size, the authors carried out an experiment in which the drops were forced to be removed from the surface by a wiper[4)]. After the experiment the authors thought of the possibility of obtaining the instantaneous values of heat transfer coefficient corresponding to the every stage of drop growth process by carrying out a transient heat transfer measurement with the same apparatus. Since the result thus obtained would reveal quantitatively the every process occurring at each location and time, it must be without doubt most useful in clarifying the mechanism of the heat transfer in dropwise condensation.

2. Method of Measurement

2.1. Principle　Consider a condensing block of the length 2ℓ as shown in Fig. 1. A side ($x=\ell$) of it

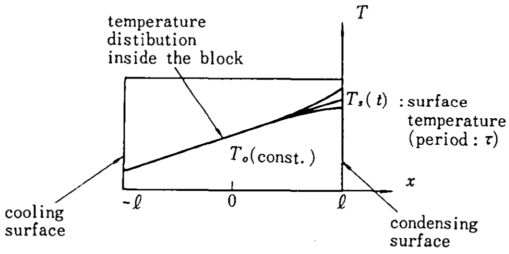

Fig. 1　Principle of transient measurement

is the condensing surface and the other side ($x=-\ell$) is the cooling surface. Usually the temperature and the heat flux at the condensing surface is neither uniform in position nor constant in time because of the coalescence and the departure of the drops taking place quite randomly. However, if all the drops are swept off simultaneously with the wiper, the surface temperature and heat flux are considered to be kept almost uniform (considering the mean value over the area several times as wide as the maximum drop size), and then the heat conduction inside the block can be assumed to be one-dimensional.

This transient heat conduction problem is formulated as follows:

$$0<x<\ell : \frac{\partial T}{\partial t}=\kappa\frac{\partial^2 T}{\partial x^2} \quad \cdots\cdots(1)$$

$$x=0 : T=T_0(\mathit{const.}) \quad \cdots\cdots(2)$$

$$x=\ell : T=T_s(t) = \overline{T}_s+\sum_{m=1}^{\infty}(A_m\cos\omega_m t+B_m\sin\omega_m t) \quad \cdots(3)$$

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$$\omega_m=\frac{2m\pi}{\tau} \quad \cdots\cdots (4)$$

$$t=0\ :\ T=f(x) \quad \cdots\cdots (5)$$

In Eq. (3) it is taken into consideration that the surface temperature T_s becomes a periodic function having the same period τ with the wiper (where $\overline{T}_s$ is the mean value of the fluctuation). Evidently the temperature T must approach the periodically steady temperature T_p, which is independent of the initial temperature distribution $f(x)$, when the time t becomes sufficiently large. As the result of calculation

$$T_p=(\overline{T}_s-T_o)\frac{x}{\ell}+T_o+\sum_{m=1}^{\infty}\{(C_mA_m-D_mB_m)\cos\omega_m t+(D_mA_m+C_mB_m)\sin\omega_m t\} \quad \cdots\cdots (6)$$

is derived, where

$$C_m=\frac{1}{2}\left\{\frac{\sinh(-1+i)\beta_m(x/\ell)}{\sinh(-1+i)\beta_m}+\frac{\sinh(1+i)\beta_m(x/\ell)}{\sinh(1+i)\beta_m}\right\} \cdots (7)$$

$$D_m=\frac{1}{2i}\left\{\frac{\sinh(-1+i)\beta_m(x/\ell)}{\sinh(-1+i)\beta_m}-\frac{\sinh(1+i)\beta_m(x/\ell)}{\sinh(1+i)\beta_m}\right\} \cdots (8)$$

$$\beta_m=\ell\sqrt{\frac{\omega_m}{2\chi}} \quad \cdots\cdots (9)$$

(It should be noted that A_m's and B_m's in Eq. (6) are not identical with those in Eq. (3). To be precise, those in Eq. (6) represent the values of A_m's and B_m's when t goes sufficiently large.) The surface heat flux is derived from above and

$$q_p=-\lambda\frac{\overline{T}_s-T_o}{\ell}-\lambda\sum_{m=1}^{\infty}\frac{\beta_m}{\ell}\{(P_mA_m-Q_mB_m)\cos\omega_m t+(Q_mA_m+P_mB_m)\sin\omega_m t\} \quad \cdots\cdots (10)$$

is obtained, where

$$P_m=\beta_m\frac{\sinh(2\beta_m)+\sin(2\beta_m)}{\cosh(2\beta_m)-\cos(2\beta_m)} \quad \cdots\cdots (11)$$

$$Q_m=\beta_m\frac{-\sinh(2\beta_m)+\sin(2\beta_m)}{\cosh(2\beta_m)-\cos(2\beta_m)} \quad \cdots\cdots (12)$$

The heat transfer coefficient at the condensing surface is calculated from

$$h_p=\frac{q_p}{T_v-T_p} \quad \cdots\cdots (13)$$

where T_v is the temperature of saturated vapor.

Thus, the instantaneous heat flux and heat transfer coefficient can be obtained by measuring both the fluctuation of the temperature at the condensing surface and the temperature T_o at the position ($x=0$) where the fluctuation is completely decayed, if the periodically steady condition is fully established.

2. 2. Apparatus The condensing chamber including the wiping mechanism used in the present experiment is the same one as described in the previous report[4] and will not be repeated here. Figure 2 shows the condensing block and the detail of the surface thermocouple.

The e.m.f. from the thermocouple for the surface temperature was, after its steady portion $\overline{T}_s$ being eliminated with a constant voltage D. C. current generator, amplified by a factor of 10^4 wih a high accuracy D. C. amplifier (YEW: Type 3128) and then displayed on a synchroscope (Iwasaki: SS-5302 B).

The fluctuation of the inside temperature T_o was smaller than the level of noise (10μV), as expected, and was measured steadily with a high accuracy

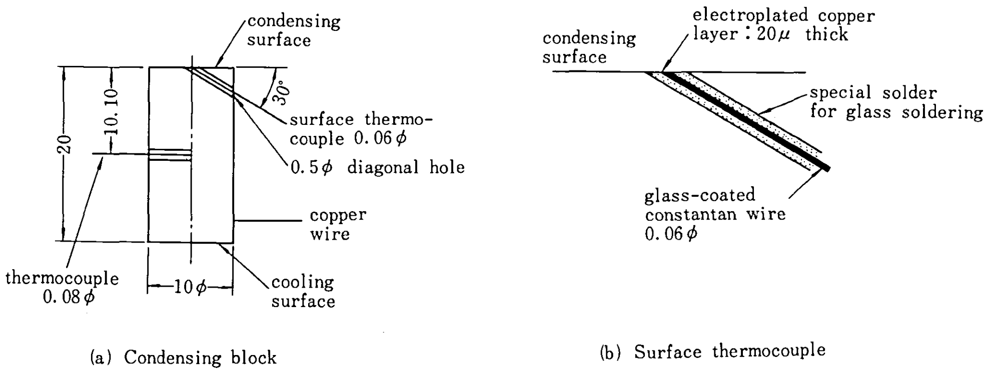

Fig. 2 Condensing block

digital voltmeter.

In parallel with the temperature measurement, the growth process of the maximum drops was photographed with 16 mm cinecamera through micr-oscope with 100 and 50 magnifications at a filming rate of 500 pictures per sec.

3. Result of Measurement

A picture of the surface temperature fluctuation displayed on the Braun tube is shown in Fig. 3. In this example the wiping period is 0.3 sec and the maximum drop diameter is 0.78 mm.

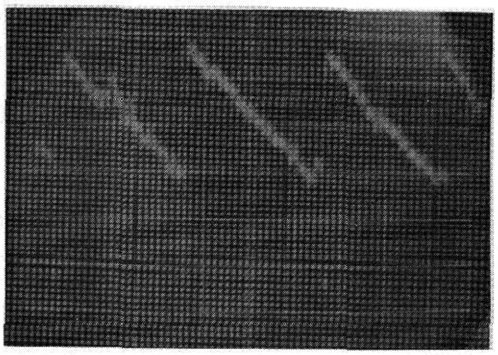

Fig. 3 Temperature variation as displayed on the Braun tube

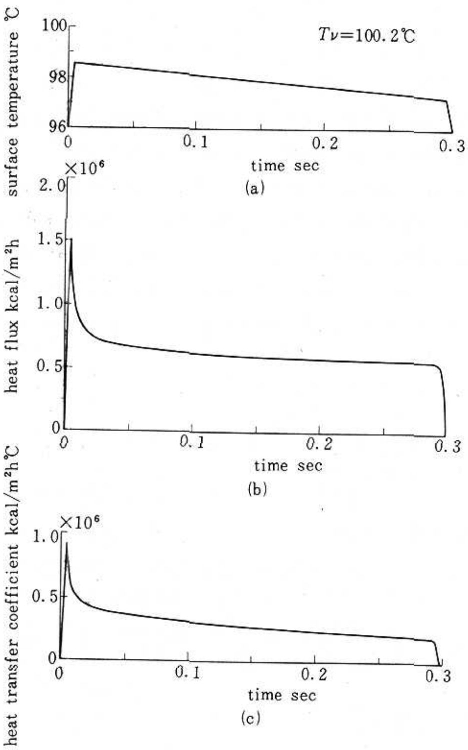

Fig. 4 Result of transient measurement

As the wiper approaches to sweep the surface, the heat transfer coefficient decreases considerably and the surface temperature lowers rapidly, because of a mass of condensate accumulated just ahead of the wiper blade. Immediately after the wiper passes through, the vapor comes in direct contact with the surface and the surface temperature rises up ab-ruptly until it reaches a maximum value $T_{s,max}$ which is a little lower than the vapor temperature. After that the surface temperature decreases almost line-arly. The typical mode of the temperature change as described above can be depicted as Fig. 4 (a). In this figure the part corresponding to the overshooting of the rapid temperature fall due to the accumulated condensate is omitted. In the case of Fig. 4 (a), the period of the abrupt temperature rise is 0.005 sec, that of temperature fall is also 0.005 sec, the maxi-mum temperature 98.5℃, the minimum temperature 96.0℃ and the mean temperature for a whole period is 97.8℃.

Such an information about the surface temperature variation, together with the value of constant tem-perature T_o=78.5℃ at the distance 10.1 mm from the surface, is used to calculate the surface heat flux from Eqs. (10)~(12). The result is shown in Fig. 4 (b). The heat transfer coefficient can be obtained using the results of Figs. 4 (a) and (b) and shown in Fig. 4 (c). It is seen that both the heat flux and the heat transfer coefficient reach the maxima at t=0.005 sec, where the surface temperature is also at its maximum, and are 1.5×10^6 kcal/m²h and 0.91×10^6 kcal/m²h℃, respectively. Prior to the measure-ment the authors made an anticipation that the max-imum heat transfer coefficient equivalent to the interfacial heat transfer coefficient derived from the kinetic theory of gases (which is for the present case approximately as high as 6×10^6 kcal/m²h) would be available. The value actually obtained, how-ever, is considerably smaller than this. It is not evident for the present whether this is owing to the possible insufficiency in the response and/or the accuracy of the temperature measuring devices or owing to the incomplete sweep of the wiper.

Comparison with the 16 mm pictures of the drop growth process taken simultaneously makes us possible to relate the maximum drop size at each instant with the heat transfer coefficient. A couple of examples are shown in Fig. 5. The curve *a* in the figure corresponds to the result of Fig. 4, while the curve *b* to another measurement. Both examples exhibit rise of the heat transfer coefficient where the maximum diameter is small. Such tendency, however, is not considered to be very reliable, because the accuracy at small maximum drop size is dependent on the accuracy of measurement of the very rapidly changing temperature. The results previously obtained by the authors are also shown in Fig. 5 as a dot-dash line and a two-dots-dash line. The former[5] corresponds to the relationship between the heat transfer coefficient and the departing drop diameter, which is varied by the vapor shear force, the centrifugal force and the inclination of the condensing surface. The latter[4] is for the correlation between the heat transfer coefficient and the maximum drop diameter which is controlled by removing the drops on the surface with the wiper.

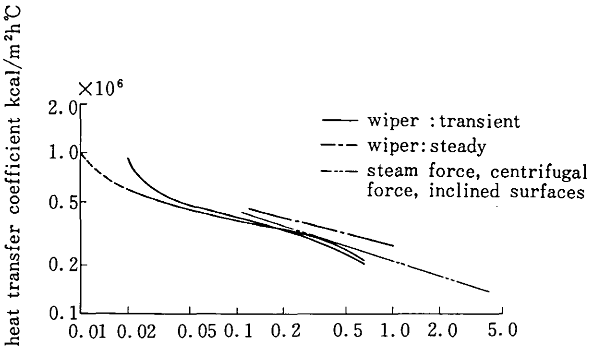

Fig. 5 Heat transfer coefficient and drop size

Although these results seem to exhibit similar tendency, a definite conclusion is not derived for the present. (Manuscript recieved, Feburary 26, 1976)

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正 誤 表 (4月号)

頁	段	行	種別	正	誤
25	左	↑5	本文	下段に破線	上段に実線
〃	〃	↑1	〃	漸減	漸増
〃	〃	↑1	〃	上段に実線	下段に破線
〃	右	↑7	〃	750kg	950kg
〃	〃	↑6	〃	破線	実線
〃	〃	↑4	〃	50m/secに上昇	40m/secに低下
26	左		図4	FとVとを入換え	