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Dropwise Condensation at Low Heat Flux and Small Surface Subcooling

小過冷度・低熱流束域における滴状凝縮の研究

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1. Introduction

The objective of this study is to make clear the process of dropwise condensation at low heat flux and small surface subcooling.

Most of the heat transfer measurements in the past were carried out at surface subcooling ΔT substantially higher than 1°C. Only a few results (e.g., Tanner et al.[1] and Graham[2]) for ΔT less than 1°C have been published, but the accuracy of those measurements is open to some doubt.

At present, the formation of initial droplets during dropwise condensation cycle is believed to be by nucleation process. According to the Kelvin-Helmholtz equation, the critical radius r_c for the nucleated drop to grow is inversely proportional to ΔT. For example, $r_c=0.02\ \mu m$ when $\Delta T=1°C$, and $r_c=0.2\ \mu m$ when $\Delta T \fallingdotseq 0.1°C$. Therefore, the number of effective nucleation sites among various kinds of defects distributed on a condensing surface is reduced as ΔT becomes smaller, and the heat transfer coefficient may possibly be reduced. The value of ΔT, below which the heat transfer coefficient begins to decrease, is guessed as around 1°C, though it may depend on surface conditions.

The heat transfer measurement at such a small surface subcooling involves considerable technical difficulty. In most of the past measurements, the temperature of condensing surface was obtained by extrapolation of thermal emfs from thermocouples placed inside a heat transfer block. In such a method, the error in the estimation of surface temperature due to uncertainty in the location of each thermocouple junction is unavoidable (Wilcox and Rohsenew[3]). Moreover, disturbance of heat flow caused by thermocouple holes brings about another error (Ochiai, Tanasawa and Utaka[4]). Thus, it is not easy to carry out precise measurement at ΔT lower than 1°C. One of the possible ways to get over the difficulty is to measure by some means or other the surface temperature directly.

In the present study, a thin-film thermocouple was formed on the condensing surface using a vacuum sputtering technique. The surface temperature was measured with sufficient accuracy.

At smaller surface subcooling, the heat flux becomes necessarily lower. The rate of drop growth is decelerated. Both the low population density of nucleation site and the low rate of drop growth make it possible for us to observe the very process of drop growth unaffected by coalescence. This was also done in the present study.

2. Experimental Apparatus

A circular glass plate (19mm dia. and thickness 0.5mm) as shown in Fig. 1 was used for the condensing surface. A thin-film of constantan (thickness 1.1 μm) was deposited on the glass plate using a radio-frequency sputtering device, and then a copper film (thickness 1.8 μm) was deposited over the other so that the most part of the glass surface (about 75% of the condensing surface area) was covered with the double layers of films. In this case the outer margin of 0.5 mm in width was left free of film. Before the measurement it was considered that the whole of the overlapped part of the films acted as the thermocouple junction and the mean

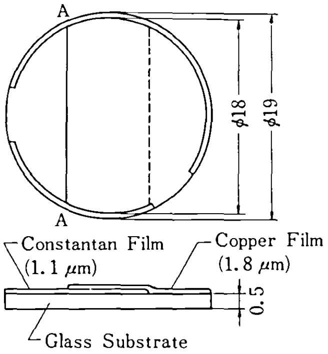

Fig. 1 Condensing surface and thin film thermocouple

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temperature over this area was to be detected. But it was not the case; it was proved both theoretically and experimentally that the mean temperature along the border line of the two metals (A-A in Fig. 1) was measured. This surface thermocouple was calibrated using a cryostat having an accuracy of ±0.03°C.

The saturation temperature corresponding to the pressure in the condensing chamber was used as the steam temperature.

The heat flux was measured with a cylindrical copper block, 18 mm dia. and 30 mm long, as shown in Fig. 2. Similar to the method used earlier in our laboratory, the copper rod was first split into two, five square grooves of 0.5 mm in width were machined on one of the split surfaces, and an end of constantan wire of 80 μm dia. was soldered just at the center of each groove. The two parts were soldered together after the positions of these junctions were measured precisely with a travelling microscope.

The glass condensing surface was adhered with silicone resin to one end of the copper block. Oleic acid was applied to the steam-side surface as the promoter. The other end of the block was used as the cooling surface which was cooled with water jets whose temperature was controlled very accurately. The outline of the apparatus is shown in Fig. 3.

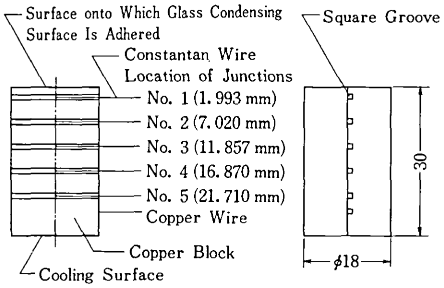

Fig. 2 Copper block for heat flux measurement

The heat flux was varied from 0.23x10^4 kcal/m^{2}h°C to 8.8×10^4 kcal/m^{2}h°C, as the temperature of cooling water was changed from 95°C to 10°C.

The rate of drop growth and the drop size distribution were measured by high-speed photomicrography. Filming rate was 160 per sec and the magnification was 50. The 16-mm pictures thus obtained were magnified again by a film analyzer, and the behavior of drops was observed.

3. Results

3.1 Heat transfer coefficient Heat transfer coefficient is plotted against surface subcooling, as shown in Fig. 4. In order to remove non-condensable gases and to make change the departing drop size the steam velocity was varied as 5 m/s and 15 m/s. The heat transfer coefficient lowered as the subcooling decreased, and very steeply where ΔT approached 0.2°C. Results reported by Tanner at al.[1] and Graham[2] are shown in Fig. 4 for comparison. Two differences are noticed. In the first place, the present result shows the lower heat transfer coefficient. This may be owing to the difference in the surface material; both Tanner et al. and Graham have used copper surfaces, while the present measurement is on the plate of glass whose thermal conductivity is about one-five hundredth of copper. (But it should be noted that the present result on the glass surface shows higher value when compared with the one on stainless steel surface obtained by Hannemann and Mikić[5].) The

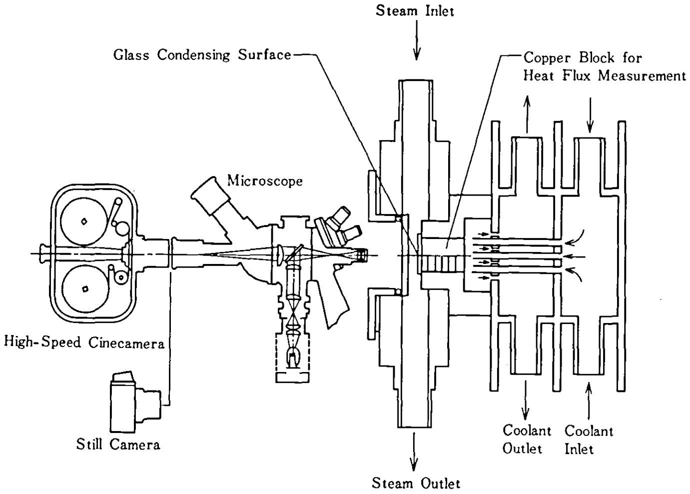

Fig. 3 Outline of the apparatus

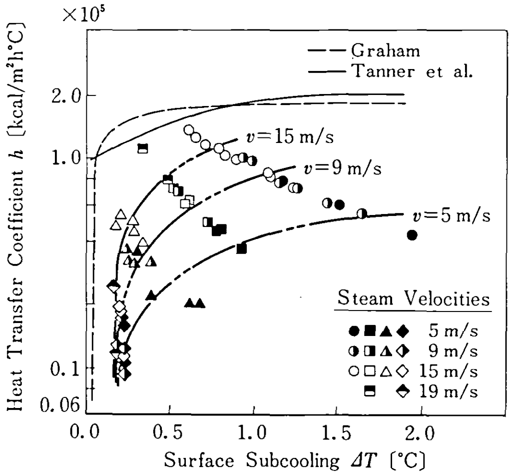

Fig. 4 Heat transfer coefficient vs. surface subcooling

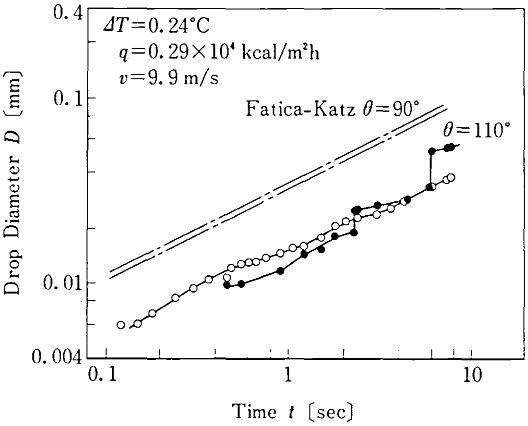

Fig. 5 Rate of drop growth

second point is that the value of ΔT, where the heat transfer coefficient begins to decrease rapidly, is different from that of Graham's. As for this the authors have doubt on the accuracy of surface temperature measurement by extrapolation method.

3.2 Rate of drop growth Figure 7 shows the pictures of process of condensation picked up from the 16-mm cine-films. The heat flux q=0.29x10^4 kcal/m^{2}h and the vapor-to-surface temperature difference ΔT=0.24°C. As seen from the pictures the drops are formed very sparsely and grow experiencing but few coalescences because of low heat flux. The rate of drop growth measured for such isolated drops is shown in Fig. 5. The open circles in the figure show the change in diameter of a drop which grew without coalescence at all; the solid circles show that of a drop which coalesced twice during observation. The resutls of analysis (for contact angles 90° and 110°) by Fatica and Katz[6], which is based on steady conduction through the drop, is drawn in the figure (as chain-dot lines) for comparison. The result of measurement shows that the rate of growth unaffected by coalescence is proportional to drop diameter D to the power about 0.4. On the other hand the analysis by Fatica et al. has revealed $D \propto t^{0.5}$. The authors consider that the difference may be due to the variation of local temperature of the condensing surface. A numerical calculation to prove it is now in preparation.

3.3 Drop size distribution Figure 6 shows the timewise change in the drop size distribution at q=1.0x10^4 kcal/m^{2}h. The instant just after the area is swept clean by a falling drop is taken as t=0. Since the drops initially originated from the surface are all very similar in size, the drop size distribution curve shows a high and steep peak. As they grow the curve becomes flattened because of frequent coalescences.

In Fig. 7 small drops are seen distributed closely on a straight line. Close examination reveals that a thin scratch exists beneath the line of drops. Although it is difficult to know exactly the depth and width of this scratch, it is evident that such a scratch offers the effective sites of nucleation, thinking that the critical drop diameter for a nucleated drop to grow is about 0.12 μm when ΔT=0.3°C.

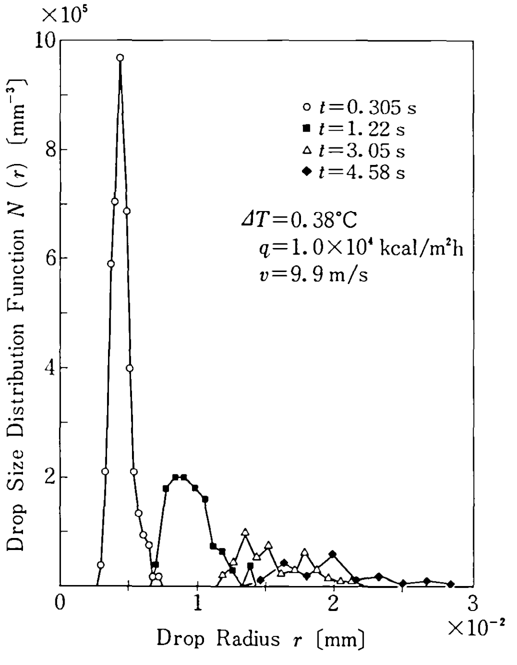

Fig. 6 Transient distribution of drop size

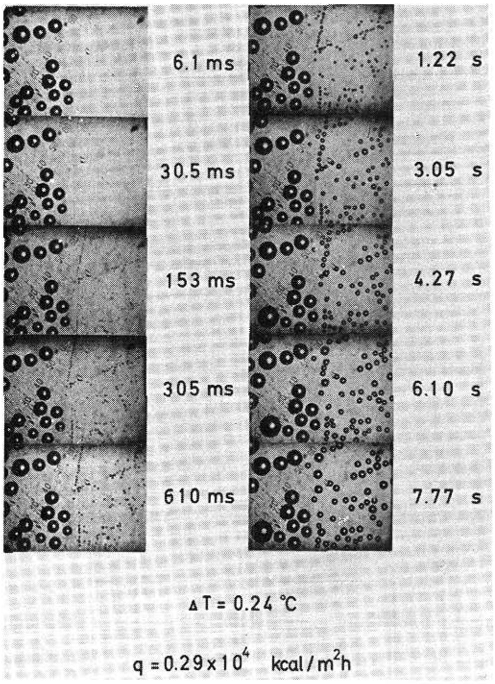

Fig. 7

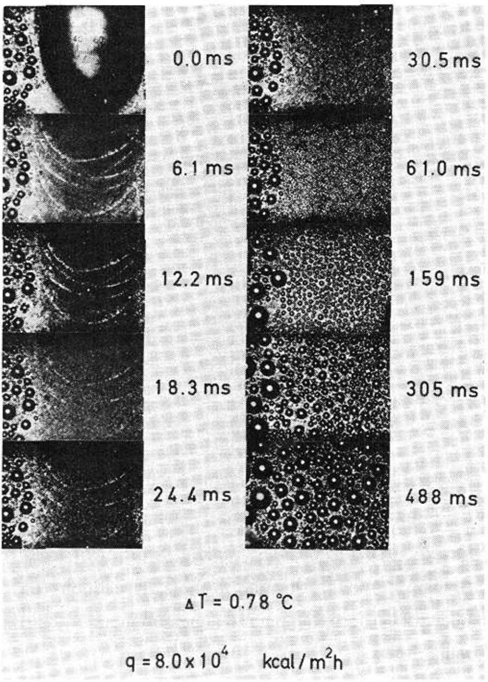

Fig. 8

3. 4 Surface temperature distribution Figure 8 shows the series of microscopic pictures taken at q=8.0×10^4 kcal/m^2 h, ΔT=0.78°C. The departing drop seen in the first picture moves upward out of sight in the following frames and leaves white stripe pattern like wave rings. This pattern is considered to be corresponding to the periphery of drop which keeps on oscillating while moving. Much larger local heat flux through the peripheral part of a drop may raise the local temperature of condensing surface and the nucleation at that part may be decelerated after the drop moves elsewhere, so that the part may be taken as a white stripe in the picture. Some people (e.g., Hurst 7)) have been proposed that the high heat transfer rate in dropwise condensation is owing to large heat flow through the periphery of drop. The pictures in Fig. 8 may offer an evidence to such a point of view. The authors consider, however, that such a phenomenon can be conspicuously observed only in case of condensation on a substrate with poor thermal conductivity such as glass. It may not be the case when the surface material has much higher thermal conductivity.

4. Conclusion

Heat transfer in dropwise condensation at low heat flux and small vapor-to-surface temperature difference was measured using a thin-film thermometry. Heat transfer coefficient was found to decrease as the surface subcooling ΔT was reduced, especially very steeply were ΔT was lower than 0.2°C. This may be due to possible decrease in the density of effective nucleation sites on the condensing surface. Observation by high-speed microphotography revealed that fine scratches on the surface offered very effective nucleation sites.

The process of drop growth at low heat flux was found to be rarely affected by coalescence and the diameter increased as proportional to time to the power of about 0.4.

In addition, the transient distribution of drop size was measured. (Manuscript received, August 2, 1978)

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