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DROP-TO-FILMWISE CONDENSATION TRANSITION: HEAT TRANSFER MEASUREMENTS FOR ETHANEDIOL

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Abstract—Measurements of vapour-to-surface temperature difference and heat flux are reported for dropwise, mixed and film condensation of ethanediol on an oleic acid-promoted copper surface and on a ptfe-coated surface. Tests were carried out at seven vapour temperatures (pressures) in the range 386 K (3.8 kPa) to 440 K (35.6 kPa). Air, ethanediol and water were used as coolants. At low and moderate cooling intensities dropwise condensation was observed for both surfaces and the ΔT–Q data for the two surfaces were in good agreement with each other and with dropwise condensation theory. At higher cooling intensities transition to mixed condensation was observed in the case of the ptfe surface. This was accompanied by departure from the theoretical ΔT–Q curve and the heat flux passed through a maximum with increasing cooling intensity. In the case of the oleic acid-promoted copper surface, ideal dropwise behaviour persisted to somewhat higher values of ΔT and Q before abrupt transition to film condensation occurred. The post transition filmwise data were in good agreement with the Nusselt theory. For both surfaces, reversion to ideal dropwise condensation occurred as the cooling intensity was reduced. Two possible mechanisms for the transition process are suggested.

NOMENCLATURE

g,	specific force of gravity;
h_{fg},	specific enthalpy of evaporation;
$I(z)$,	function defined in equation (A5);
K_1,	constant in dropwise condensation theory;
k,	thermal conductivity of condensate;
k_p,	thermal conductivity of ptfe layer;
L,	$\sigma T_v/\rho h_{fg}\Delta T_t$;
N_1,	$Q_t\mu/\sigma\rho h_{fg}$;
N_2,	$(Q_t/h_{fg})(r/\rho\sigma)^{1/2}$;
$N(r)$,	distribution function; number of drops per area having base radius in range r, $r+\mathrm{d}r$ divided by $\mathrm{d}r$;
Q,	heat flux;
Q_{max},	peak heat flux;
Q_t,	heat flux at onset of drop-to-film transition;
Q_b,	heat-transfer rate through drop divided by base area;
q,	dimensionless heat flux defined in equation (A6);
R,	ideal-gas constant;
r,	base radius of drop;
$\hat{r}$,	mean base radius of largest drops;
$\check{r}$,	$2\sigma T_v/\rho h_{fg}\Delta T$;
T_c,	temperature at copper surface or copper-ptfe interface determined by extrapolation from plate thermocouples;
T_s,	condensing surface temperature taken as T_c for oleic acid-promoted surface and T_c+Qt_p/k_p for ptfe-coated surface;
T_v,	vapour temperature;
t_c,	coalescence time of drops [see equations (1) and (2)];
t_g,	growth time of drops [see equation (3)];
t_p,	thickness of ptfe layer;
ΔT,	$T_v - T_s$;
ΔT_t,	value of ΔT at onset of drop-to-film transition.

Greek symbols

β,	contact angle;
γ,	ratio of isobaric to isochoric specific heat-capacity of vapour;
θ,	dimensionless vapour-to-surface temperature difference [see equation (A7)];
θ_0,	dimensionless parameter [see equation (A8)];
μ,	viscosity of condensate;
ρ,	density of condensate;
ρ_g,	density of vapour;
σ,	surface tension;
ϕ,	ratio of base area to curved surface area of a drop.

1. INTRODUCTION

AS THE vapour-to-surface temperature difference is progressively increased during dropwise condensation, the heat flux at first increases, passes through a maximum and subsequently decreases. At relatively low values of ΔT ideal dropwise condensation takes place and the rate of increase of Q with ΔT is greatest. At higher values of ΔT a smaller rate of increase and eventually a decrease of Q are associated with transition to mixed condensation. At sufficiently high values of ΔT the mode eventually becomes that of filmwise condensation.

Heat-transfer coefficients can be predicted satisfactorily for ideal filmwise and dropwise condensation. However, since the ratio of the dropwise-to-filmwise coefficient may be as high as 10 or 20, it is important to be able to predict which mode will occur in given circumstances and to estimate heat-transfer coefficients

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in the transition regime. Particularly significant parameters are the values of ΔT and Q at which transition from dropwise condensation begins, the maximum heat flux and the value of ΔT at which the maximum heat flux occurs.

Few experimental data for dropwise–filmwise transition are available. Wilmshurst and Rose [1] obtained data for ethanediol, aniline and nitrobenzene. In the case of all three fluids, the appearance of the condensing surface at low and moderate cooling intensities was that of ideal dropwise condensation. Comparison of the results with dropwise condensation theory, however, indicated that some of the data were in the transition regime, suggesting that transition sets in at the microscopic level. For ethanediol, the appearance of ideal dropwise condensation persisted even at the highest cooling intensities while transition to film condensation was observed for aniline and nitrobenzene. The transition phenomenon was found to depend on the vapour temperature, occurring sooner (at lower Q) at the lower temperatures. The scatter of these data was such that only crude estimates of the Q and ΔT values at onset of transition could be made. Peak heat fluxes, on the other hand, were quite well defined and are given in Table 1.

For steam at atmospheric pressure, transition data were first obtained by Takeyama and Shimizu [2] who found a peak heat flux of about 7 MW m^{-2}. More detailed measurements, of enhanced accuracy, have been made by Tanasawa and Utaka [3]. These are shown in Fig. 1. It may be seen that the results appear to depend systematically but weakly on the maximum drop size. (The different maximum drop sizes were realised experimentally by using different vapour velocities over the condensing surface.) In the dropwise condensation regime (at lower values of Q) the data are in good agreement with theory [4], the latter correctly predicting the dependence on maximum drop size. Estimates of the Q and ΔT values at onset of transition may be made by reference to departure of the data from theory. That the onset seems to occur sooner for larger $\hat{r}$, might at first be thought to indicate that transition is a 'large drop phenomenon'. This is more probably due to the fact that, for a given value of Q (average heat flux for the whole surface), the condensation intensity on regions covered by very small drops is greater when a greater proportion of area is covered by large drops.

Table 1. Approximate peak heat flux values from Wilmshurst and Rose [1]

Fluid	T_v (K)	Q_{max} (MW m^{-2})
aniline	332	0.15
	387	0.35
	424	0.40
nitrobenzene	335	0.10
	363	0.15
	386	0.25

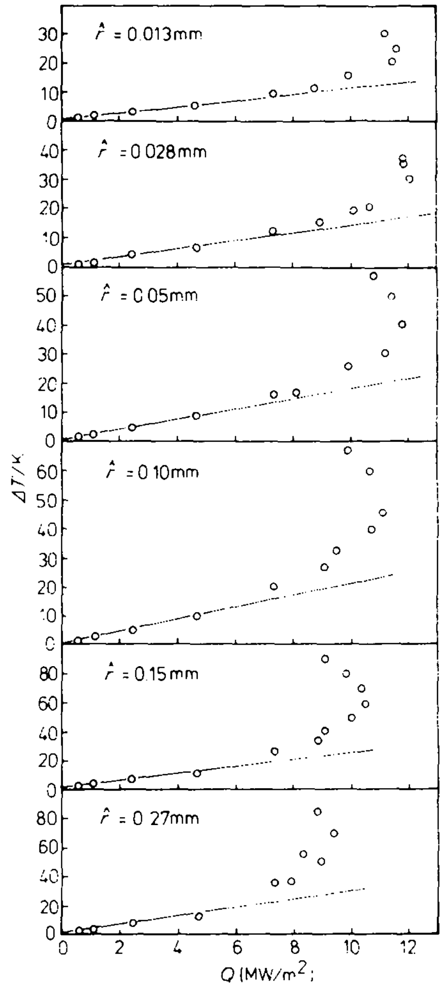

Fig. 1. Condensation of steam at atmospheric pressure, ○ data of Tanasawa and Utaka [3], dropwise condensation theory [4].

To summarize: transition data are available only for aniline and nitrobenzene, each at three vapour temperatures, and for steam at one temperature only. Apart from a tentative suggestion that 'coalescence time' might be an important factor [1, 5], no transition mechanism has been advanced. The present work was undertaken in order to throw further light on this issue by providing comprehensive data for a fourth fluid, ethanediol, using two different condensing surfaces and several vapour temperatures.

2. APPARATUS AND PROCEDURE

Referring to Fig. 2, vapour was generated in a glass boiler by three 3 kW immersion heaters connected via variable transformers. The vapour passed from the boiler into a cruciform glass chamber. One of the horizontal limbs of the chamber was closed by an electrically-heated double-glazed observation window and the other by the test plate and cooling box assembly. The condensate was returned by gravity to the boiler.

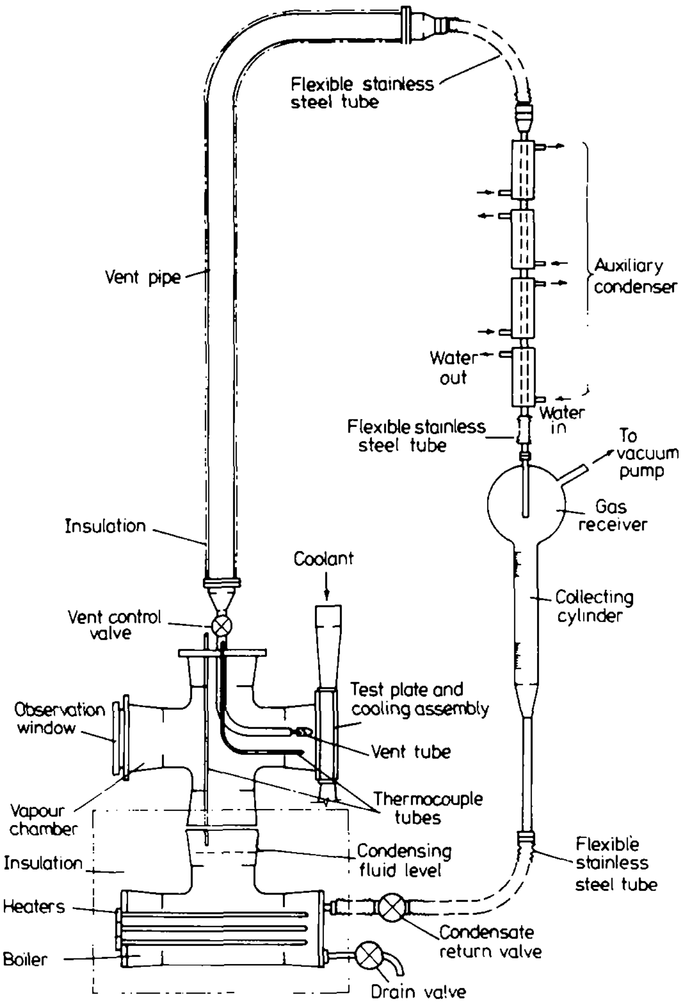

FIG. 2. Apparatus.

The test plate (Fig. 3) could be cooled by air, ethanediol and water for operation at low, medium and high cooling intensities. In order to achieve the high cooling intensities required, the rear side of the plate was finned and provision for high coolant flow rates was made using a 7.5 kW pump.

Strenuous efforts were made to ensure a good leak-tight apparatus. All joints were either welded or were flanged couplings with viton gaskets. The assembled apparatus could be pumped down to a pressure of about 0.1 torr in 15 min and the pressure rise over a 12 h interval, when isolated, was about 1 torr.

In order to eliminate the effects of traces of non-condensing gases a stainless steel vent tube was sited close to the condensing surface. During operation, the vented vapour was passed through a well-insulated stainless steel tube and into a stainless steel auxiliary condenser from which the condensate returned by gravity to the boiler. A spherical glass receiving vessel, located between the auxiliary condenser outlet and the boiler, was connected via two ice traps to a vacuum pump for removal of non-condensing gas. The venting rate could be varied by means of a valve in the vapour line between the boiler and auxiliary condenser, and observed by means of a graduated glass cylinder located between the receiving vessel and the boiler return line. A range of venting rates was established in preliminary tests (described in detail in refs. [6, 7]) for which the build-up of gas near the surface was rendered insignificant but for which the condensate was negligibly disturbed. Subsequent tests were performed using venting rates in this range.

Five butt-welded thermocouples were located in 0.4 mm diameter holes drilled horizontally at the mid-height through the plate. The junctions were at the central vertical plane and the leads were taken out to either side (along isotherms). The surface temperature and heat flux were found by 'least squares' fits to the temperature distributions. The standard error of the extrapolated surface temperature was approximately 0.1 K. Two thermocouples, made from the same reels as those used in the plate, were used to measure the vapour temperature. For the vast majority of the tests the indications of the two vapour thermocouples differed

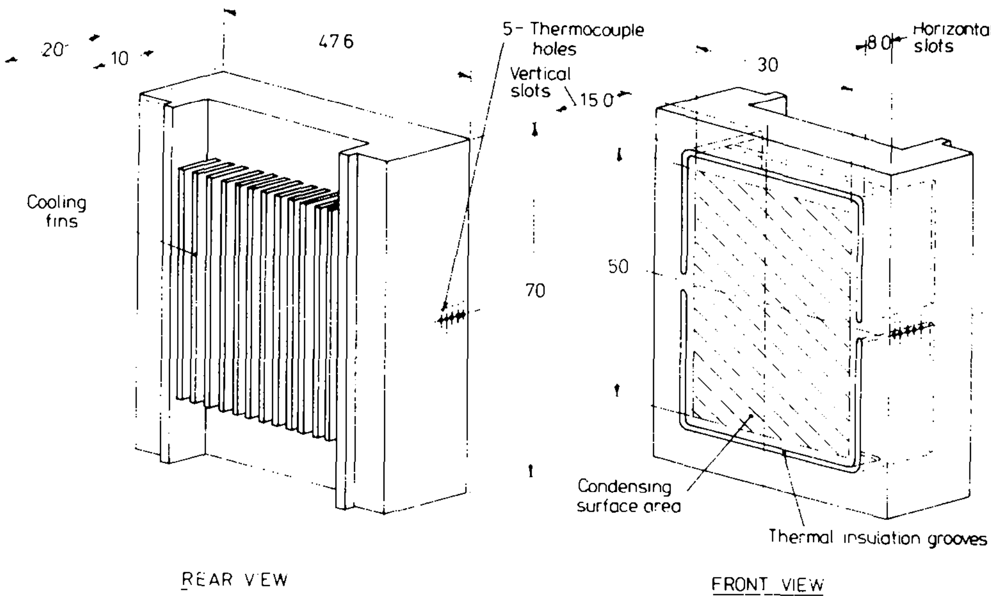

FIG. 3. Test plate.

by less than 0.1 K. The thermocouple calibration accuracy was better than 0.05 K. The vapour-to-surface temperature difference was thus determined with an accuracy of 0.1–0.2 K. The accuracy of the heat flux determination, as judged by the standard deviation on the temperature gradient, was around 3–4%. Heat flux measurements obtained from the coolant flow rate and temperature rise agreed with those from the test plate temperature distribution to within 5%.

Measurements were made both with oleic acid as promoter and with a layer of ptfe (thickness 13.4 ± 0.4 μm). In the case of oleic acid, the polished condenser surface was first cleaned with acetone and carbon tetrachloride and covered with oleic acid for about 30 min before assembling with the vapour chamber. Oleic acid was also added to the ethanediol in the boiler to give a promoter concentration of about 250 ppm. In the case of the ptfe-coated surface, pure ethanediol was used and the condensing surface was cleaned with carbon tetrachloride prior to assembly.

3. RESULTS

3.1. *Oleic acid-promoted surface*

Measurements were made at five vapour temperatures in the range 386–424 K using air, ethanediol and water as coolants. It was established earlier [6, 7] that oleic acid is unsatisfactory as a promoter for ethanediol if the surface temperature exceeds 423 K. Care was taken to ensure that this surface temperature was not reached throughout this investigation.

The results obtained are shown in Figs. 4–8. For all vapour temperatures, dropwise condensation was obtained at low and moderate cooling intensities. As the cooling intensity was increased, an abrupt transition to film condensation was observed. Only for $T_v = 386$ K were results obtained which showed evidence of impending transition.

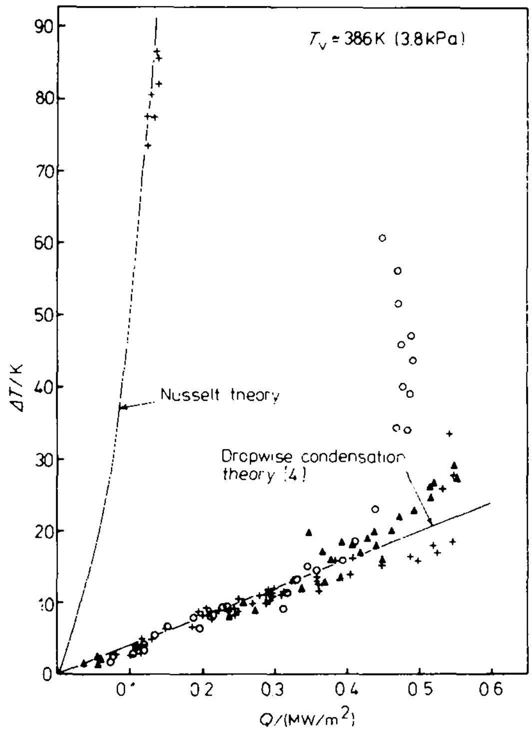

FIG. 4. Condensation of ethanediol, + present data, oleic acid-promoted copper surface, ○ present data, ptfe-coated copper surface, ▲ data of Wilmshurst and Rose [1], ptfe-coated copper surface.

At the onset of transition to film condensation the drops appeared to become rather larger and irregular in shape. Further increase in coolant flow rate led to the appearance of patches of film. With increase in coolant

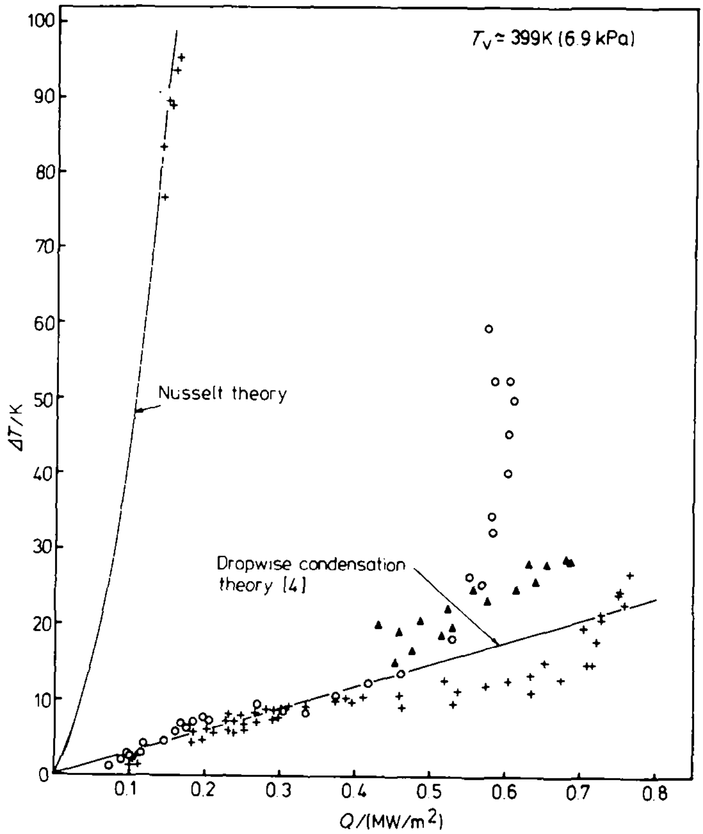

FIG. 5. Condensation of ethanediol, + present data, oleic acid-promoted copper surface, ○ present data, ptfe-coated copper surface, ▲ data of Wilmshurst and Rose [1], ptfe-coated copper surface.

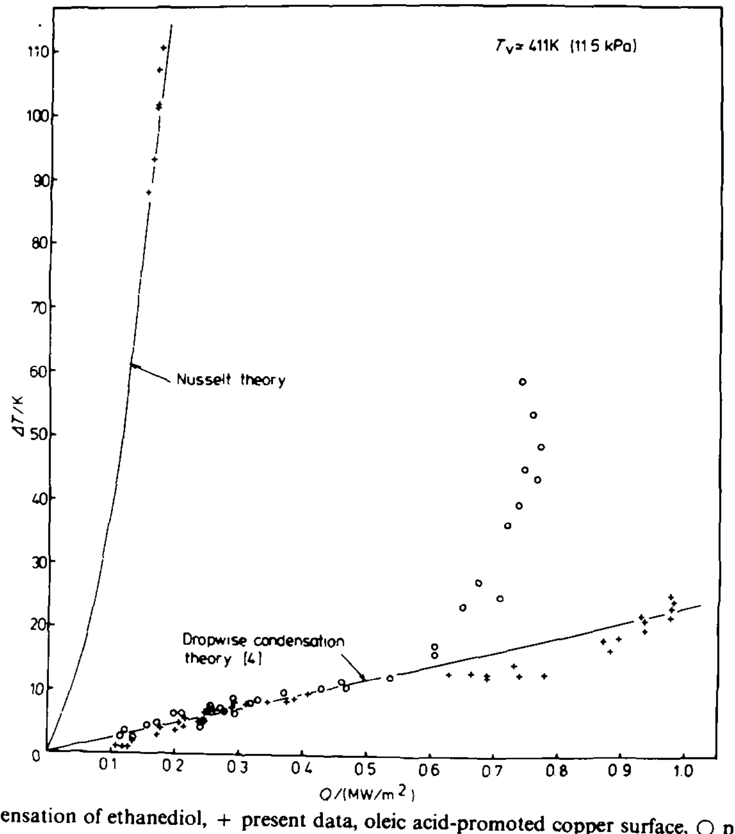

FIG. 6. Condensation of ethanediol, + present data, oleic acid-promoted copper surface, ○ present data, ptfe-coated copper surface.

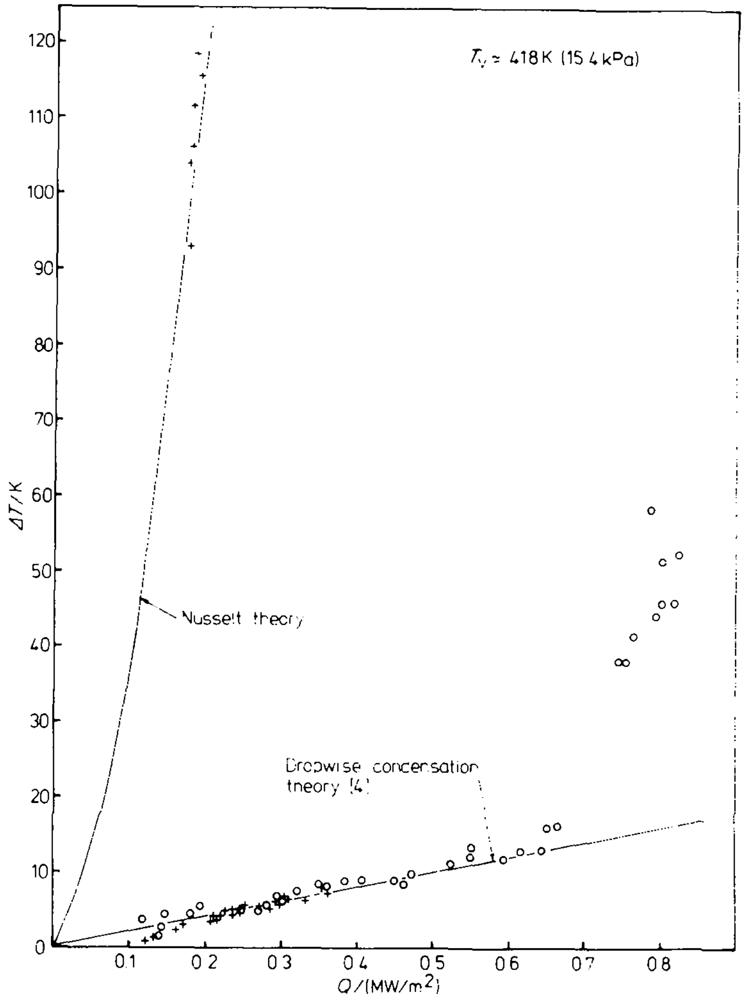

FIG. 7. Condensation of ethanediol, + present data, oleic acid-promoted copper surface, ○ present data, ptfe-coated copper surface.

flow rate the patches grew larger and new ones formed. When about one-third of the surface area was covered by film this progressed to occupy the whole surface in about 30 s without further increase in coolant flow rate. The appearance of transition at three vapour temperatures is shown in Fig. 11. When the cooling intensity was reduced (following transition to film condensation) reversion to ideal dropwise condensation occurred abruptly. The time from break-up of the condensate film to the appearance of ideal dropwise condensation was about 10 s.

It may be seen from Figs. 4–8 that the pre-transition results are in good agreement with dropwise condensation theory [4] (detailed comparisons are given in refs. [6, 7]) while the post-transition film condensation results are in good agreement with Nusselt theory.

Measurements were also made at vapour temperatures of 432 K and 440 K. At these temperatures only film condensation was obtained and the results were again in good agreement with Nusselt theory as seen in Figs. 9 and 10. Since the surface temperature was always well below 423 K it is concluded that at the higher vapour temperatures, even at the lowest cooling intensities, the prevailing conditions were appropriate to the post-transition regime.

3.2. *ptfe surface*

Measurements were made using the same vapour temperatures and coolant conditions as those for the oleic acid-promoted surface. The results are included in Figs. 4–10. As in the oleic acid case, ideal dropwise condensation was observed at low and moderate cooling intensities (when using air and ethanediol as coolants). At the higher cooling intensities (when using water as coolant), the mode of condensation progressed from dropwise to mixed condensationwith increasing coolant flow rate. It was observed that the change of mode to mixed condensation with increase in coolant flow rate was much more gradual than that found for the oleic acid-promoted surface. Complete transition to film condensation was not observed, even at the highest cooling intensity and highest vapour temperature.

At the onset of transition, the drops were observed to

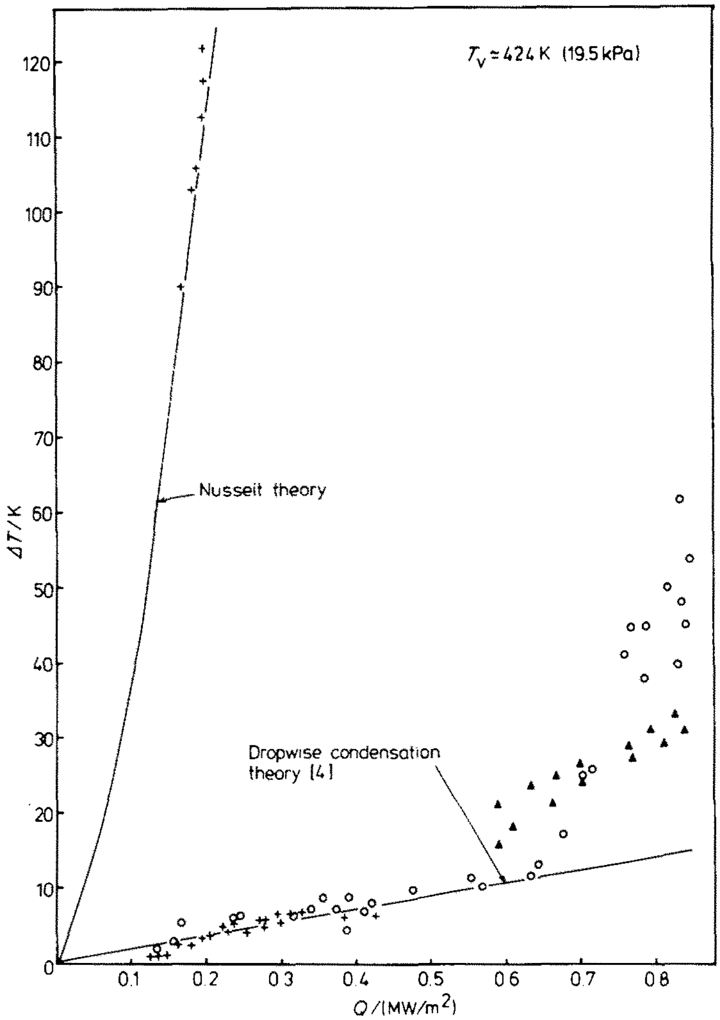

FIG. 8. Condensation of ethanediol, + present data, oleic acid-promoted copper surface, ○ present data, ptfe-coated copper surface, ▲ data of Wilmshurst and Rose [1], ptfe-coated copper surface.

become somewhat irregular in shape. Falling drops became elongated as they moved down the surface. Increase in cooling intensity led to the appearance of unstable strips of film. Further increase in cooling intensity led to spreading of these strips and to the appearance of new ones. Figure 12 shows the appearance of transition at three vapour temperatures.

It may be seen from Figs. 4–10, that for all vapour temperatures, the results are in good agreement with dropwise condensation theory at moderate and low cooling intensities. The deviation from theory at higher cooling intensities indicates a stable transition region.

4. DISCUSSION AND TRANSITION MECHANISM

Comparison of the results for the oleic acid-promoted surface and those for the ptfe indicates that the two surfaces (polished copper in the presence of oleic acid and ptfe) behave similarly in the dropwise condensation regime but significantly differently in the transition regime. Many of the earlier data [1] shown in Figs. 4, 5, 8 and 10 appear to be in the transition regime.

For the oleic acid case, the transition is very abrupt, while for ptfe there exists a stable transition range of Q and ΔT. The data of Tanasawa and Utaka [3] (Fig. 1) also show a stable transition region for condensation of steam on an oleic acid-promoted copper surface.

The differing behaviour of different surfaces in the transition regime suggests that surface properties play an important role in the mechanism of transition.

Three possible transition mechanisms may be considered:

(1) With increasing condensation rate it seems reasonable to suppose that a state of 'flooding' would eventually occur on the lower part of the condensing surface. In the present case, however, it was clear from visual observation that this was not the correct mechanism. Onset of transition was accompanied by the appearance of patches of film at apparently random locations which did not result from the running together of falling drops.

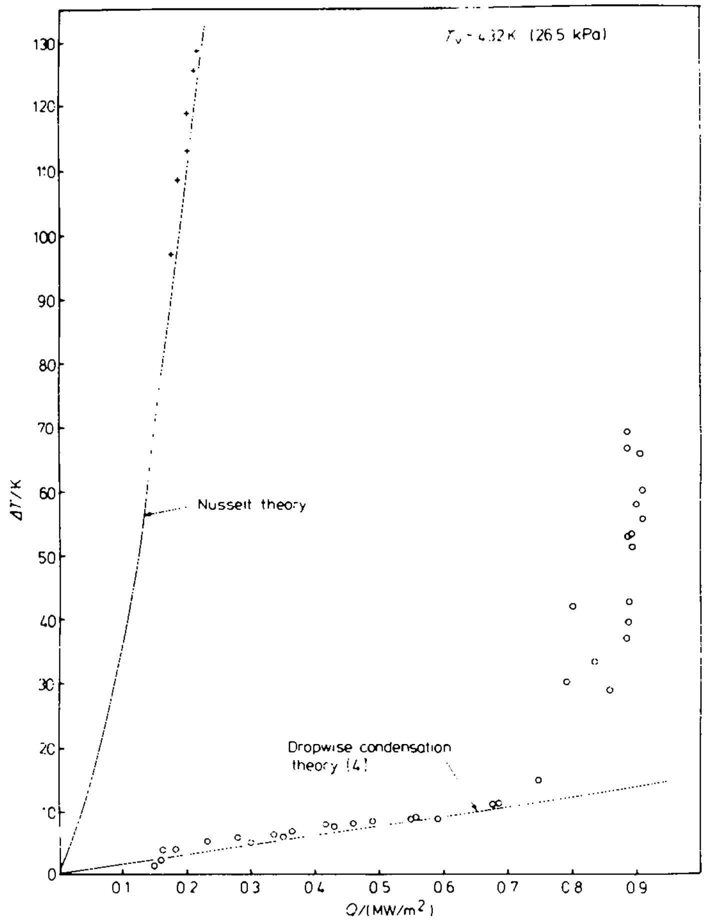

FIG. 9. Condensation of ethanediol, + present data, oleic acid-promoted copper surface, ○ present data, ptfe-coated copper surface.

(2) A second possible mechanism suggested by Rose [5] and Wilmshurst and Rose [1] is associated with the fact that coalescences do not occur instantaneously. For two drops of given size, the time required for coalescence, i.e. the time from the instant of touching to that when the coalesced drop has attained its final shape, is presumably constant, while the rate of condensation on newly-exposed (by coalescence) area increases with increasing condensation rate. Transition may thus be associated with the fact that, at a sufficiently high condensation rate, the rate at which new surface is exposed by coalescences becomes inadequate to accomodate the increasing condensation rate. Such a mechanism might be termed 'coalescence-limited transition'.

(3) A third possible mechanism may be associated with the fact that, as ΔT is increased, smaller potential nucleation sites become active (the radius of curvature of the smallest viable drop is inversely proportional to ΔT). With continued increase in ΔT a situation may be reached where, at certain locations on the surface, the sites become so close as to be effectively touching each other and so to give rise to a 'wetted' patch. With further increase in ΔT, the number and extent of the wetted regions would increase and eventually the whole surface would be covered with a liquid film. Mechanisms 2 and 3 are tentatively analysed below.

4.1. *Coalescence-limited transition*

Following Rose [5], we consider a time t_c for two drops of radius r to coalesce, and estimate, on grounds of dimensional analysis, that

$$t_c \propto r\mu/\sigma \qquad (1)$$

if viscosity effects dominate, while

$$t_c \propto (r^3\rho/\sigma)^{1/2} \qquad (2)$$

if inertia effects are controlling.

We further estimate that the growth time t_g, is inversely proportional to the mean volume condensation flux $(Q/\rho h_{fg})$ times the drop surface area at coalescence divided by the drop volume at coalescence, i.e.

$$t_g \propto r\rho h_{fg}/Q. \qquad (3)$$

For ideal dropwise condensation we must have $t_g \gg t_c$. We then anticipate that transition might occur when Q reaches a sufficiently large value, Q_t, that $t_g \approx t_c$, i.e. transition would be associated with a characteristic

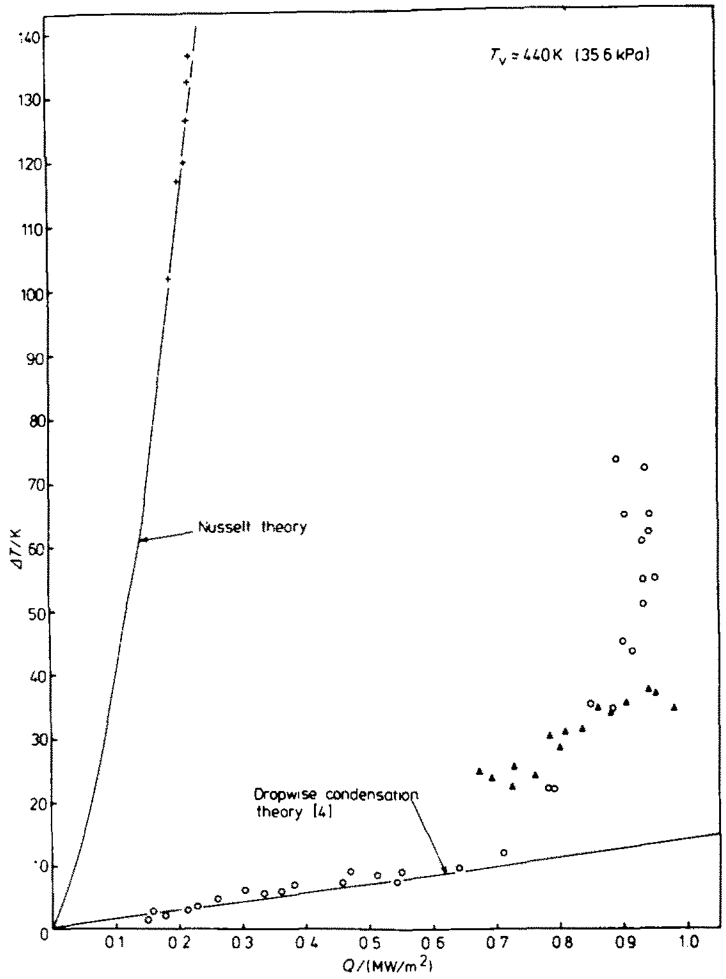

FIG. 10. Condensation of ethanediol, + present data, oleic acid-promoted copper surface, ○ present data, ptfe-coated copper surface, ▲ data of Wilmshurst and Rose [1], ptfe-coated copper surface.

value of

$$N_1 = Q_t\mu/\sigma\rho h_{fg} \tag{4}$$

if viscosity effects dominate, and

$$N_2 = Q_t(r/\rho\sigma h_{fg}^2)^{1/2} \tag{5}$$

if inertia effects are controlling. It is interesting to note that N_1 is independent of r.

Values of Q_t may be estimated (albeit imprecisely) from Figs. 1–8 and values of N_1 determined to check whether this has approximately the same value in all cases. The results are given in Table 2. The thermophysical property data and sources are given in ref. [6]. It may be seen that, for the two fluids and two condensing surfaces, the values of N_1 do not differ widely. For the case of ethanediol, the values for the ptfe and oleic acid-promoted copper surfaces show a small systematic discrepancy and the values for steam indicate systematic dependence on $\hat{r}$. The latter effect might result from inadequacy of the estimate of t_g.

When considering inertia-controlled coalescence it is necessary to decide which drop size is important in this context since N_2 involves r. Whether these be the largest or smallest drops we should not expect the relevant value of r to vary for a given surface and condensing fluid. The quantity $N_2/r^{1/2}[=(Q_t^2/\rho\sigma h_{fg}^2)^{1/2}]$ was determined [6] and found to depend strongly on vapour temperature for a given fluid and surface, and to take widely different values for steam and ethanediol. It is therefore concluded that inertia-governed coalescence is not a relevant transition mechanism.

4.2. *Nucleation site saturation transition*

As ΔT increases, the radius of curvature of the smallest viable drop ($\hat{r} = 2\sigma T_v/\rho h_{fg}\Delta T$) decreases and more nucleation sites become active. Each surface presumably has a characteristic distribution of potential sites and when, for a given surface, ΔT reaches a value such that a significant proportion of the total surface has sites separated by distances of $2\hat{r}$ or less, a significant proportion of the surface becomes wetted and departure from the ideal dropwise condensation ΔT–Q curve is observed. For a given surface, therefore, we might expect transition to be associated with a

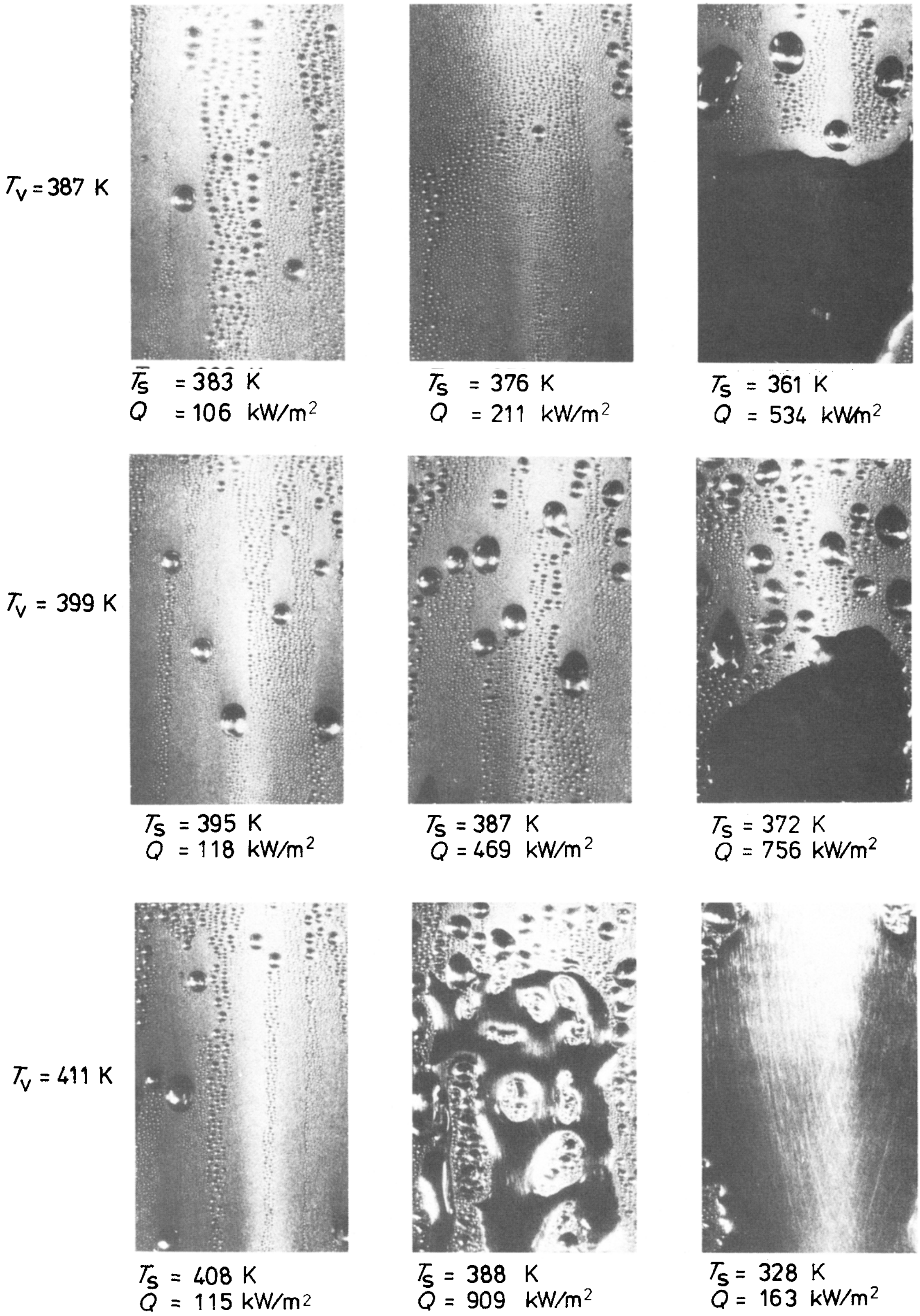

FIG. 11. Condensation of ethanediol on oleic acid-promoted copper surface.

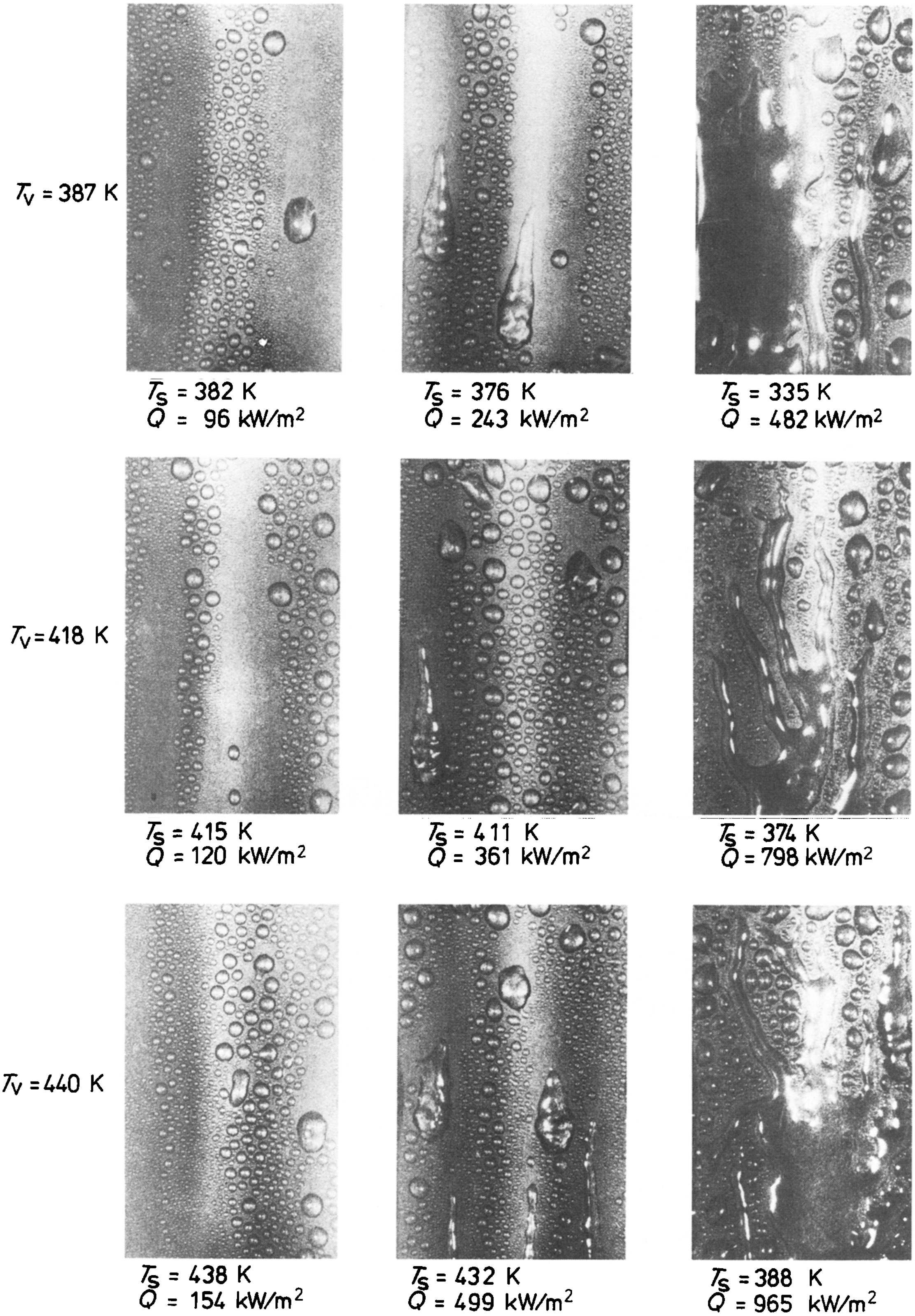

FIG. 12. Condensation of ethanediol on ptfe-coated copper surface.

Table 2. Estimated transition parameters

(a) Present data for ethanediol

Surface	T_v (K)	Q_{max} (MW m^{-2})	Q_t (MW m^{-2})	$N_t \times 10^5$	ΔT_t (K)	L (nm)
oleic acid-promoted copper	386	0.54	0.52	2.10	19	0.82
	399	>0.75	0.68	2.26	15	1.02
	411	>0.98	0.90	2.64	20	0.79
ptfe	386	0.48	0.38	1.48	15	0.99
	399	0.59	0.49	1.63	15	1.03
	411	0.76	0.55	1.62	13	1.22
	418	0.79	0.63	1.76	13	1.23
	424	0.81	0.66	1.68	13	1.26
	432	0.91	0.70	1.75	12	1.38
	440	0.94	0.72	1.65	12	1.39

(b) Based on data of Tanasawa and Utaka [3] for condensation of steam at atmospheric pressure on oleic acid-promoted copper

$\hat{r}$ (mm)	Q_{max} (MW m^{-2})	Q_t (MW m^{-2})	$N_t \times 10^5$	ΔT_t (K)	L (nm)
0.27	9.5	5.0	1.10	15	0.68
0.15	10.5	5.5	1.20	14	0.73
0.10	11.0	5.7	1.25	12	0.85
0.05	11.5	6.5	1.42	12	0.85
0.028	12.0	7.2	1.58	11	0.93
0.013	11.5	8.8	1.93	11	0.93

characteristic value of $L = \sigma T_v/\rho h_{fg}\Delta T_t$. Values of L are given in Table 2 and, as may be seen, are reasonably uniform. In particular, the values for the oleic acid-promoted copper surface found for ethanediol in the present work are very close to those for steam obtained from [3]. There is however, no obvious explanation for the evidence of possible systematic dependence of L on vapour temperature, in the present data for the ptfe surface, or on $\hat{r}$, in the results for steam [3].

The difference in heat-transfer behaviour after the transition point, between the copper and ptfe surfaces, observed in the present work, can also be explained on the basis of nucleation site saturation. If the copper surface were fairly uniformly covered with closely packed potential nucleation sites of particular size then, when ΔT reached a sufficiently high value to activate these sites, the whole surface would quickly become wetted, giving rise to abrupt transition as observed. The more gradual transition found with the ptfe surface would suggest a non-uniform distribution of potential nucleation sites, so that onset of transition would only occur at particular areas for a given value of ΔT. As ΔT was increased, smaller nucleation sites would become active and other regions, where these sites were closely packed would become wetted. In these circumstances, stable conditions are possible in the transition region and the shape of the ΔT–Q curve would depend on the nucleation site distribution for the particular surface.

5. CONCLUDING REMARKS

On the basis of the evidence currently available it would seem that the dropwise-to-filmwise transition might be explained on the basis of a viscosity-limited coalescence mechanism or a nucleation site saturation mechanism. The following criteria are tentatively suggested for the respective cases:

$$Q\mu/\sigma\rho h_{fg} > \text{about } 2 \times 10^{-5}, \tag{6}$$

$$\sigma T_v/\rho h_{fg}\Delta T < \text{about 1 nm}. \tag{7}$$

It is possible that both mechanisms are important and that transition occurs when active nucleation sites are sufficiently close to each other that primary drops, on touching their neighbours, coalesce more slowly than new drops can grow.

It is important to note that expression (7) relates to a pure vapour. In the presence of a non-condensing gas the value of ΔT appropriate for use in expression (7) is the effective temperature drop across the condensate, i.e. the vapour-to-surface temperature difference less the temperature drop across the vapour–gas boundary layer. In the presence of non-condensing gases the value of ΔT for the condensate could be obtained from the heat flux on the basis of the theoretical dropwise condensation ΔT–Q curve (see Appendix).

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APPENDIX

OUTLINE OF DROPWISE CONDENSATION THEORY [4, 8, 9]

This theory models the dropwise condensation process as a steady distribution of non-growing, non-coalescing drops. The heat-transfer rate through a single drop is calculated and the average heat flux found by integration over all drop sizes.

When ΔT is the temperature difference between the vapour and the surface of the promoter (so that the resistance of the promoter layer is not involved) the mean heat flux at the base of a drop is

$$Q_{\mathrm{b}} = \frac{\Delta T - \dfrac{2\sigma T_{\mathrm{v}}}{r\rho h_{\mathrm{fg}}} \sin \beta}{\dfrac{K_1 r}{k} + \dfrac{\phi T_{\mathrm{v}}}{\rho_{\mathrm{g}} h_{\mathrm{fg}}^2}\left(\dfrac{RT_{\mathrm{v}}}{2\pi}\right)^{1/2}\left(\dfrac{\gamma+1}{\gamma-1}\right)} \tag{A1}$$

and the distribution of drop sizes is given by

$$N(r) = \left(\frac{1}{3\pi r^2 \hat{r}}\right)\left(\frac{r}{\hat{r}}\right)^{-2/3}. \tag{A2}$$

The numerator of equation (A1) is the available vapour-to-surface temperature difference less the amount by which the vapour must be sub-cooled below its normal 'saturation' temperature in order that condensation may take place on the convex liquid surface. The denominator is an approximate representation of the combined resistances of the liquid and the vapour–liquid interface. Equation (A2) has the property that it gives zero area covered by drops greater than $\hat{r}$ and complete coverage as the radius of the smallest drop tends to zero.

The mean heat flux for the whole surface is given by

$$Q = \pi \int_{(\check{r} \sin \beta)}^{\hat{r}} Q_{\mathrm{b}} r^2 N(r)\, \mathrm{d}r \tag{A3}$$

which, with equations (A1) and (A2), leads to the required relationship between the heat flux and the vapour to surface temperature difference

$$q = \theta_0^{1/3}[(1+\theta)I(\theta^{1/3}) - (1/2)\theta^{2/3}] \tag{A4}$$

where

$$I(z) = \frac{1}{\sqrt{3}}\left[\frac{\pi}{2} - \arctan\left(\frac{2-z}{z\sqrt{3}}\right)\right] - \frac{1}{6}\ln\left[\frac{(1+z)^3}{1+z^3}\right] \tag{A5}$$

$$q = \left[\frac{\phi^2 \rho k T_{\mathrm{v}}^2 R(\gamma+1)^2}{4K_1 \pi\sigma\rho_{\mathrm{g}}^2 h_{\mathrm{fg}}^3 (\gamma-1)^2 \sin \beta}\right] Q \tag{A6}$$

$$\theta = \left[\frac{\phi\rho k (RT_{\mathrm{v}})^{1/2}(\gamma+1)}{2K_1(2\pi)^{1/2}\sigma\rho_{\mathrm{g}} h_{\mathrm{fg}}(\gamma-1)\sin \beta}\right]\Delta T \tag{A7}$$

$$\theta_0 = \frac{5\phi k g^{1/2}(\rho-\rho_{\mathrm{g}})^{1/2} T_{\mathrm{v}}^{3/2} R^{1/2}(\gamma+1)}{2K_1(2\pi)^{1/2}\rho_{\mathrm{g}} h_{\mathrm{fg}}^2 \sigma^{1/2}(\gamma-1)} \tag{A8}$$

where g is the specific force of gravity, K_1 is a constant in dropwise condensation theory [4, 7–9] with values of 2/3 and 0.427 for steam and ethanediol, respectively, and $\phi = 1/2$ for steam and 0.65 for ethanediol.

TRANSITION DE CONDENSATION EN GOUTTES ET EN FILM: MESURES DE TRANSFERT THERMIQUE POUR L'ETHANEDIOL

Résumé—On présente des mesures de différence de température entre vapeur et surface et de flux thermique pour la condensation en gouttes, ou mixte ou en film de l'éthanédiol sur une surface de cuivre traitée à l'acide oléïque et sur une surface recouverte ptfe. Des essais sont conduits à sept températures de vapeur dans le domaine 386 K (3,8 kPa), 440 K (35,6 kPa). L'air, l'éthanédiol et l'eau sont utilisés comme réfrigérants. Aux intensités de refroidissement faibles ou modérées la condensation en gouttes est observée sur les deux surfaces et les données ΔT–Q sont en bon accord avec la théorie de la condensation en gouttes. Aux intensités plus élevées, on observe la transition à une condensation mixte dans le cas de la surface ptfe. Ceci s'accompagne d'un écart avec la courbe théorique ΔT–Q et le flux thermique passe par un maximum quand l'intensité du refroidissement augmente. Dans le cas de la surface couverte d'acide oléïque, le comportement idéal de condensation en gouttes persiste jusqu'à des valeurs plus élevées de ΔT et Q avant qu'apparaisse une transition brutale vers la condensation en film. Les données de condensation en film, au delà de la transition sont en bon accord avec la théorie de Nusselt. Pour les deux surfaces le retour à la condensation en gouttes s'obtient lorsque l'intensité du refroidissement est diminuée. Deux mécanismes possibles sont suggérés pour le phénomène de transition.

DER ÜBERGANG VON TROPFEN- ZU FILMKONDENSATION: WÄRMEÜBERGANGSMESSUNGEN MIT ÄTHANDIOL

Zusammenfassung Es wird über Messungen von Temperaturdifferenz und Wärmestrom zwischen Wand und Dampf berichtet, und zwar bei Tropfen-, Misch- und Filmkondensation von Äthandiol an einer mit Oleinsäure behandelten Kupferfläche und an einer mit PTFE beschichteten Fläche. Die Versuche wurden bei sieben Dampftemperaturen (-drücken) im Bereich von 368 K ($3{,}8 \times 10^3$ Pa) bis 440 K ($35{,}6 \times 10^3$ Pa) durchgeführt. Luft, Äthandiol und Wasser wurden als Kühlmittel verwendet. Bei niedrigen und mäßigen Kühlleistungen wurde Tropfenkondensation an beiden Oberflächen beobachtet. Die Werte der Temperaturdifferenz und des Wärmestroms stimmten bei beiden Oberflächen gut untereinander und mit der Theorie der Tropfenkondensation überein. Bei stärkerer Kühlung wurde der Übergang zur Mischkondensation bei der PTFE-Oberfläche beobachtet. Dies ging einher mit einer Abweichung von der theoretischen ΔT, $\dot{Q}$-Kurve, außerdem durchlief der Wärmestrom bei zunehmender Kühlleistung ein Maximum. Bei der mit Oleinsäure behandelten Kupferoberfläche hielt die ideale Tropfenkondensation bis zu etwas höheren Werten von ΔT und $\dot{Q}$ an, ehe ein abrupter Übergang zur Filmkondensation eintrat. Die Meßwerte bei Filmkondensation und nach dem Übergang befanden sich in guter Übereinstimmung mit der Nusselt'schen Theorie. Bei beiden Oberflächen erfolgte die Rückkehr zur idealen Tropfenkondensation, wenn die Kühlleistung vermindert wurde. Zwei mögliche Mechanismen für den Übergang werden vorgeschlagen.

ПЕРЕХОД ОТ КАПЕЛЬНОЙ К ПЛЕНОЧНОЙ КОНДЕНСАЦИИ: ДАННЫЕ ПО ТЕПЛООБМЕНУ ЭТАНДИОЛА

Аннотация—Измерены перепады температур пар - поверхность и тепловые потоки при капельной, смешанной и пленочной конденсации этандиола на медной поверхности, обработанной олеиновой кислотой, а также на покрытой фторопластом-4. Опыты проводились при семи значениях температуры (давления) в диапазоне от 386 K (3,8 кн/м^2) до 440 K (35,6 кн/м^2) для теплоносителей: воздух, этандиол и вода. При низких и средних значениях интенсивности охлаждения капельная конденсация наблюдалась на обеих поверхностях, и данные по ΔT Q для них хорошо согласовались между собой и с теорией капельной конденсации. При более высоких значениях интенсивности охлаждения переход к смешанной конденсации отмечен для поверхности, покрытой фторопластом-4, где наблюдался отход полученной зависимости от теоретической кривой ΔT Q. Тепловой поток проходил через максимум при возрастании интенсивности охлаждения. На обработанной олеиновой кислотой поверхности идеальная капельная конденсация наблюдалась при несколько более высоких значениях ΔT и Q с последующим резким переходом к пленочной конденсации. Данные по пленочной конденсации в период после такого перехода хорошо согласуются с теорией Нуссельта. Для обеих поверхностей возврат к идеальной капельной конденсации происходил по мере снижения интенсивности охлаждения. Предложено два возможных механизма процесса перехода.