Int. J. Heat Mass Transfer. Vol. 21, pp. 947–953
© Pergamon Press Ltd. 1978. Printed in Great Britain

0017-9310/78/0701-0947 $02.00/0

THE ROLE OF CONTACT ANGLES AND CONTACT ANGLE HYSTERESIS IN DROPWISE CONDENSATION HEAT TRANSFER

A. W. NEUMANN, A. H. ABDELMESSIH and A. HAMEED*
Department of Mechanical Engineering, University of Toronto, Toronto, Canada

(*Received* 15 *July* 1977 *and in revised form* 30 *November* 1977)

Abstract—Data were obtained for dropwise condensation of steam on well-prepared and characterized surfaces. The results show that the heat-transfer in dropwise condensation of water vapour strongly depends on the hysteresis of the contact angle. The surface conductance increases with decreasing contact angle hysteresis and values of the heat-transfer coefficient of up to 340000 W/(m^2 K), (60000 Btu/h ft^2°F), were obtained. Detailed experimental results are presented for different surface characteristics.

NOMENCLATURE

g,	gravitational acceleration;
h,	heat-transfer coefficient;
k,	thermal conductivity;
m,	limiting mass of drop;
P_c,	condensation pressure;
q'',	heat flux;
ΔT_{VS},	temperature difference between saturated vapor and average surface temperature;
$\frac{dt}{dx}$,	temperature gradient along condenser.

Greek symbols

α,	angle of inclination of solid surface;
γ_{LV},	surface tension of liquid;
θ_a,	limiting advancing contact angle;
θ_r,	limiting receding contact angle.

1. INTRODUCTION

IT HAS been surmised by a number of authors [1–3] that the efficiency of dropwise condensation heat transfer is connected with properties of the condenser surface, or more specifically, with contact angle phenomena. A quantitative correlation of the heat-transfer flux or the heat-transfer coefficient with such quantities has, however, not been attempted. It is the purpose of this paper to make an initial step of such a development.

It is a well known experimental fact that, in dropwise condensation, most of the heat transfer occurs during the early stages of the formation and growth of a droplet [4]. It must therefore be the aim of any pretreatment of the condenser surface to cause the condensate droplet to depart as early and as quickly from the condenser surface as possible.

The departure of the drop, on the other hand, is resisted by the adhesion of the droplet to the condenser surface; this resistance has been attributed to contact angle hysteresis [5–6, 7]. A contact angle is the angle formed between a liquid meniscus and solid surface with which it intersects. As a rule, this angle is different in a situation where the liquid advances from one where it recedes. The fact that such a distinction exists, as well as the actual difference between advancing and receding contact angle is referred to as contact angle hysteresis. While contact angle hysteresis may be due to dynamic effects, it is to be noted that it also exists under static conditions: advancing a liquid meniscus and stopping it will lead to the static advancing contact angle; receding the meniscus prior to a static measurement will yield the static receding contact angle. The difference between the two contact angles, which is as a rule finite, may be termed the static contact angle hysteresis. Two of the main causes of static contact angle hysteresis are surface heterogeneity and roughness [8].

The effect of contact angle hysteresis on the departure of droplets adhering to surfaces is readily illustrated by a raindrop on a dirty window pane: an adhering water droplet will show a relatively large contact angle hysteresis, due to roughness and heterogeneity. On the other hand, a water droplet on a smooth and homogeneous paraffinic surface, such as certain plant leaves, may show very little contact angle hysteresis and the water droplet will run off readily. Thus it becomes plausible that in order to reduce the resistance to drop removal in dropwise condensation heat transfer, the heterogeneity and roughness of the condenser surface should be made as small as possible. It is also clear from the above illustration of the water drop on the plant leaf, that the contact angles should be as large as possible. Very small contact angles lead of course to filmwise condensation, a very inefficient mechanism of condensation heat transfer.

An analytical expression for the limiting size of a drop to slide on an inclined surface is given in [5]

$$mg\sin\alpha = \gamma_{LV}(\cos\theta_r - \cos\theta_a). \qquad (1)$$

Equation (1) strictly applies to a drop of cylindrical symmetry with the cylinder axis normal to the paper (Fig. 1), but it should qualitatively also describe the

---

*This paper presents, in part, the MASc. Thesis of A. Hameed, University of Toronto, Toronto, Canada (1976).

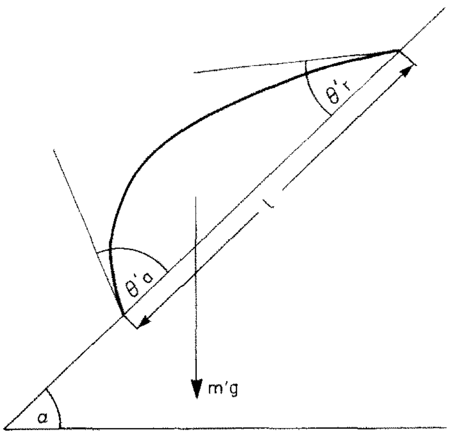

FIG. 1. Profile of drop on inclined surface; θ'_a represents an advancing contact angle and θ'_r a receding contact angle. Sliding of the drop is initiated when limiting contact angles θ_a and θ_r are reached while the angle of inclination α is increased, at constant mass of the drop m'. Alternatively, at constant inclination, the drop may grow, accompanied by changes in θ'_a and θ'_r until it reaches a critical mass m, at which the contact angles assume their critical values θ_a and θ_r, and sliding starts.

behaviour of real droplets on inclined surfaces. Obviously, the limiting mass m for drop removal will decrease with decreasing contact angle hysteresis.

It will be our aim in this paper to prepare smooth and homogeneous condenser surfaces in order to reduce contact angle hysteresis, and to study the effect of varying contact angle hysteresis on the efficiency of dropwise condensation heat transfer.

2. EXPERIMENTAL APPARATUS

The heat-transfer apparatus used in this investigation was described elsewhere [9]. However, the preparation of the condenser surface, the contact angle measurement and the temperature measurement need to be described here.

2.1. *Condenser surface polishing*

In order to reduce contact angle hysteresis due to roughness, the condenser surfaces were polished. Four of the five condensers used (S1–S4) were of the best available quality copper, OFHC (Oxide Free High Conductivity) to facilitate optimun results in polishing. The fifth condenser (S5) was made of 99.9% pure commercial copper. Fig. 2 shows the details of a typical condenser and the locations of thermocouples. The condensers were polished in the following stages:

(a) *Grinding*. After fabrication, the condensing face of the condenser was ground carefully using different grit sizes from 200 to 600.

(b) *Polishing*. The condensers were cleaned thoroughly with water in order to remove all coarse grains of polishing compound, and then polished on a high speed polishing wheel. A fine grade of AP-alumina polishing compound was used with demineralized water. This process removed the big scratches left from grinding and made the surface highly reflective.

(c) *Fine polishing*. The condensers were rinsed repeatedly in water and alcohol and dried in a current of hot air. For the fine polishing "Lindsay B, 0.05 μ" was used on a polishing cloth "Mentron B"; a slowly rotating polishing wheel was used. The resulting surface had a mirror finish: under the light microscope at magnifications of approximately 1000×, only a few minor scratches were visible.

After fine polishing the condenser surface was rinsed and cleaned sequentially in doubly distilled water, methanol, acetone and benzene. To remove any possible traces of organic material, the condensers were finally treated in a radio frequency glow discharge apparatus.

2.2. *Deposition of gold film and promoter monolayer*

In order to avoid oxidation of the condenser surface, which might make it heterogeneous, a thin and uniform layer of gold was coated onto the condenser surface by a vacuum vapor deposition technique [8]. Since gold may be relatively hydrophilic, layers of promoter were deposited on top of the gold films. Two types of promoter materials were used, palmitic and stearic acid. Adsorption of the promoter from solution onto the gold film as well as melt retraction [10,11] were examined, but vacuum vapour deposition was found to yield the best results, as judged from contact angle measurements. After vapour deposition the excess (not

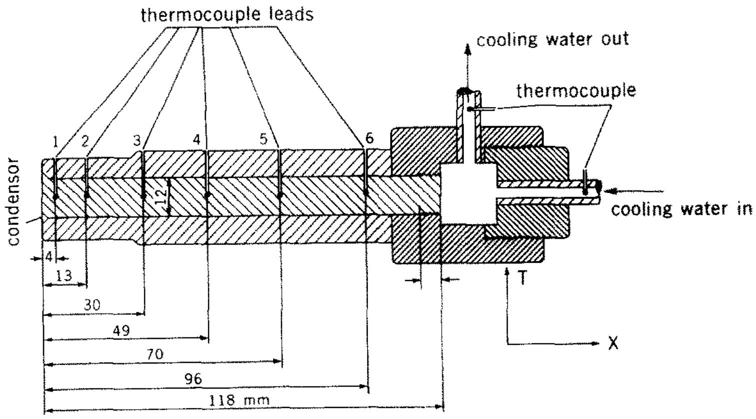

FIG. 2. Details of the condenser.

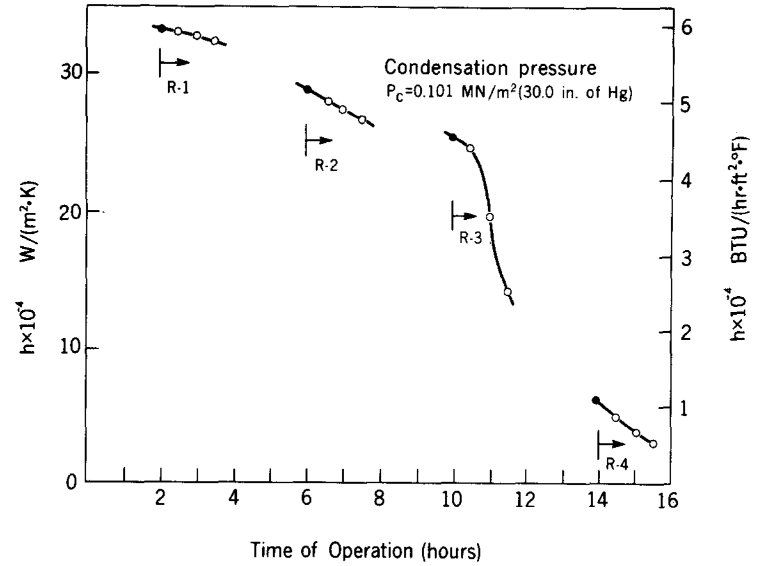

FIG. 3. Heat-transfer coefficient as a function of time of condenser operation.

chemisorbed) promoter was dissolved and rinsed off with benzene, leaving a relatively homogeneous, tightly bound monomolecular layer of the promoter on the condenser surface.

2.3. *Contact angle measurements*

Contact angle measurements were performed on the condenser surfaces repeatedly after the application of the promoter layer: the first measurement was performed prior to introducing the condenser into the heat transfer apparatus for the first run, and also before each subsequent run. Advancing and receding contact angles were measured using the conventional sessile drop technique [12]. Direct measurement of advancing and receding contact angles by means of a telescope with goniometer eye-piece were performed; triply distilled water was used in these measurements.

2.4. *Temperature measurements*

Chromel–alumel thermocouples were mounted into the thermocouple wells of an OFHC unpolished condenser (Fig. 2) and calibrated. The resulting distribution curves (temperature vs thermocouple distance from the condenser surface) were found to be straight lines. This justified the use of the one-dimensional steady conduction equation for the evaluation of the heat flux q'' and the average surface temperature.

It was found in preliminary measurements that the surface quality of the condensers decreased after several hours of operation while the efficiency of the heat transfer process decreased. Therefore relatively short runs, of approximately 2 h duration were performed. During each of these runs 15–20 temperature readings at 5 min intervals were performed. Before and between runs, contact angle measurements were performed, to facilitate a correlation between contact angle hysteresis and heat transfer. Four runs (R1–R4) were normally performed with each specimen.

The temperature data obtained during each run were used to plot the temperature distribution curves; these curves were straight lines in all cases, justifying the use of the one-dimensional conduction equation, as explained above. The condenser surface temperature was found by extrapolation of the straight line up to the surface, while the temperature gradient was obtained as the slope of the temperature distribution line.

Using this information the heat flux density q'' and the heat-transfer coefficient h were evaluated from the equation

$$q'' = -k\frac{\mathrm{d}T}{\mathrm{d}x} \tag{2}$$

$$h = \frac{q''}{\Delta T_{vs}}. \tag{3}$$

Thus there are in our experiment two primary independent heat-transfer quantities, which are being determined: $\mathrm{d}T/\mathrm{d}x$ [or q'', through equation (2)] and the steam/surface temperature difference ΔT_{vs}; the heat-transfer coefficient h is only a derived, secondary quantity.

3. RESULTS AND DISCUSSION

It was found that after a few hours of operation the heat flux density started to decrease considerably. We expected that this decrease would be caused by a deterioration of the condenser surface, which in turn would cause an increase in contact angle hysteresis. For this reason, each run was terminated after 2 h, the condenser was removed, and contact angle measurements were performed on the condenser surface and photomicrographs were taken. The condenser was then installed again in the heat-transfer apparatus and a second run (R2) was performed for 2 h, and so on. Three or four runs were performed with each of the condensers. Figure 3 shows the plot of the heat-transfer coefficient h as a function of the operating time t for the condenser (S1); the condenser surface was coated with palmitic acid. The plot given in Fig. 3 is quite typical for the other four condensers as well.

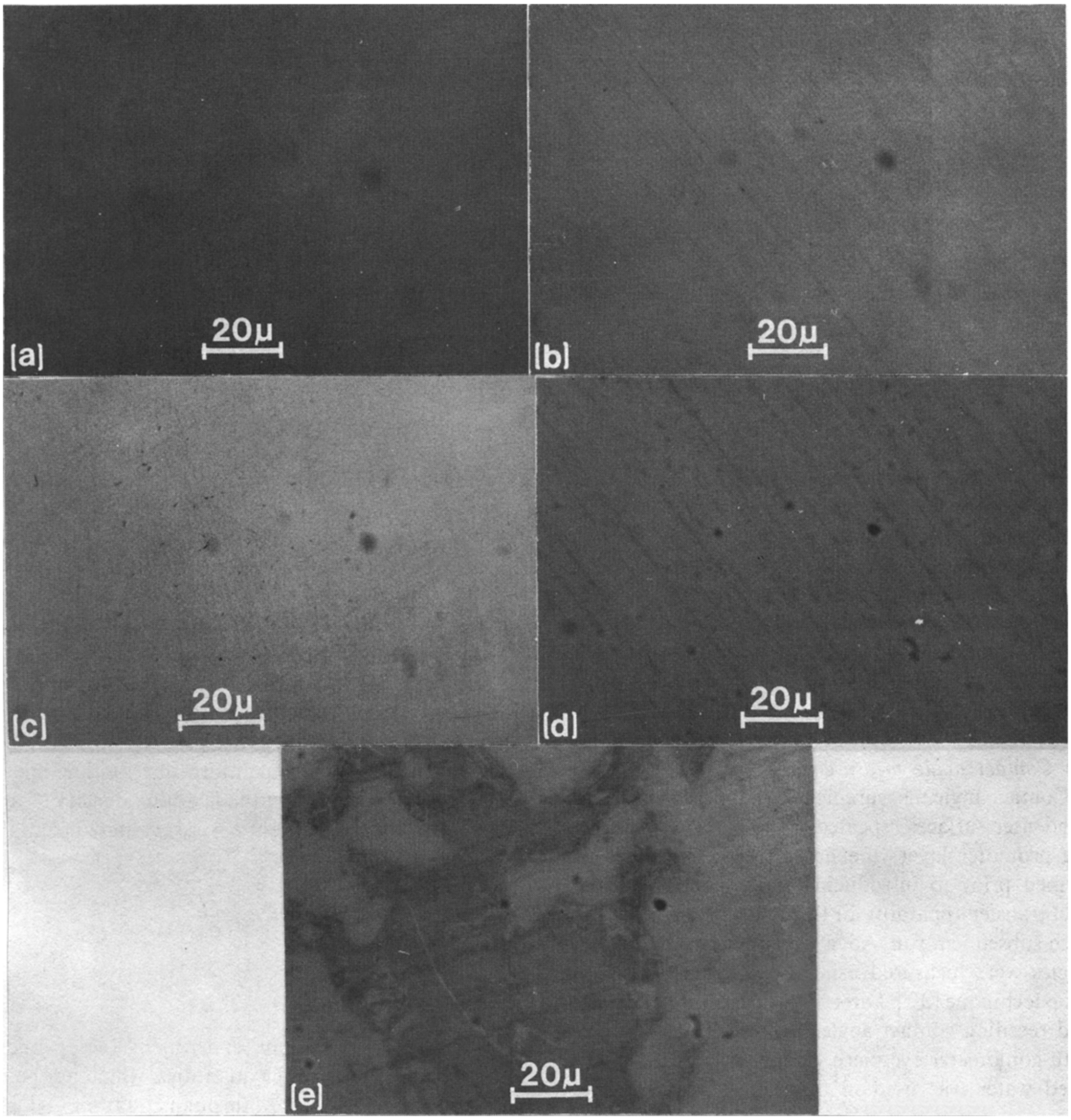

FIG. 4. Photomicrographs of condenser used in Fig. 3. a; before first run (R1); b; before second run (R2); c; before third run (R3); d; before fourth run (R4); e; after fourth run.

Figure 4 shows for the same condenser S1 a sequence of photomicrographs taken, in order, before the first run and after each of the four runs. These photomicrographs clearly illustrate how the condenser surface deteriorates with operating time. It is interesting to note that this deterioration of the condenser surface, minor on a macroscopic scale, reduces the heat-transfer coefficient by almost an order of magnitude. Equation (1) suggests that the size of the drops required before drop removal occurs increases with increasing contact angle hysteresis, i.e. with increasing $(\cos\theta_r - \cos\theta_a)$. Therefore the first heat-transfer measurement performed in each run (the solid symbol in Fig. 3) is plotted against the contact angle hysteresis measured on the condenser surface prior to inserting the condenser into the heat-transfer apparatus for that run. Since the heat flux density q'' and the temperature difference ΔT_{vs} between the condenser surface and the saturated steam are the primary heat-transfer quantities, they (rather than the heat-transfer coefficient h) are plotted first in Figs. 5 and 6, for the condensers S3–5. The curves for S3 and S4 are almost identical: for both, the coating is palmitic acid, whereas the surface of the condenser S5 is coated with stearic acid. The main difference between the two coatings is that the advancing contact angle measured with distilled water is 101° on palmitic acid and 87° on stearic acid. It is to be noted that these advancing contact angles remained virtually constant through all four runs, whereas the receding contact angles decreased continuously. Figure 5 shows, as expected, that the heat flux q'' is larger for high advancing contact angles (S3 and S4) than for low contact angles (S5). In all cases, however, q'' decreases with increasing contact angle hysteresis, as expected. The vapor to surface temperature difference ΔT_{vs} in Fig. 6 shows a somewhat similar behaviour, in that it becomes quite large at large values of the contact angle hysteresis. On the

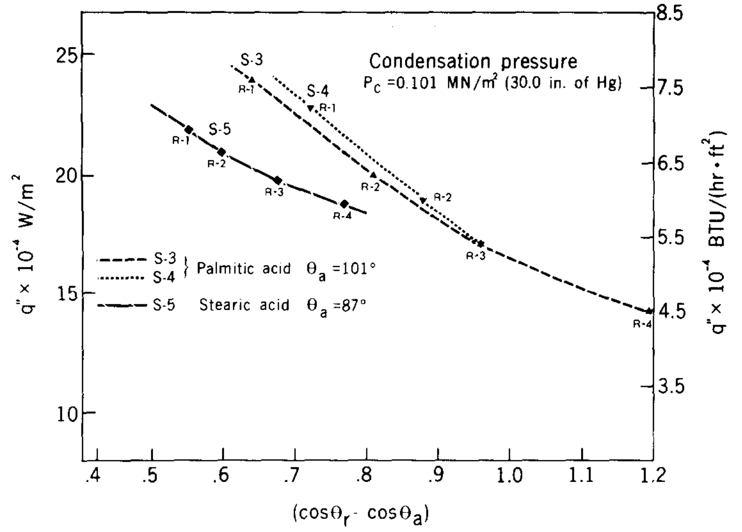

FIG. 5. Heat flux q'' as a function of contact angle hysteresis for promoter coatings with different advancing contact angles θ_a.

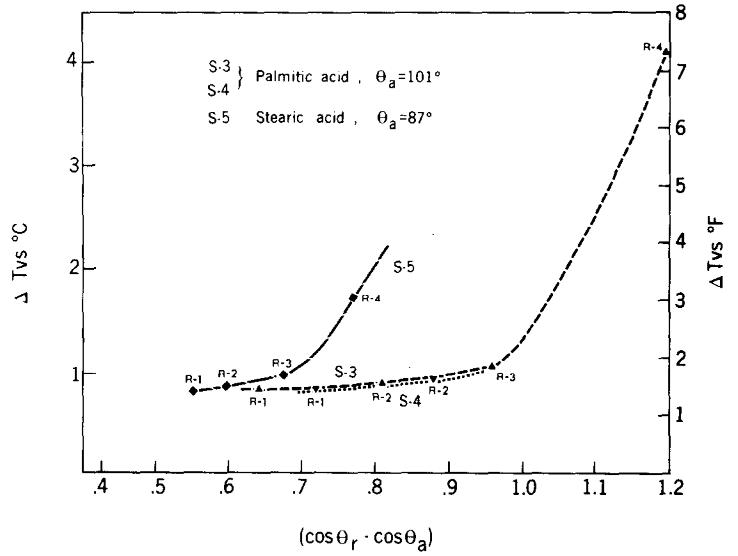

FIG. 6. Vapour to surface temperature difference ΔT_{vs} as a function of contact angle hysteresis for the systems shown in Fig. 5.

other hand, there does not seem to be a large difference between the condensers with larger and smaller values of the advancing contact angles, respectively, at the smallest values of the contact angle hysteresis. The only difference is apparently the fact that at lower values of the advancing contact angle, the drastic increase in ΔT_{vs} starts at lower values of $(\cos\theta_r - \cos\theta_a)$ than for larger advancing contact angles.

Figure 7 represents the heat-transfer coefficient h as a function of contact angle hysteresis for the same three systems shown in Figs. 5 and 6. Since these curves were calculated from the corresponding curves in Figs. 5 and 6 by means of equation (3) no additional physical insight can be expected.

It is well known [3, 13, 14] that non-condensible gases accumulate near the condensing surface, reducing the efficiency of the heat-transfer process. To reduce this effect, a venting ring with small holes on its circumference was placed near the condensing surface and connected to an outside moderate vacuum. This venting process was continuously in operation in all tests.

The apparatus used here has been used previously for similar heat-transfer studies [15, 16], the main difference being a lower quality condenser surface in the earlier work. Originally, with a copper surface with no special treatment, a heat-transfer coefficient of 68 000 W/(m² K), [12 000 Btu/(h ft² °F)], was obtained, and with a hydrophobic promoter which did not chemisorb on the metal and hence wash off relatively easily [3] a maximum value of h = 170 000 W/(m² K), [30 000 Btu/(h ft² °F)] was

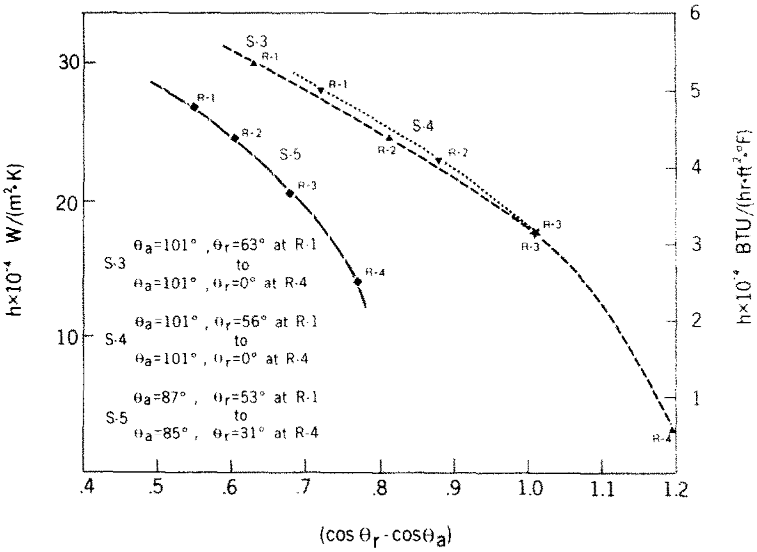

FIG. 7. Heat-transfer coefficient *h* as a function of contact angle hysteresis for the systems shown in Figs. 5 and 6.

observed. The value of almost 340 000 W/(m² K), [60000 Btu/(h ft² °F)], in this paper illustrates the importance of the preparation of the condenser surface.

CONCLUSIONS

Dropwise condensation heat transfer depends strongly on surface properties and surface phenomena, specifically on contact angle phenomena. The heat-transfer flux and the heat-transfer coefficient increase with the decrease in contact angle hysteresis, as expected from considerations of surface thermodynamics. On the basis of measurements with a single condenser with a different promoter, it appears that the efficiency of dropwise condensation heat transfer increases with increasing advancing contact angle.

Acknowledgement—The authors wish to acknowledge the financial support provided by the National Research Council of Canada through grants No. A4172 and A8278.

REFERENCES

1. B. T. Nijaguna, Precoalescence droplet growth in dropwise condensation, Ph.D. Thesis, University of Toronto (1970).
2. C. Graham and P. Griffith, Drop size distribution and heat transfer in dropwise condensation, *Int. J. Heat Mass Transfer* **16**, 337–346 (1973).
3. A. H. Abdelmessih, A. W. Neumann and S. W. Yang, The effect of surface characteristics on dropwise condensation, *Lett. Heat Mass Transfer* **2**, 285–292 (1975).
4. P. Griffith, *Handbook of Heat Transfer*, edited by W. M. Rohsenon and J. P. Hartnett, pp. 12–34. McGraw-Hill, New York (1972).
5. R. E. Johnson, Jr. and R. H. Dettre, Wettability and contact angles, in *Surface Coll. Sci.* Vol. 2, edited by E. Matijévic, pp. 85–153. Wiley, New York (1969).
6. A. M. Schwartz, C. A. Rader and E. Huey, Contact angle wettability and adhesion: resistance to flow in capillary systems of positive contact angles, *Adv. Chem. Ser.* **43**, 250–267 (1964).
7. C. G. L. Furmidge, Studies at phase interfaces: 1—The sliding of liquid drops on solid surfaces and a theory for spray retention, *J. Colloid Sci.* **17**, 309–324 (1962).
8. A. W. Neumann, Contact angles and their temperature dependence: thermodynamic status: measurement, interpretation and application, *Adv. Colloid Interface Sci.* **4**, 105–191 (1974).
9. A. H. Abdelmessih and B. T. Nijaguna, Surface temperature in dropwise condensation, in *Proceedings of the Heat Transfer and Fluid Mechanics Institute*, Monterey, California, pp. 74–87 (1970).
10. E. G. Shafrin and J. Zisman, Hydrophobic monolayers absorbed from aqeous solutions, *J. Colloid Sci.* **4**, 571–590 (1949).
11. H. R. Baker, E. G. Shafrin and W. A. Zisman, The adsorption of hydrophobic monolayers of carbonylic acids, *J. Phys. Chem.* **56**, 405–412 (1952).
12. A. W. Adamson, *Physical Chemistry of Surfaces*, 3rd edn., p. 343, New York (1976).
13. D. W. Tanner, C. J. Potter, D. Pope and D. West, Heat transfer in dropwise condensation—Part 1: The effects of heat flux, steam velocity and non-condensible gas concentration, *Int. J. Heat Mass Transfer* **8**, 419–426 (1965).
14. J. L. McCormick and J. W. Westwater, Drop dynamics and heat transfer during dropwise condensation of water vapor on a horizontal surface, *Chem. Engng. Prog. Symp. Ser.* **62**, 120–134 (1966).
15. B. T. Nijaguna and A. H. Abdelmessih, Precoalescence drop growth model for dropwise condensation: influence of condensing surface properties on precoalescence drop growth, ASME Paper No. 71-WA/HT-47 (1971).
16. P. Michalek, The effect of the substrate material thermal properties on the transfer of heat in dropwise condensation, M. Eng. Thesis, University of Toronto (1971).

LE ROLE DES ANGLES DE CONTACT ET DE L'HYSTERESIS DE L'ANGLE DE CONTACT DANS LE TRANSFERT THERMIQUE LORS DE LA CONDENSATION EN GOUTTES

Résumé—On obtient des résultats pour la condensation en gouttes de la vapeur d'eau sur des surfaces bien préparées et caractérisées. Ils montrent que le transfert thermique dépend fortement de l'hystérésis de l'angle de contact. La conductance surfacique croît quand diminue l'hystérésis de l'angle de contact et on obtient des coefficients de transfert allant jusqu'à 340 000 W/(m^2 K). On présente des résultats détaillés pour différentes caractéristiques de surface.

DER EINFLUSS DES RANDWINKELS UND DER RANDWINKELHYSTERESIS BEIM WÄRMEÜBERGANG DURCH TROPFENKONDENSATION

Zusammenfassung—Es wurden Meßwerte für Tropfenkondensation an besonders vorbereiteten Oberflächen gewonnen. Die Ergebnisse zeigen, daß der Wärmeübergang bei der Tropfenkondensation von Wasserdampf stark von der Hysteresis des Randwinkels abhängt. Die Leitfähigkeit der Oberfläche nimmt mit abnehmender Kontaktwinkelhysteresis zu. Es traten Wärmeübergangskoeffizienten bis 340 000 W/m^2 K auf. Für verschiedene Oberflächeneigenschaften werden ausführliche experimentelle Ergebnisse angegeben.

РОЛЬ УГЛОВ СМАЧИВАНИЯ И ИХ ГИСТЕРЕЗИСА В ТЕПЛООБМЕНЕ ПРИ КАПЕЛЬНОЙ КОНДЕНСАЦИИ

Аннотация — Получены данные по капельной конденсации пара на тщательно обработанных поверхностях с известными характеристиками. Результаты показывают, что гистерезис контактного угла оказывает сильное влияние на перенос тепла при капельной конденсации водяного пара. Проводимость поверхности увеличивается с уменьшением гистерезиса контактных углов. Получены значения коэффициента теплообмена до 340 000 Вт/(м^2.К). Приводятся подробные экспериментальные результаты для поверхностей с различными характеристиками.