

THE INFLUENCE OF CONDENSATE DROP SIZE ON THE DROPWISE FILMWISE TRANSITION FOR PURE VAPORS*

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Introduction

Condensation of vapors may take place in two distinct ways such that either a liquid film results or a series of droplets occurs on the solid surface. The distinction is important in engineering practice since the latter mode produces higher heat transfer coefficients by as much as 8–10 fold over that produced by the filmwise mechanism. For filmwise conditions to be established the contact angle must lie between zero and 90° where the forces of adhesion between the solid and liquid are higher than the liquid force of cohesion, whilst above this value dropwise condensation will result. Topper and Baer⁷⁾ have reported that increased heat transfer may be achieved by coating copper tubes with polytetrafluoroethylene when condensing ethylene glycol, nitrobenzene, water and aniline. For these systems dropwise condensation has been observed. Here the effect of the increase in thermal resistance due to the low conductivity of the polytetrafluoroethylene is outweighed because of the transition from the filmwise to the dropwise process.

However using carbon tetrachloride and methanol much lower heat transfer coefficients have been reported by Mizushina *et al.*⁵⁾ as only filmwise condensation results. Davies and Ponter¹⁾ showed that the mechanism of condensation could be predicted from the surface properties of the solid and liquid phases and later Davies *et al.*²⁾ measured contact angles for condensing benzene, carbon tetrachloride and aniline on a polytetrafluoroethylene surface at atmospheric and reduced pressures. The data confirmed that dropwise condensation occurred only for the aniline system where the contact angle reached 90 degrees at approximately 70 torr.

The droplets employed in the experiments were large since in all cases the equilibrium drop height was achieved, so that the addition of a further volume of liquid did not give an increase in drop height but the liquid drop spread to a new position. Under

normal conditions of condensation however the drop size are much smaller, and to assess the effect of drop size on the contact angle an investigation was carried out, which is now described, where both water and benzene were condensed on copper and polytetrafluoroethylene surfaces, for a range of pressures of up to one atmosphere.

Experimental

The apparatus shown in Fig. 1 consisted essentially of a 1-liter flask, an observation cell, and a cold finger condenser. The flask was fitted with a thermometer pocket and a condensate return line, and was heated with a 450-watt Isomantle. The observation cell (15 cm \times 10 cm o.d.) comprised two sections, the lower section being fitted with two optical flats situated on opposite sides of the cell. The copper or polytetrafluoroethylene plate was supported by the glass structure above the central vapor line from the flask. The upper section was fitted with a thermometer pocket, a vapor exit line to the condenser, and a hollow rubber plug to allow the introduction of a sessile drop via a hypodermic needle. The cell sections were fitted with electrical heaters and lagged with asbestos to minimize heat losses.

The specimen surface was carefully prepared by polishing, degreasing, and finally washing in the fluid under test, before introduced to the cell. Care

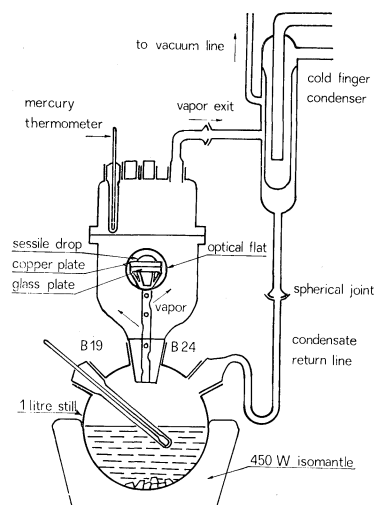


Fig. 1 Contact angle cell

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was taken to ensure that the plate was horizontal. To achieve this, the vertical cross wire in the travelling microscope was aligned against a thin plumb line. The goniometer eyepiece was then rotated through 90° and the specimen plate adjusted until its surface lay parallel to the new position of the cross wire. Variations of plate inclination of up to $1/2$ degree to the horizontal did not affect the value of contact angle obtained. A period of 3 hours was then allowed for the system to come to equilibrium, after which time a liquid sample of known volume was taken from the flask through the thermometer pocket via a hypodermic needle and introduced to form a sessile drop on the surface.

The drop was allowed to come to equilibrium with its vapor, and the contact angle was measured by observation through a traveling microscope fitted with a goniometer eyepiece. The above procedure was repeated 5 times for one particular liquid composition and the average value taken. The value were reproducible to $\pm 1\%$. For the low pressure experiments the apparatus was modified to prevent any contaminants from the vacuum pump reaching the cell by placing a cold-temperature trap in the inter-connecting line.

Results

It was found that benzene completely wetted the copper surface for the whole pressure range considered, that is from 72–760 torr. Plots of contact angle versus drop diameter for the other three systems were recorded and are presented in Figs. 2–4. A plot is also included of contact angle versus pressure for water drops which have attained their equilibrium drop height on both copper and polytetrafluoroethylene surfaces (Fig. 5).

Discussion

For water condensing on a polytetrafluoroethylene surface at one atmosphere pressure it is observed that for all drop diameters the contact angle is greater than 90° so that dropwise condensation will always result on this surface. Similarly for benzene on a polytetrafluoroethylene surface, the contact angle values will always be less than 90° for the pressure range considered and filmwise condensation will always occur. However for the water-copper system it would appear that at one atmosphere pressure filmwise condensation should result if the angle value for a large drop was taken as seen in Fig. 5. However it is well substantiated that dropwise condensation always results under these conditions. From Fig. 2 this implies that the drop diameter was below 0.5 mm and it has been shown^{3,4,6} that much smaller drop diameters occur under actual conditions.

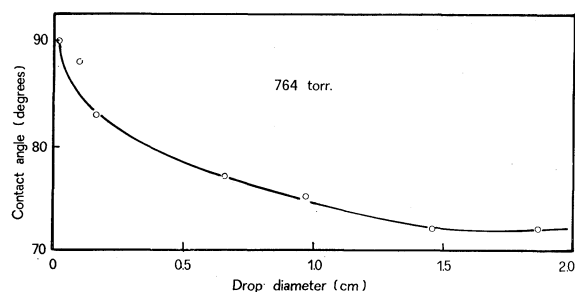


Fig. 2 Contact angles for water on a copper surface at atmospheric pressure under condensation conditions

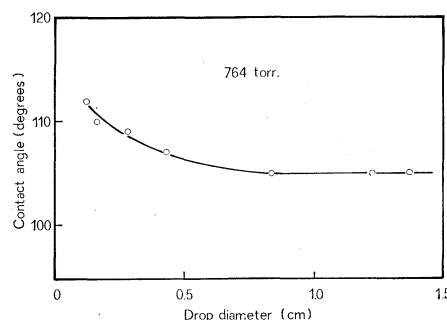


Fig. 3 Contact angles for water on a polytetrafluoroethylene surface at atmospheric pressure under condensation conditions

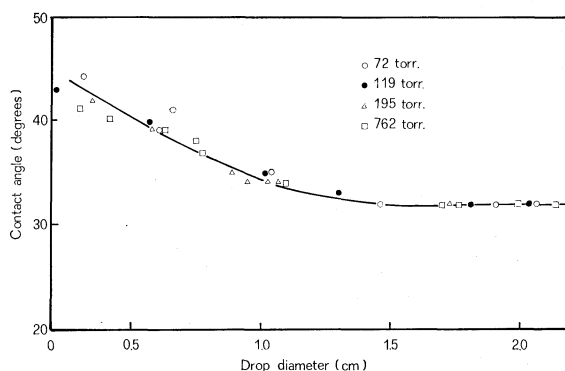


Fig. 4 Contact angles for benzene on a polytetrafluoroethylene surface for a pressure range 72–760 torr

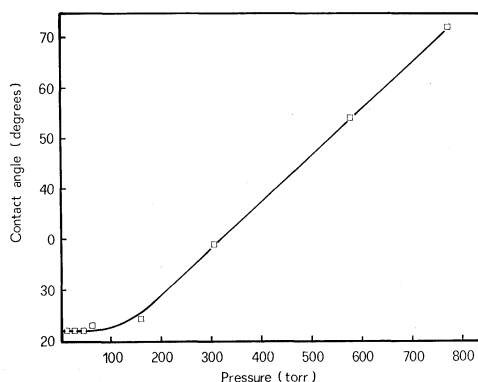


Fig. 5 Contact angles for water drops exhibiting maximum height on both copper and polytetrafluoroethylene surfaces for a pressure range 10–760 torr

Conclusions

It has been demonstrated when certain pure vapors condense on a surface that if the contact angle between the liquid and the solid lies close to 90° then the mode of condensation will depend upon the size of the drops residing on the surface. This has important implications, where the nucleation of droplets from the gas phase can be controlled, to heat transfer enhancement.

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EXPERIMENTAL STUDY OF OPERATING LIMITS OF FALLING FILM COLUMN IN VACUUM DISTILLATION*

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In the previous paper⁵⁾, it was predicted for vacuum distillation that the vapor flow rate in falling film columns is restricted within a range enclosed by the following four limits. The upper limit varies with the operating pressure. At higher pressure the flooding is controlling, but as the operating pressure is reduced either the sonic velocity at the top of the column (sonic velocity limit, SVL) or a desirable absolute pressure at the top of the column (top pressure limit, TPL) becomes controlling. On the basis that the reflux should wet the entire surface of the wall, the lower limit is introduced and determined by the minimum wetting rate (MWR).

In this paper, an experimental verification of these limits has been attempted except for the flooding limit, which could not be examined due to the insufficient vaporizing capacity of the present still.

Experimental

Since details of the experimental apparatus and procedure have been described elsewhere⁵⁾, only an outline is given here. The apparatus used was made of glass. Its rectifying section consisted of a falling film column, 2.2 cm i.d. and 143 cm long, insulated by a silvered vacuum jacket.

The three binary mixtures used were ethyl oxalate ($C_6H_{10}O_4$, E.O.)—methyl salicylate ($C_8H_8O_3$, M.S.) for

relatively low-vacuum conditions, and methyl palmitate ($C_{17}H_{34}O_2$, M.P.)—di-*n*-butyl phthalate ($C_{16}H_{22}O_4$, D.B.P.) and D.B.P.—di-*n*-butyl sebacate ($C_{18}H_{34}O_4$, D.B.S.) for higher vacuum. The properties of the materials also have been described elsewhere⁶⁾.

Experimental Range and Data of Pressure Drop

Table 1 shows the experimental range. Since the maximum value of the Knudsen number at the top of the column Kn_2 is 4.75×10^{-3} , i.e. less than 10^{-2} , the vapor phase is in a continuum flow region. The Reynolds numbers of vapor and liquid, Re_G and Re_L , respectively, are less than 2627 and 13.8, and so both flows are laminar. The maximum value of the isothermal Mach number at the top of the column Ma_2 is nearly unity.

In vacuum distillation, generally, the upper limit of the bottom pressure p_1 will be decided from the thermal stability of liquid mixtures to be treated^{1,2,4)}. Hence, to verify experimentally the SVL and the TPL described in the introduction, it is desirable as an experimental procedure to increase the vapor flow rate by reducing the top pressure p_2 under a constant bottom pressure p_1 .

In the present operation, however, it was not easy to keep p_1 a specified value, therefore data in a series of runs were taken under p_2 maintained as constant as possible by adjusting the pressure at the outlet of a condenser p_3 in response to the input power of a still heater. In Fig. 1 p_1 , p_2 , p_3 and Ma_2 thus obtained for the E.O.—M.S. system at total reflux are plotted

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