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THE VISUALIZATION STUDY OF CONTACT LINE CHARACTERISTICS IN TRIANGLE WETTING REGION OF RECTANGLE MICROGROOVE

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ABSTRACT

The paper acquires the images of triple phase contact line along the axial direction in microgroove triangle wetting region by the direct visualization means. The contact line images are processed by computer software, and the change law for triple phase contact line is obtained. The contact line angle between contact line and axial direction along microgroove is obtained by analyzing contact line. Results indicate that the length of contact line and the thickness of liquid film on side wall of microgroove reduce along with heat flux addition; but increase as the tilt angle increases. The contact line angle increases with the increase of tilt angle and the decrease of heat flux. In addition, changes of the length of contact line, the thickness of liquid film and the contact line angle for ethanol case is more significant than that for distilled water.

INTRODUCTION

There is high-strongly compound phase change heat transfer near the triple phase contact line in microgrooves[1-3], which can apply to the thermal management of laser, electric power and electronic equipment. The triple phase contact line can be easily formed in microgrooves[4,5], so great efforts have been made on the working liquid film distribution, flow and heat transfer characteristics in microgrooves. Xu[6] studied the liquid flow characteristics of v-grooves from the experimental and theoretical aspect. Ha[7,8] studied the change of intrinsic meniscus along the axial of v-grooves, and the correlation of the location of dryout point with the heat flux, thermophysical properties and microgroove geometric shapes. The research found that the liquid contracts to the bottom angle and disappears at the bottom angle finally.

Chen[9] and Do[10] developed a thermal model for a heat pipe with rectangular microgrooves and analyzed numerically to predict the heat transfer capacity and total thermal resistance. Stroes[11] and Nilson[12] analysed the liquid distribution along with the axial direction of rectangle microgroove. At the initial contact location of microgroove and liquid pool, the liquid will fill whole microgroove. With the position elevation, the working liquid in microgroove reduces to tangency with the microgroove bottom, and then shrinks to the bottom angle until the liquid disappears. Hu[13] proposed a new theoretical model to predict the wetted height supported by vertical rectangular capillary microgrooves subject to heating from back and then to verify the results by comparison with experimental data.

So the wetting characteristics in rectangle microgroove and v-groove are different from each other. In rectangle microgrooves, the working liquid is divided into rectangle and triangle wetting region. But only a few references studying for the wetting characteristics in the triangle wetting region of rectangle microgrooves have been reported so far and it is much less well studied and should be the subject of continuing speculation.

In order to clearly observe the distribution of liquid flow and the triple phase contact line in microgrooves, the microgrooves are directly machined on the borosilicate glass.This paper mainly studies the change of triple phase contact line. By the

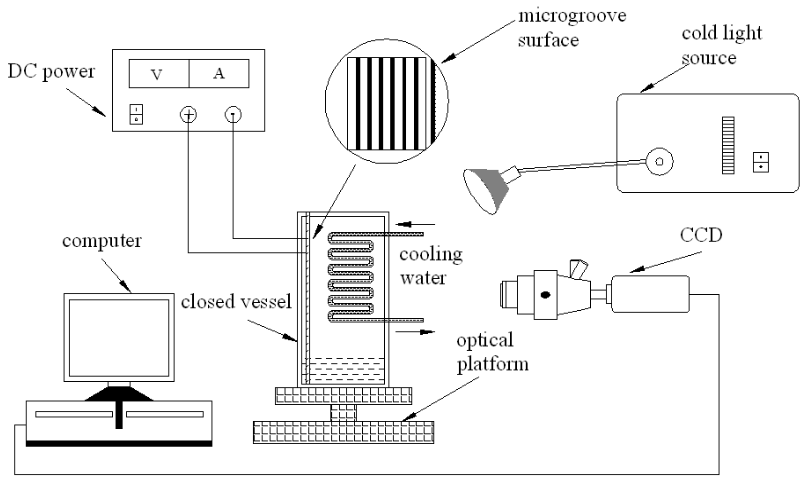

Fig.1 Experimental setup

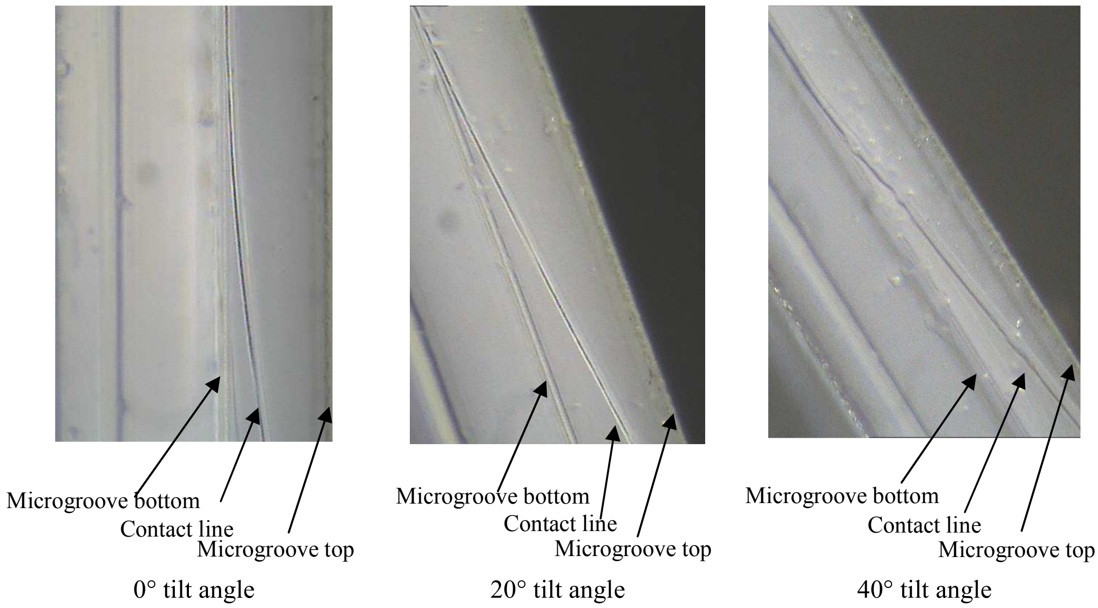

Fig.2 Contact line in triple wetting region (distilled water)

contact line characteristics, the wetting characteristics of working liquid and contact line angle are studied under different tilt angles (the acute angle between microgrooves surface and gravity direction), heat flux and working liquid.

EXPERIMENTAL SETUP AND METHOD

Fig.1 is the experimental system which measures the characteristics of triple phase contact line along with the axial direction of microgroove. The transparent closed vessel is fixed on the optical table whose motion precision is ±0.02 mm. The optical table can rotate with revolution precision of ±0.02°. The rectangle microgroove is put into the closed vessel. In order to obtain clear contact line, the microgroove is directly machined on the transparent borosilicate glass with a length of 90 mm, a width of 20 mm, and a thickness of 1 mm. The heating film (length: 20 mm, width: 10 mm, thickness: 0.1 mm) is fixed on the back of microgroove and connected with high accuracy DC power (DH1718E-5, China) as well. The heat power can be obtained from ampere meter and voltmeter, whose precision is ±0.1 A and ±0.1 V respectively. The organic glass is fixed on the back of heating film by adiabatic tape and plays the role of thermal insulation and reinforcement. In order to reduce the contact thermal resistance, heat conduction silicon grease is used between the heating film and microgrooves.

In the closed vessel, a cooling coil is equipped to cool the liquid steam in microgrooves. The working liquid contacts with inner surfaces of microgrooves and flows under the drive of the capillary force. The steam of working liquid releases the heat to cooling water and then turns into the liquid. During the course of experiment, the liquid surface in closed vessel is stable.

Hiring the 350 W cold light source with multi-angle focus (XD-300, China), the CCD (WV-CP240/G, Japan) camera and microscope are used to observe the triple phase contact line in microgrooves. The wide-angle stereoscopic microscope (PXS VI, China) has long working focus distance of 100 mm, and the resolution is 0.2 μm. The CCD is connected to computer to record the contact line images online.

Before the experiment, the greasy dirt is firstly removed from the microgrooves surface. Secondly, the microgroove is cleaned by ultrasonic washing until the working liquid can evenly distribute. Finally, the dry microgroove is put into closed vessel.

During the course of the experiment, a proper quantity of working liquid is put into the closed vessel and maintained invariably. The capillary microgroove is gently put into the closed vessel. The capillary force drives working liquid flow upward. When the liquid film is up to balance, heating film begins to work. The input power is adjusted by DC power with high accuracy. After the system reaches heat balance, the contact line image is recorded. Similarly, the contact line distributions in microgroove heat sink are recorded under other operating modes.

RESULTS AND DISCUSSIONS

The images of contact line in triple wetting region of microgroove are shown in Fig.2, which are recorded using CCD camera and microscope. The microgroove width is 0.15 mm, and the depth is 0.4 mm. The working liquid is distilled water. The tilt angle of the three images is 0°, 20° and 40° respectively. The microgroove bottom, contact line, and microgroove top are marked separately. At the contact line terminal, the contact line angle between the distilled water and borosilicate glass is small; it is almost tangency with microgroove bottom. At the triangle wetting region, the contact line contracts to microgroove bottom along the axial direction of microgrooves.

With the help of the MATLAB program, the contact line images (shown in Fig.2) are translated to gray images, the boundary curves of which are detected according to the gray value. Since the boundary curves are also the contact lines, the changes of contact line along the axial direction of microgroove can be obtained.

Every pixel can stand for a fixed dimension through calibration, so the coordinate value can be confirmed by the pixels of the boundary curve. The wetting length and liquid film thickness are able to be obtained correspondingly. The boundary curves of contact line in triangle wetting region are fitted, then the angle between the tangent of fit curve and the microgroove bottom at the dry point is computed，thus the contact line angle then can be obtained. All the following figures (Fig.3-6) are acquired by the above mentioned method.

Fig.3 shows the change of the contact line along the axial direction of microgroove. The microgroove width is 0.15 mm, the depth is 0.4 mm. The working liquid is ethanol. Input heat flux is 1.7 W/cm^2, 3.0 W/cm^2, and 3.8 W/cm^2, respectively. It is observed that the length of contact line decreases with the increase of heat flux, namely, the wetting length and liquid film thickness decrease. The reason is that with the increase of heat flux, the ethanol evaporation is enhanced, flow rate increases, and flow resistance becomes higher, so the contact line and wetting length decrease. The supplement difficulty of working liquid along axial direction leads to cross-section supplementary shortage. Moreover, the thin film near the triple phase region of contact line is the key area of evaporation heat transfer, so the contact line shrinks to the bottom corner of microgroove, and the thickness liquid film decreases.

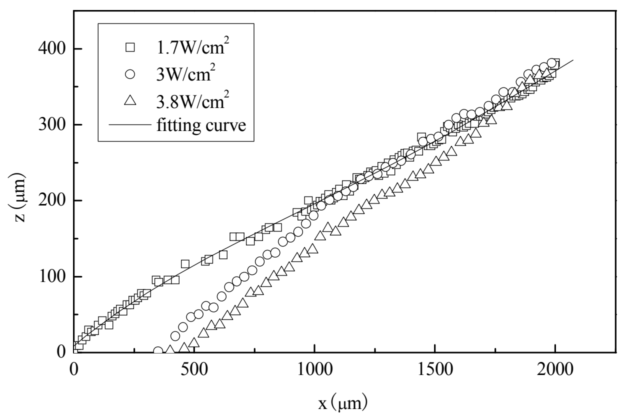

Fig.3 The effect of heat flux on contact line (ethanol)

In Fig.3, the real line is the fitting curve of triple phase contact line, when the heat flux is 1.7 W/cm^2. The fitting formula obtained is as follows:

$$z = -1.1634e^{-11}x^4 + 6.9755e^{-8}x^3 - 1.3371e^{-4}x^2 + 0.2625x + 9.1035$$

The derivative fitting formula is:

$$z' = -4.6536e^{-11}x^3 + 20.9265e^{-8}x^2 - 2.6742e^{-4}x + 0.2625$$

At $x = 0$, $z' = 0.2625$. The contact line angle between ethanol and borosilicate glass is 14.7°.

Employing the above method, the contact line angle is obtained when the distilled water and ethanol are adopted as working liquid at different heat fluxes.

Table 1 The effect of heat flux on contact line angle

Heat flux(W/cm^2)	contact line angle(°)	
	Distilled water	Ethanol
1.7	5.1	15.7
3.0	2.6	14.7
3.8	0.3	13.8

It can be seen from table 1 that the contact line angle decreases with the increase of heat flux for both distilled water and ethanol. The reason is that when the triple phase contact line contracts to the bottom angle; the liquid film becomes thinner near the dry out point in both cases. However at the same condition of heat flux, the contact line angle between distilled water and borosilicate glass is smaller than the case of ethanol, which means the borosilicate glass surface is eaiser to be wetted by the distilled water than ethanol, resulting in a larger wetting and thin film area. Therefore, distilled water as working liquid can get higher heat flux than ethanol.

The effect of title angle on the triple phase contact line without and with thermal load is shown in Fig.4 and Fig.5 respectively. The microgroove width is 0.2 mm, and the depth is 0.4 mm. From Fig.4, it is seen that both of the liquid film thickness and contact line length increase with the increasing tilt angle. Moreover, film thickness and contact line increase faster at larger tilt angle since the impact of gravity on the distribution of distilled water film decreases with the increase of tilt angle.

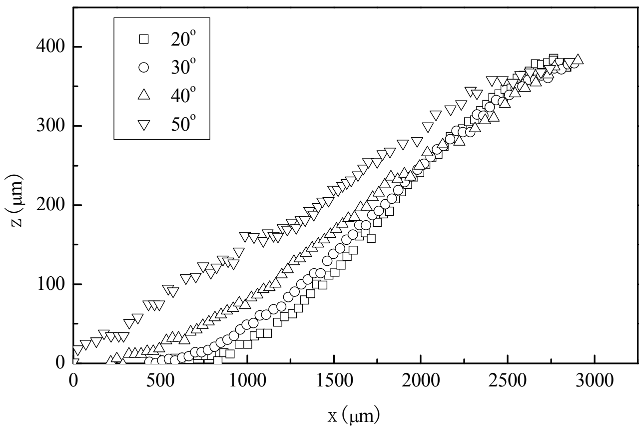

Fig.4 The effect of tilt angle on contact line without thermal load

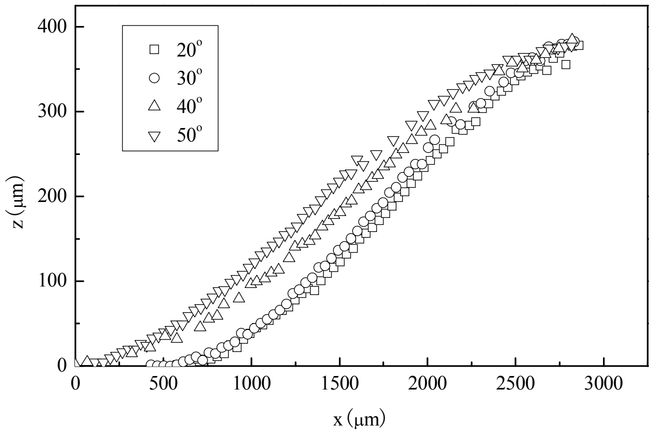

Fig.5 The effect of tilt angle on contact line with thermal load

In Fig.5, the heat flux is 1.7 W/cm^2. Compared with the data in Fig.4, the distance of four curves along z-axis direction decreases. As the evaporation thin film near the contact line is the main region of heat transfer, the triple phase contact line will contract to the bottom angle along with the addition of thermal load. Due to the flow resistance deference, the thermal load affects more obviously with the longer wetting length, resulting in the distance of four curves decreases.

Table 2 illustrates the effect of tilt angle on contact line angle. It is noticed that the contact line angle increases with the increase of the tilt angle. One reason is that there is a certain surface roughness and the working liquid needs to overcome the friction and remove the air in pits. Another reason is that the gravity influence reduces resulting from the increasing tilt angle, and can't make liquid film thinner. So the contact line angle is larger at the bigger tilt angle.

Table 2 The effect of tilt angle on contact line angle

Tilt angle(°)	contact line angle(°)	
	0 W/cm^2	1.7 W/cm^2
50	13.8	2.3
40	2.8	1.4
30	2.3	1.1
20	0.3	0.2

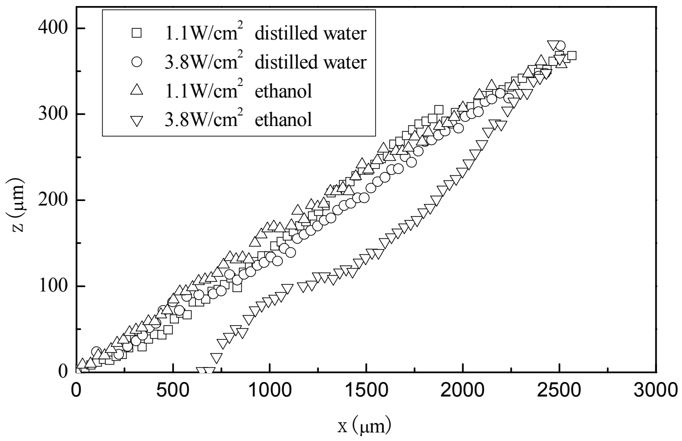

Fig.6 The effect of working liquid on contact line

Fig.6 shows that the effect of working liquid with distilled water and ethanol on the contact line. The microgroove width is 0.15 mm, and the depth is 0.4 mm. The tilt angle is 30°. As shown in Fig.6, the contact line length and liquid film thickness are little different for distilled water and ethanol, when the heat flux is 1.1 W/cm^2. But at the heat flux of 3.8 W/cm^2, for ethanol working liquid, the contact line length and liquid film thickness suddenly decrease. While for the distilled water working liquid, changes of both the length and thickness are weak. The explanation is that the vaporization latent heat of distilled water is larger than that of ethanol. When the heat flux is small, the latent heat of vaporization doesn't affect the liquid wetting that much. With the increase of heat flux, the ethanol evaporation quantity becomes larger than distilled water; consequently the increase of flow resistance becomes greater. So the positions of contact line for distilled water and ethanol are different.

CONCLUSIONS

With the direct visualization means, this paper obtains the triple phase contact line of triangle wetting region along the axial direction of microgrooves. The contact line images are processed with computer software, and the change laws are obtained. The research results are shown as follows:

(1) The length of contact line and the liquid film thickness reduce with the increase of heat flux; moreover, the change becomes more significant when ethanol is adopted as the working liquid.

(2) Both the length of contact line and the thickness of liquid film increase as the tilt angle increases.

(3) The contact line angle increases with the increase of tilt angle and the decrease of heat flux.

(4) The contact line angle between ethanol and borosilicate glass is larger than that of distilled water and borosilicate glass.

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