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STUDY ON THE CHARACTERISTICS OF CONTACT LINE AND LIQUID FILM IN RECTANGULAR MICROGROOVES UNDER VIBRATION CONDITIONS

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ABSTRACT

With the help of a high-speed camera (30000 Frames/second) and a wide-field stereo-microscope, the effects of mechanical vibration on the meniscus film and triple-phase contact line in rectangular microgrooves were experimentally investigated. Distilled water was used as working liquid. The images of the oscillated meniscus film in an oscillation period were captured through the high speed camera and they were analyzed using a MATLAB program. The results show that as the vibration table moves upward, the length of contact line increases; as the vibration table moves downward, the length of contact-line decreases. During the oscillation, the axial liquid film spreads upward further along the microgrooves and the deformation of the contact line becomes more obvious. The increase of the triple-phase contact line length caused by the external mechanical vibration is helpful for contact line heat transfer enhancement. Besides, deformation curve of the contact line with and without heat input under different vibration conditions is similar, while the contact line with heat input is shorter.

INTRODUCTION

The heat sink with axial microgrooves has been widely studied because of its high heat transfer rate. Wayner et al. [1, 2] established a mathematical model to describe the heat transfer characteristics in the three-phase contact-line region and studied the thickness and the distribution of the meniscus film with scanning microscope photometer. Ma and Peterson[3]developed an analytical model for the evaporating heat transfer coefficient and found that the evaporating heat transfer coefficient through the thin film region depends on the meniscus radius and the superheat. Sharma[4] analyzed the effect of evaporation and condensation on the stability of the thin film domains. In the article, dynamic simulations are performed, and simple analytical results are obtained for the length and time scales of the surface instability for water films. Hu and co-workers[5] observed the axial liquid flow and dry out point (wetting height) in vertical rectangular capillary grooves heat sink under pure evaporation heat transfer conditions and studied the effect of the geometric parameters of microgrooves, working fluid on the wetting height. While in most of these theoretical and experimental studies, they assume the evaporation occurs in a steady or quasi-steady condition, but in many cases, the contact line region between the air and liquid in microgrooves is unstable or oscillates which will affect the heat transfer characteristic of the microgrooves seriously. Zheng[6] and Panchamgam[7] studied the transport process and instabilities associated with an evaporating, extended meniscus of pentane with a novel Constrained Vapor Bubble Loop Thermosyphon, CVBLT. They found that as the heater power input was increased to a certain level, the film started to oscillate and the meniscus was made to recede and advance by increasing and decreasing the heat input. By the wetting length measured, they calculated the moving velocities of the oscillating film and studied the effect of the regional stress on the oscillating meniscus. There are few works has been done on the instability of liquid film in microgrooves caused by external mechanical force. To apply the microgroove heat sink work safely under fierce vibration condition, the oscillation of meniscus film in rectangular microgroove needs to be studied deeply. Herein, we developed a mechanical vibration system to study the general characteristic of contact line and liquid film in rectangular microgrooves under external vibration conditions.

EXPERIMENTAL PROCEDURE

Figure1 (a) shows a schematic diagram of the experimental apparatus. A reservoir (made of transparent glass) with microgrooves in it, was mounted on the vibration table. The vibration table (square cross section 50cm×50cm, height 20cm), was used to simulate the mechanical vibration condition. The vibration conditions were changed by adjusting the frequency and voltage of a vibration controller (the ranges of the frequencies and amplitudes are 1～600Hz and 0～5mm, the vibration wave-form is sinusoidal). One end of the vibration controller is connected to the vibration table; the other end is attached to the computer. Besides, the experimental equipment also consists of a high-speed camera connected with computer to capture the images, a data logger, a 350W cold light and a power supplier. To measure the changes of the contact line along the microgrooves under vibration condition conveniently, the microgrooves was made of borosilicate glass. The thickness of borosilicate glass is 1mm, the width 20mm and the length 90mm. A cross section profile of the heat sink with axial microgrooves is shown in the Figure1 (b) and the sizes of the microgrooves will be mentioned in the following part. A K-type thermocouple was pasted onto the back of the microgrooves with thermal double-sided gum. The thermocouple was connected with DC power supply and the heat input was got by the data on the ammeter and voltmeter of the DC power supply. An insulation paste on the back of the thermocouple was applied to fasten the organic glass.

The working fluid used in the experiment was distilled water. The microgrooves were cleaned by an ultrasonic bath. This procedure ensured the distilled water can distribute in microgrooves surface uniformly. In experimental process, the working liquid was firstly put in the reservoir, and then the microgrooves were put into the reservoir slowly. In the reservoir, liquid rose along the microgrooves due to capillarity and thereby formed a continuous extended meniscus in the microgrooves. After the liquid distributed in the microgrooves uniformly, power was applied to the test system, and then the meniscus film started to oscillate. The film oscillated fiercely by increasing the parameters of the vibration controller such as frequencies, the voltages and so on. The meniscus movement was observed through a high-speed camera and the images during one period of oscillation were analyzed using a computer program written in MATLAB.

Monochromatic light from a 350W cold light was used to illuminate the microgrooves and a high-speed camera (30000 Frames/second) was used to capture the images of the meniscus film oscillation. The images could be showed in a real time.They were recorded by a data logger and processed by image processing software in the computer. Microgrooves with different dimensions used in experiments are listed in Table 1.

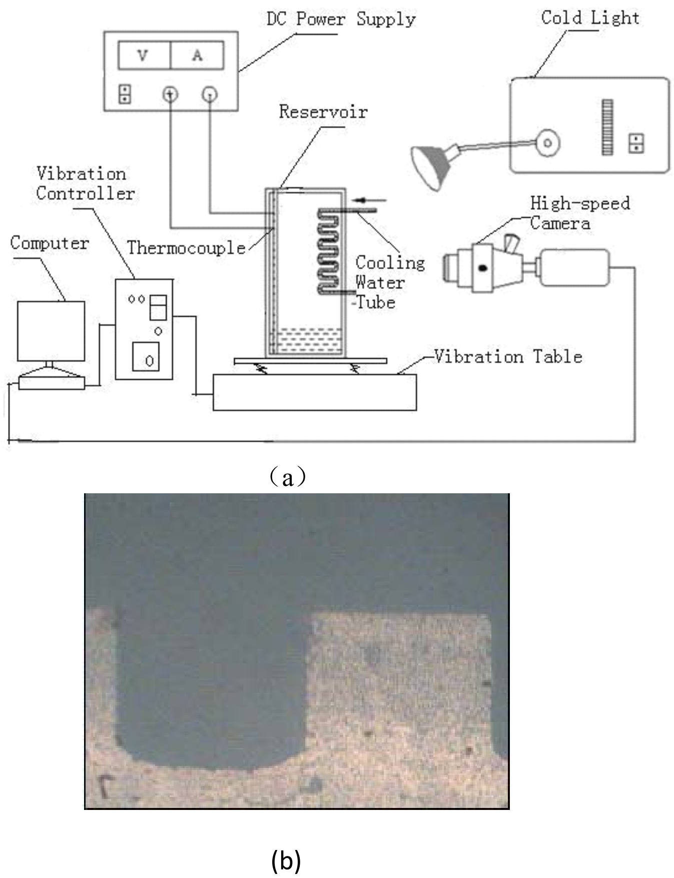


Figure1 (a) Schematic diagram of the experimental apparatus and (b) a profile of the heat sink with axial microgrooves

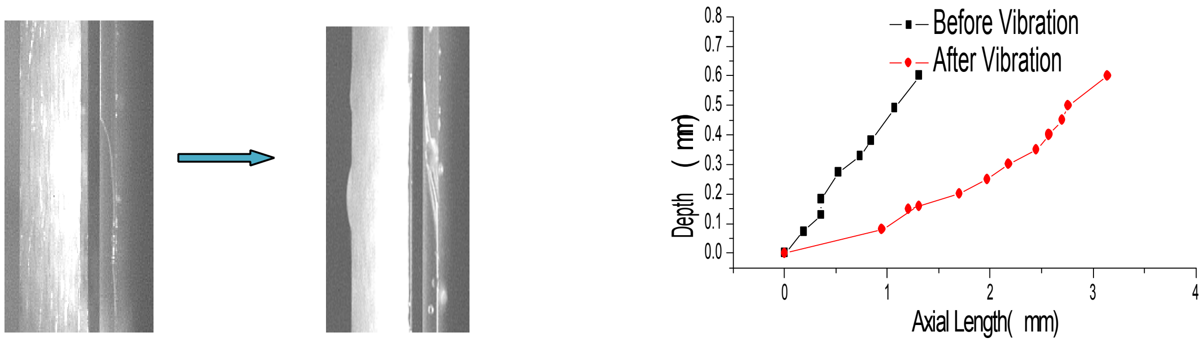
Table1 microgroove dimensions

No.	Groove depth (mm)	Groove width (mm)
1	0.4	0.2
2	0.6	0.2
3	0.6	0.3
4	0.6	0.4
5	0.6	0.6

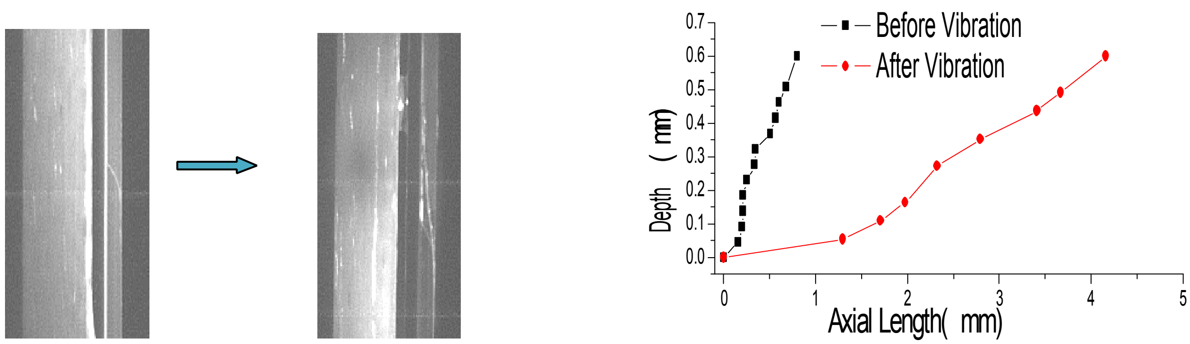
EXPERIMENTAL RESULTS

The images captured from the microscope through the CCD were converted into grayscale images, firstly. The edges of the images were found by a computer program written in MATLAB according to the different gray values of the images. Then, the edge images of the contact line were got by filtered the noise points manually. Assuming the existence of the images is in the form of M * N matrixes, “1” and “0” were used to represent the positions with and without images, respectively.

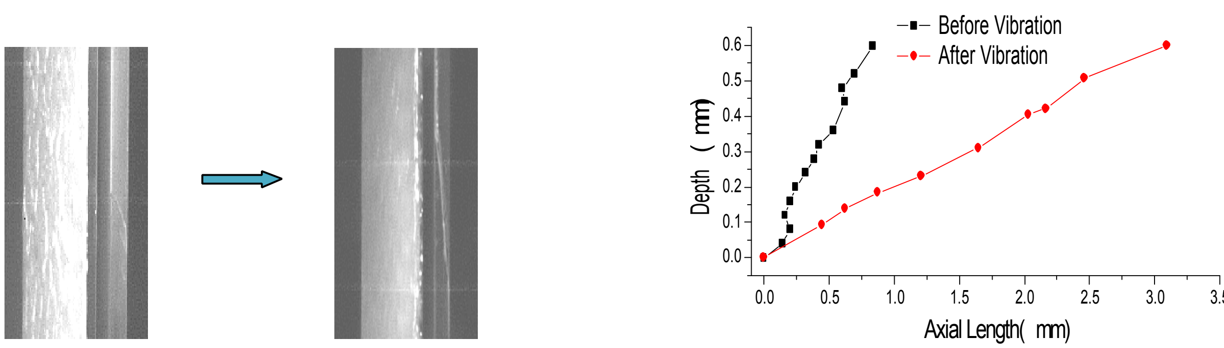
By the above step, we could get the images of the contact line expressed by the matrix form. The line number M in the matrix represents the axial length of the contact line, and the column number N represents the liquid film thickness. For a row in the matrix, there may be several columns of point "1". In this case, the average of these columns is taken as the position of the image edge and it needs to calculate the position of each point "1" in the matrix. Then, the liquid film thickness can be obtained based entirely on the experimental data.



(a) The groove depth is 0.2 mm, the groove width is 0.6mm



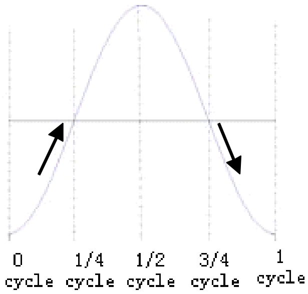
(b) The groove depth is 0.3mm, the groove width is 0.6mm



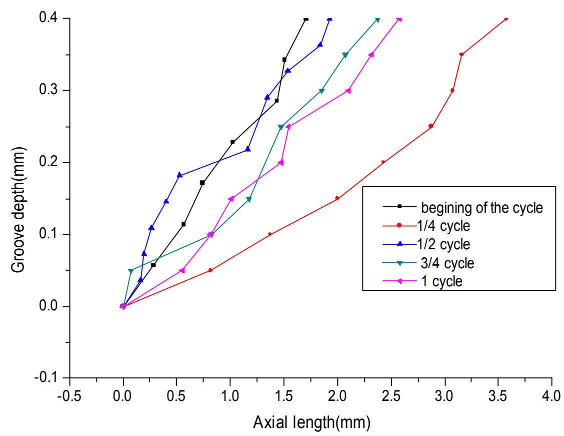
(c) The groove depth is 0.4mm, the groove width is 0.6mm

Figure2 Particular phenomenon of the oscillation film

Figure2 presents a series of images of the liquid film under the same oscillation condition. The depth of the microgrooves in Figure3 (a), (b), (c) is 0.6mm and the width is 0.2 mm, 0.3mm and 0.4 mm, respectively. The lengths of the contact lines before and after vibration are plotted in figure2, respectively. During the oscillation, the axial liquid film spreads upward further along the microgrooves and the deformation of the contact line becomes more obvious. A great number of studies [8-10] show that the intensive evaporation rate in the extended meniscus is the main reason for high heat transfer rate of the heat sink with capillary microgrooves. The heat transfer is higher as the liquid film region is larger. Therefore, vibration enhances the contact line heat transfer to an extent.



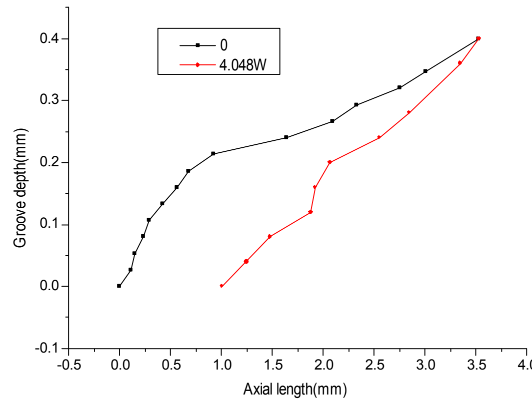
(a)



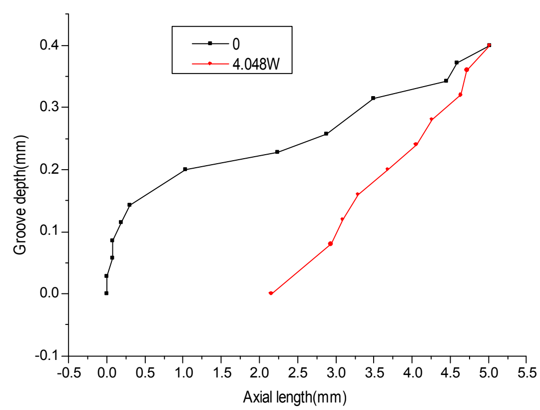
(b)

Figure3 (a) One cycle of the vertical vibration ;
(b) Deformation of the contact line in a cycle

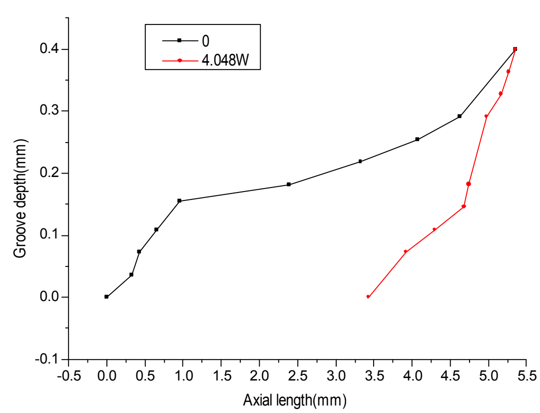
Figure 3 (b) shows the deformation of the contact line in a cycle. The groove width and depth are 0.2mm and 0.4mm, respectively. The vibration frequency is fixed at 10 Hz and the amplitude is approximately 2.5mm. In addition, the heat input is 4.048W. As shown in Fig. 3, the contact line is elongated to the largest length in 1/4 cycle because the microgroove moves up at that time and the liquid film is elongated by the downward acceleration; the contact line shrinks and the evaporating thin film becomes short in 1/2 cycle because the microgroove begins to move down at that time and the liquid film is shortened by the upward acceleration. So the liquid film is obviously deformed by the external mechanical vibration. The pictures of the microgrooves with other sizes and the microgrooves under different vibration conditions with or without heat input are similar with the one shown in Figure4. Herein, we don't list all of these in detail.



(a) The vibration frequency is 6Hz;
The vibration amplitude is 2.5 mm;



(b) The vibration frequency is 10Hz;
the vibration amplitude is 2.616 mm;



(c) The vibration frequency is 30Hz;
the vibration amplitude is 2.534 mm;

Figure4 Deformation of the contact line under different vibration condition with and without heat input

As shown in Figure4, the vibration frequencies are 6Hz, 10Hz and 30Hz; the amplitude is around 2.5mm and the heat input is 0 W or 4.048W, the deformations of the liquid film in the microgroove with and without heat input are different. The length of the contact line with heat input is shorter than the one without heat input. The reason is that the intensive evaporation occurs in the meniscus makes the liquid film shrink, which has been studied by Wang and co-workers[11]. They studied on the characteristic of the contact line of the rectangular capillary microgrooves and explained the reason why the length of contact line with heat input is shorter than the one without heat input. The evaporation occurring in the meniscus leads to the axial flow resistance is greater than the one without heat input.Therefore, heat input has a great influence on the liquid film distribution of the rectangular microgrooves under vibration condition.

CONCLUSIONS

Experimental studies were carried out to find the characteristics of contact Line and liquid film in rectangular microgrooves under vibration condition. Some interesting conclusions are made as follows:

1. During the vertical oscillation, the axial liquid film spreads upward further along the rectangular microgrooves and the deformation of the contact line becomes more obvious. Because of the intensive evaporation rate in the extended meniscus, vibration enhances the contact line heat transfer to an extent. The increase of the triple-phase contact line length caused by the external mechanical vibration is helpful for contact line heat transfer enhancement.

2. Deformation of the contact line in microgrooves occurs during one vibration cycle. The contact line is elongated when the microgrooves move up and reduces when the microgrooves move down. The length of the contact line with heat input is shorter than that without heat input. The reason is that the intensive evaporation occurs in the meniscus makes the length of contact line shorter.

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