THERMAL PERFORMANCE OF WICKLESS AND ORIENTATION INDEPENDENT THIN VAPOR CHAMBERS WITH WETTABILITY PATTERNED MICRO STRUCTURE

by

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The wettability patterned micro structure (WPMS) arrays by laser etching are proposed to enhance the thermal performance of wickless thin vapor chamber (TVC). The effects of filling ratio and inclination angle on the thermal performance of wickless TVC with WPMS are investigated, and the untreated bare wickless TVC is also studied as comparison. The results show that the wickless TVC with WPMS can work stably at filling ratio ranging from 19.0% to 42.8%, and the optimum filling ratio is 42.8%. The maximum heat transfer capacity is 190 W with the lowest thermal resistance of 0.146 K/W. Since WPMS is superhydrophilic, it can provide nucleate sites to promote early onset nucleate boiling and capillary pressure to enhance the liquid supply. Thus, the wickless TVC with WPMS shows 10.98% lower thermal resistance and 18.75% higher maximum heat transfer capacity than that of the untreated bare wickless TVC. In addition, the thermal performance of wickless TVC with WPMS is insensitive to the orientation of the TVC.

Key words*: wickless TVC, WPMS, laser etching, filling ratio, orientation independent, thermal performance*

Introduction

As a passive liquid-vapor two-phase and high-efficient heat transfer device, vapor chamber has been widely used in cooling electronic systems [1, 2]. Recent development of microelectronic devices has led to an increase of heat flux and decrease of installation space for cooling device [3]. Therefore, vapor chamber has also been developed towards ultra-thin thickness. Ultra-thin vapor chamber (UTVC) has become popular in recent years [4, 5]. It is defined as having a thickness less than 2 mm in Ref. [4, 5], and the thickness below 1 mm have become the current research hotspot [4].

The wick structure is the key component of a vapor chamber, which can provide enhanced interface for liquid evaporation and capillary pressure for liquid supply [6]. There-

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fore, numerous researchers have focused on the design of wick structure in UTVC. Screen mesh and spiral woven mesh are widely used in UTVC as wick structure, due to its thin thickness, low cost, easy fabrication, flexibility, considerable capillary pressure, and high permeability. Wu *et al*. [7] fabricated a polyethylene-terephthalate UTVC with size of 110 mm × 20 mm × 1.8 mm, the screen mesh was bonded on both covers, and its maximum heat transfer capacity was 26 W with a thermal resistance of 0.157 K/W. Xu *et al*. [8] introduced a #500 stainless steel screen mesh onto micro pillar arrays as wick structure for a UTVC with size of 100 mm × 50 mm × 0.28 mm. It could work at the heat load of 7.9 W, with a thermal resistance of 4.2 K/W. Shi *et al*. [9] designed a #200 copper screen mesh on the bottom sheet of an 80 mm × 50 mm × 0.65 mm UTVC. The thermal resistance was ~1.2 K/W in the range of heat load of 7.1 W ~ 13.7 W. Chen *et al*. [10] bonded a #300 copper screen mesh on the bottom sheet as wick structure and micro pillar arrays on upper sheet as support structure, and the size of the UTVC was 104 mm × 14 mm × 0.4 mm. The maximum heat transfer capacity was 4.50 W and the thermal resistance was 1.06 K/W. Huang *et al*. [11, 12] proposed a composite wick structure that consisted of copper screen mesh and copper spiral woven meshes for a 100 mm × 15 mm × 0.5 mm UTVC. When the number of spiral woven meshes was 4 and 6, the maximum heat transfer capacity was 7.58 W and 10 W, and the thermal resistance was 0.48 K/W and 0.57 K/W, respectively. Yu *et al*. [13] introduced spiral woven meshes for a 100 mm × 15 mm × 0.4 mm UTVC. The maximum heat transfer capacity of UTVC with 3 spiral woven meshes was 6 W, and the thermal resistance was 0.87 K/W. On the other hand, many researchers have proposed surface modification to enhance the capillary capacity of the thin wick structure in UTVC as well. Li *et al*. [14] developed #150 superhydrophilic sintered screen mesh wick by etching and sintering process for a 100 mm × 50 mm × 0.5 mm UTVC. Lee *et al*. [15] proposed a 106 mm × 65 mm × 0.91 mm UTVC with a superhydrophilic screen mesh wick by chemical etching. The boiling heat transfer behavior in the wick of UTVC also has been studied by visualization method. Zu *et al*. [16] carried out a visualization study of UTVC with a layer of screen mesh as wick. The size of the chamber was 124 mm × 14 mm × 1 mm. The working fluid was anhydrous ethanol and the filling ratio was 38%. The nucleate boiling could be observed at high input heat load.

When the vapor chamber becomes much thinner, the wick structure will be removed from the vapor chamber, and the vapor chamber becomes wickless [17, 18]. However, the wickless vapor chamber shows poor thermal performance. In this study, low-cost and east fabrication WPMS arrays by laser etching are proposed to enhance the thermal performance of the wickless vapor chamber. A 70 mm × 70 mm × 1.5 mm wickless vapor chamber with WPMS on the bottom sheet is fabricated. Currently, due to the progress of manufacturing technology, when the thickness of vapor chamber is less than 1 mm, it is commonly called UTVC. In the present work, the thickness of the vapor chamber is 1.5 mm, it is called TVC. The effects of filling ratio and inclination angle on the thermal performance of wickless TVC with WPMS are experimentally investigated. The untreated bare wickless TVC is also studied as comparison.

Design and fabrication of the wickless TVC with WPMS

As shown in fig. 1, the wickless TVC is made of an upper sheet, a bottom sheet and a charging tube, with size of 70 mm × 70 mm × 1.5 mm. The material of the TVC is oxygen free copper. The wall thicknesses of the upper and bottom sheet are both 0.4 mm, and the chamber height is 0.7 mm. As illustrated in fig. 2(a), 108 ×108 aligned circular WPMS arrays are manufactured on the bottom sheet by laser etching operating at 40 W power, 2500 mm/s scanning speed, 100 ns pulse width, 40 kHz pulse repetition rate, and 1 time scanning number.

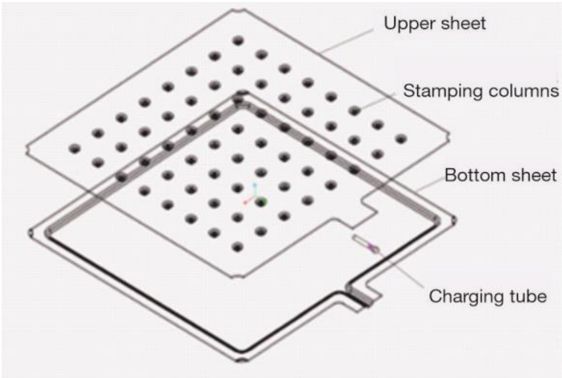

Figure 1. Schematic diagram of exploded view of the UTVC

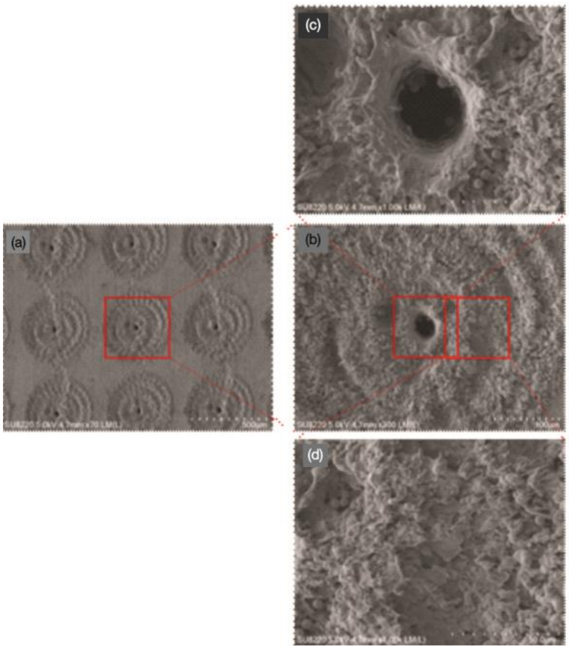

Figure 2. The SEM images of WPMS

The diameter of a WPMS is 0.5 mm, and the pitch of adjacent WPMS is 0.1 mm. The parameters of WPMS and processing parameters of laser etching are also listed in tab. 1. Enlarged views of the WPMS are shown in figs. 2(b)-2(d). As seen in figs. 2(b)-2(d), a WPMS contains hierarchical structures with a 25 μm diameter cavity in center, and spherical and flake-like cluster structures around the cavity. The cavity in center and the concaves formed by spherical and flake-like cluster structures can provide a large number of potential nucleation sites to enhance the boiling heat transfer coefficient and enlarge the heat transfer surface. Moreover, water contact angle on untreated bare copper surface and modified copper surface with WPMS is carried out to characterize the wettability. As displayed in fig. 3(a), the contact angle of water droplet on untreated bare copper surface is ~83°, whilst as seen in figs. 3(b) and 3(c), the contact angle on modified copper surface with WPMS approaches ~0° (superhydrophilic), suggesting that modified copper surface with WPMS can provide capillary action to drive liquid working fluid returning back to evaporation zone. This is because that micro structures form a layer of thin porous media to improve liquid spreading. The upper sheet without wick is stamped to form 64 support columns to prevent deformation and provide shortcut for the liquid working fluid back to the bottom

Table 1. Parameters of WPMS and processing parameters of laser etching

Parameters		
Parameters of WPMS	Number of WPMS	108 × 108
	Diameter of a WPMS	0.5 mm
	Pitch of adjacent WPMS	0.1 mm
Processing parameters of laser etching	Power	40 W
	Scanning speed	2500 mm/s
	Pulse width	100 ns
	Pulse repetition rate	40 kHz
	Scanning number	1

sheet. Then the upper sheet, bottom sheet, and charging tube are clamped together and welded by SnPb solder at 300 ℃. After that, the process including leak detection, working fluid charging, vacuuming and charging tube sealing will successively take place to complete the manufacturing of TVC. Degassed and deionized water is used as working fluid, and the filling mass is 0.20 g, 0.40 g, 0.60 g, 0.90 g and 1.20 g, respectively. The corresponding filling ratio defined as the ratio of the water volume to the total volume of the container is 9.5 %, 19.0 %, 28.6 %, 42.8 % and 57.1 %, respectively.

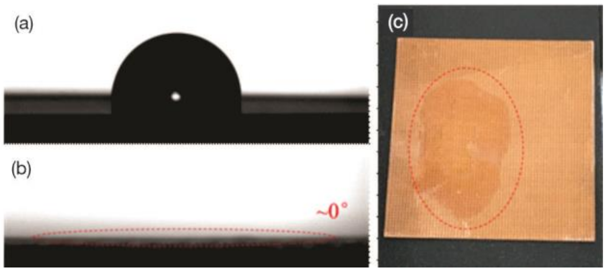

Figure 3. (a) Water contact angle on untreated bare copper surface, (b) water contact angle on copper surface with WPMS, and (c) image of water spreading on copper surface with WPMS

Experimental details

Experimental apparatus and operating conditions

The test rig for thermal performance test of TVC is shown in fig. 4. The test apparatus is composed of a heating module, a cooling module and a data acquisition module. Four heating rods embedded into the copper heating block with heating surface of 30 mm × 30 mm are used as the heating module, which is powered by an adjustable DC power source with an accuracy of 0.1 W. The cooling water supplied from the thermostatic water bath with an accuracy of 0.05 ℃ to cooling plate is used as the cooling module to dissipate the heat transfer rate from the condenser of TVC. The size of the cooling plate is 80 mm × 80 mm × 14 mm. The data acquisition logger Keysight 34970A with a temperature acquisition module Keysight 34901A is used to record the data of temperatures. Ten Omega *K*-type thermocouples named as T1-T10 with an accuracy of 0.1 ℃ are used to measure temperatures at different positions. The detailed location of thermocouples are presented in figs. 4 and 5. The TVC is sandwiched between the heating block and the cooling plate, and thermal grease with a thermal conductivity of 4.0 W/(mK) is smeared on the contact surface to reduce the contact thermal resistance. The whole test systems including the heating block, the TVC and the cooling plate are wrapped with fiber glass to ensure the thermal insulation.

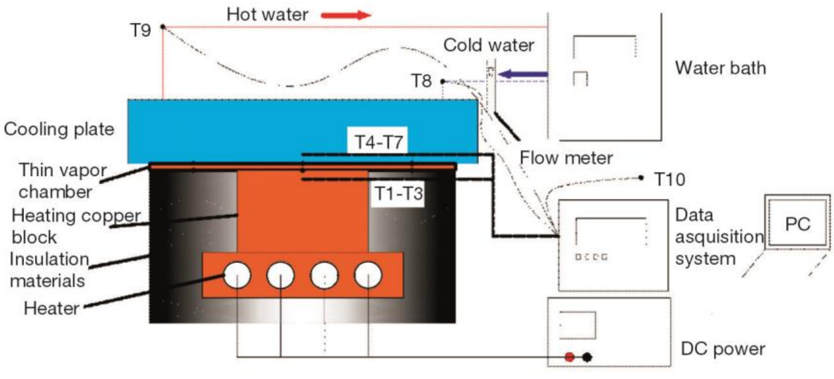

Figure 4. Schematic diagram of the test rig

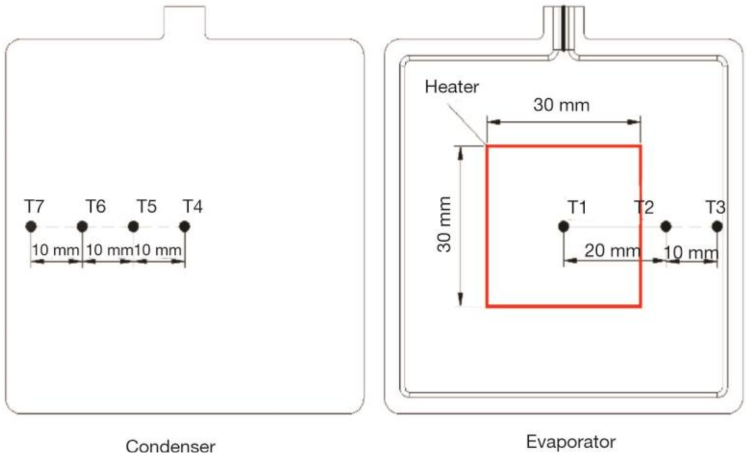

Figure 5. Thermocouples distribution on condenser and evaporator of the TVC

The ambient temperature is about 25 ±1 ℃ during the test. The cooling water temperature is 30 ℃ and the flow rate is 10 Lph. The inclination angle is set at 0°, 45°, 90°, 135°, and 180°, respectively, and the details of the rotating test system are shown in fig. 6. The test will be terminated when the junction temperature T1 exceeds 100 ℃ to avoid the breakdown of the TVC.

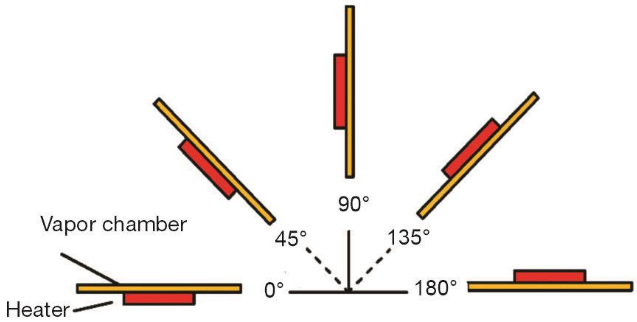

Figure 6. Schematic diagram of relative location of heater and vapor chamber in incli-nation test

Data reduction and uncertainty analysis

The thermal resistance of TVC R_{vc} is defined as:

$$R_{VC} = \frac{T_{hs} - \overline{T}_{cond}}{Q} = \frac{T_1 - \frac{1}{4}\sum_{i=4}^{7} T_i}{Q} \tag{1}$$

where T_{hs} is the center temperature of the evaporator T_1, – $\overline{T}_{cond}$ – the average temperature of the condenser, and Q – the input heat load.

Besides, based on the standard uncertainty analysis method, the relative uncertainty of the thermal resistance is below 5%.

Results and discussion

Effect of filling ratio

Figure 7 presents the effect of filling ratio on the thermal performance of the wickless TVC with WPMS. The filling mass in the wickless TVC with WPMS is 0.20 g, 0.40 g, 0.60 g, 0.90 g, and 1.20 g, respectively, and their corresponding filling ratio is 9.5 %, 19.0 %, 28.6 %, 42.8 % and 57.1 %, respectively.

As shown in fig. 7(a), at filling ratio of 9.5%, 19.0%, and 28.6%, with increasing the input heat load, the thermal resistance of the wickless TVC with WPMS drops firstly. Then when the input heat load reaches a certain value, the thermal resistance of the TVC with WPMS increases, indicating that the partial dry-out occurs. The reason is that at low input heat load, the evaporation rate is small and the initial liquid film is thicker, leading to higher thermal resistance. With increasing the input heat load, the evaporation rate increases, and the liquid film above heat input region becomes thinner, leading to the decrease of thermal resistance. When the partial dry-out condition occurs, due to insufficient liquid working fluid returning to the heat input region, the thermal resistance begins to rise. The lowest thermal resistances of the wickless TVC with filling ratio of 9.5%, 19.0%, and 28.6% are 0.219 K/W at 20 W, 0.207 K/W at 110 W, and 0.164 K/W at 110 W, respectively. It can be seen that when the filling ratio is 9.5%, the partial dry-out comes at low input heat load of 20 W, and rises rapidly after 20 W, because of insufficient working fluid inside the wickless TVC with WPMS. At medium filling ratio of 19.0% and 28.6%, partial dry-out can occur at higher input heat load of 110 W, due to sufficient working fluid recirculating in the wickless TVCs before 110 W.

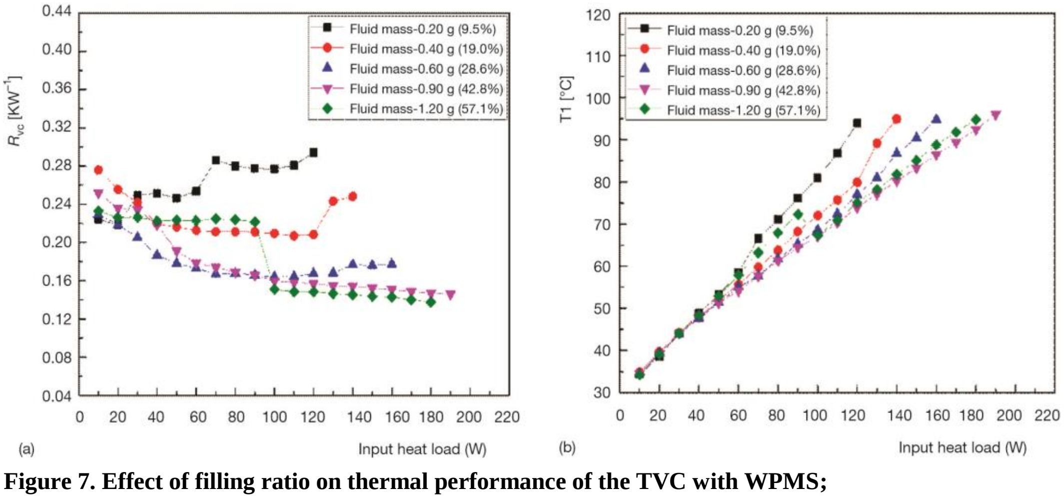

Figure 7. Effect of filling ratio on thermal performance of the TVC with WPMS; (a) thermal resistance and (b) temperature T_1

Further shown in fig. 7(a), partial dry-out does not occur within the range of input heat load at large filling ratio of 42.8% and 57.1%, as the thermal resistance always drops with the increase of input heat load. However, the thermal resistance of wickless TVC with filling ratio of 57.1% almost stays constant at 0.23 K/W and is higher than that with filling ratio of 42.8% before 90 W. When the input heat load is higher than 100 W, the thermal resistance suddenly drops and begins to be lower than that with filling ratio of 42.8% and continues to drop gradually. This is because that the initial thickness of liquid film in the TVC with filling ratio of 57.1% is too thick and the evaporation rate is small, the large thickness liquid film results in larger thermal resistance at low input heat load. At high input heat load, the thickness of the liquid film and evaporation rate reach a certain value, the nucleate boiling will occur at high filling ratio, resulting in the start-up of TVC with large filling ratio of 57.1%. As the heat transfer efficiency increases at high input heat load, the thermal resistance of TVC with large filling ratio of 57.1% will drop. The thermal resistance suddenly drops in high filling ratio of 57.1%, indicating that high filling ratio will lead to instable heat transfer performance. The lowest thermal resistances of the wickless TVCs with filling ratio of 42.8% and 57.1% are 0.146 K/W at 190 W and 0.138 K/W at 180 W, respectively. Although the thermal resistance of TVC with filling ratio of 57.1% is smaller than that with filling ratio of 42.8% at high input heat load, the maximum heat transfer capacity of TVC with filling ratio of 42.8% is still higher than that with filling ratio of 57.1%. The reason is that the temperature T_1 of TVC with filling ratio of 57.1% is much higher than that with filling ratio of 42.8% at identical input heat load before 90 W, as shown in fig. 7(b).

It can also be known in figs. 7(a) and 7(b) that except for the large filling ratio of 57.1%, the thermal resistance decreases at high input heat load and the maximum heat transfer capacity increases with increasing the filling ratio. This is because that increasing the filling ratio will more easily induce nucleate boiling at high input heat load, the higher heat transfer efficiency is, the lower the thermal resistance. When the filling ratio is not too high (≤42.8%), the TVC can work stably, more working fluid will increase the flow rate back to the evaporator, which can increase the maximum heat transfer capacity.

Based on the previous analysis, the optimum filling ratio of the TVC with WPMS is 42.8%, due to low thermal resistance at high input heat load and the highest heat transfer capacity.

Effect of inclination angle

Figure 8 shows the effect of inclination angle on the thermal performance of the wickless TVC with WPMS. The filling ratio of the wickless TVC with WPMS is 42.8%. The inclination angle of the test system is 0°, 45°, 90°, 135°, and 180°, respectively, and the details are shown in fig. 6. As shown in figs. 8(a) and 8(b), the thermal resistance and temperature T_1 along with input heat load are insensitive to the inclination angle. The lowest thermal resistances of the wickless TVC with WPMS at all inclination angle are within the range of 0.141 K/W ~ 0.146 K/W at 190 W, and the maximum heat transfer capacities at all inclination angle are 190 W, indicating that the wickless TVC with WPMS is orientation independent. The reason is that the height of the inner channel is very small (0.7 mm), and the number of support columns is large (64), and the filling working fluid is sufficient (42.8%), the condensate on the condenser easily flows back to the evaporator under the assistance of the support columns with short path, bringing about orientation independence.

Performance comparison

The thermal performance comparison of the wickless TVC with WPMS and the untreated bare wickless TVC is shown in fig. 9, and the filling ratio is 42.8% in both of the TVC. As shown in figs. 9(a) and 9(b), when the input heat load is larger than 40 W, the thermal resistance of the TVC with WPMS is lower than that of the untreated bare TVC, and the maximum heat transfer capacity of the TVC with WPMS is larger than that of the untreated bare TVC. The lowest thermal resistances of the TVC with WPMS and the untreated bare TVC are 0.146 K/W and 0.164 K/W, respectively, and the maximum heat transfer capacities are 190 W and 160 W, respectively. This can be attributed to the WPMS (WPMS) on the evaporator. As

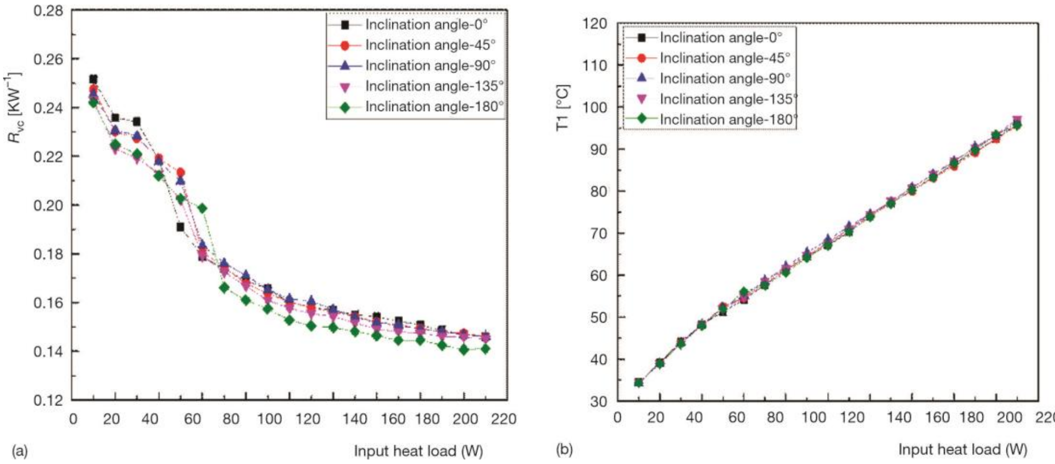

Figure 8. Effect of inclination angle on thermal performance of the TVC with WPMS; (a) thermal resistance and (b) temperature T_1

analysis in section *Design and fabrication of the wickless TVC with WPMS*, the WPMS shows superhydrophilic, which can enhanced the liquid working fluid supply capacity. The liquid working fluid can be pump rapidly back to the input heat region by the capillary force of the WPMS. Moreover, the large micro cavity formed on the center of the WPMS and micro concaves formed by the spherical and flake-like cluster structure can provide a number of potential nucleation sites to promote early onset nucleate boiling, which can enhance liquid film boiling within the WPMS. Therefore, the thermal resistance of TVC with WPMS is reduced and the maximum heat transfer capacity is enlarged.

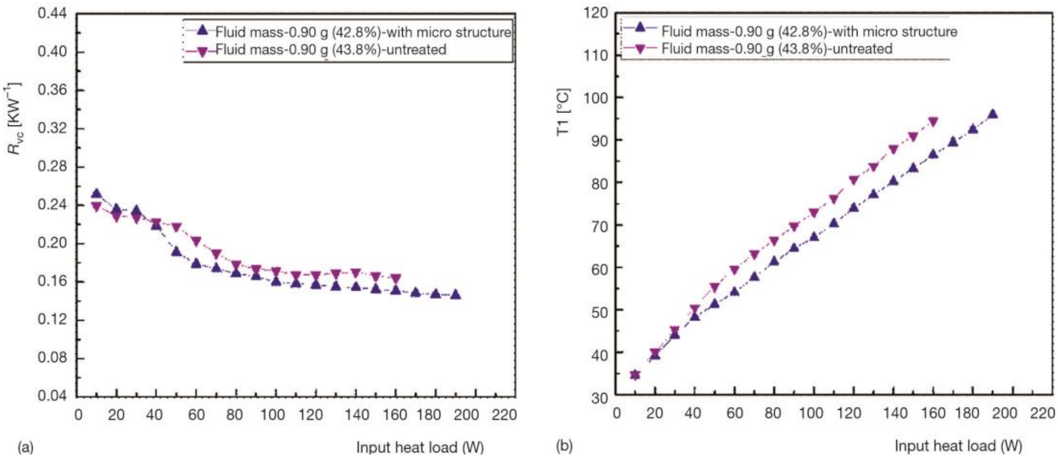

Figure 9. Performance comparison of the TVC with WPMS and the untreated bare TVC; (a) thermal resistance and (b) temperature T_1

Conclusions

In this study, a 70 mm × 70 mm × 1.5 mm wickless and orientation independent TVC with WPMS by laser etching has been developed for improving the thermal performance of untreated bare wickless TVC. The effects of filling ratio and inclination angle on the thermal performance of wickless TVC with WPMS are experimentally investigated, and the untreated bare wickless TVC is also studied as comparison. The main conclusions can be as follows:

- When the filling ratio ranges from 19.0% to 42.8%, the wickless TVC with WPMS can work stably. The optimum filling ratio of the wickless TVC with WPMS is 42.8%. The lowest thermal resistance can reach 0.146 K/W and the maximum heat transfer capacity is 190 W.
- The WPMS contains hierarchical structure with a micro cavity in center and concaves formed by spherical and flake-like cluster structure, it can provide a number of potential nucleate sites to promote early onset nucleate boiling. Meanwhile, the WPMS is superhydrophilic, it can enhance the liquid supply capacity. Therefore, the thermal performance of the wickless TVC with WPMS shows 10.98% lower thermal resistance and 18.75% higher maximum heat transfer capacity than that of the untreated bare wickless TVC.
- The thermal performance of wickless TVC with WPMS (filling ratio of 42.8%) is insensitive to the orientation of the TVC.

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