Thermal Performance of Vapour Chamber in Different Tilting Configurations for Battery Liquid Cooling System

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Abstract. Vapour chamber is a planar heat pipe and has been widely used in the thermal management of electronic device. In this work, a grooved aluminium vapour chamber was presented with a one-through cooling plate to develop a simplified and practicable battery liquid cooling system. The impact of filling ratio and tilting configuration on the thermal performance of vapour chamber was experimentally investigated. The results showed that the thermal resistance of the vapour chamber increased gradually with the increase in filling ratio, and there was a deterioration of the heat transfer in tilting configuration. However, the vapour chamber at 20% filling ratio had a better performance at positive tilting angle configuration compared with that at negative tilting angle configuration. Moreover, the temperature distribution of the heating surface is fairly uniform with the application of the vapour chamber. Despite the temperature rise of the cooling water in the cooling plate up to 3.8ºC, the minimum temperature difference of the heating surface could be kept within 1ºC and the minimum thermal resistance could be kept within 0.075ºC/W. The results indicate that the temperature difference of the heating surface can be suppressed through the heat and mass transport of phases inside the vapour chamber.

1. Introduction

For the battery cooling system, the main target are to keep the temperature uniform of cells on the large-area heating surface in an appropriate range of operating temperature. Some studies investigated the application of the PCM [1] and liquid cooling system [2, 3] in battery cooling system, which can improve the temperature uniformity of battery modules. However, this complicated combinations of liquid cooling system with high flow resistance were high-cost and large weight [4-7]. Vapour chamber (VC) is a heat exchanger with high equivalent thermal conductivity, which can uniform the temperature by the internal phase change process. In previous studies, vapour chamber has been widely used in the electronic cooling system, which can spread the heat from concentrated heat source. Some literatures investigated on the thermal resistance [8], the structure of grooved wick [9, 10] and the best operating parameters [11, 12], which were aimed to study the performance of novel vapour chamber in cooling system. Aluminium grooved vapour chamber meets the requirement of light weight in the field of electric vehicles, which is applicable in battery thermal management system. Moreover, one-through cooling plate is a non-isothermal heat sink with low flow resistance, but large temperature rise of the coolant. The combination of the vapour chamber and the one-through cooling plate can not only simply the design of liquid cooling system but also keep the temperature uniform of
cells with the effect of temperature non-uniformity of the coolant. However, some studies [13, 14] has found that the gravity had a deterioration on the thermal performance under different road environments. It is necessary to investigate the thermal performance of vapour chamber with the effect of the different tilting configurations in this liquid cooling system for the battery cooling system.

In this work, a liquid cooling system for battery thermal management was developed with an aluminium grooved vapour chamber and a one-through cooling plate to keep the temperature uniformity of heating surface. The influence of the tilting configurations on the thermal performance were investigated, and the effect mechanisms on thermal resistance and temperature uniformity in tilting configurations were discussed according to the experimental results.

2. Experimental setup and definitions

The profile of experimental setup is illustrated in figure 1, which contains an aluminium grooved vapour chamber, one-through cooling plate, and imitated heat sources. The vapour chamber, was sandwiched between a one-through cooling plate and three metal ceramics heaters (MCHs). The total heat power was 40W, which was similar to the generated heat flux of the battery cell under the high rate discharging condition (5333.33W/m²). The ratio of the total heat source area to the heat sink area was approximate 0.98. The generated heat transfers from the bottom to the coolant through a phase change process of vapour chamber.

![Figure 1. Schematic profile of experimental setup.](image-url)

2.1. Experimental setup

Figure 2 shows the geometry of the evaporator base, and the filling pipe was mounted in the middle of the side wall. The interior volume of the vapour chamber was 24ml, which was separated into nine longitudinal channels by fins. Ten Type-T thermocouples, calibrated with an absolute error of ±0.2ºC, were embedded on the upper and lower surface of the vapour chamber along the direction of the coolant flowing. The temperature distribution of the heating and cooling surface can be measured by a data logger (Agilent 34972A) in test conditions.

![Figure 2. Geometry of evaporator base and temperature measuring points of vapour chamber (unit: mm).](image-url)

Figure 3 shows the explosive view of the cooling plate (with the dimension of 237mm×55mm×6mm), fabricated with 304 stainless steel. The interior of the cooling plate were divided by fins into 12 channels to level the velocity of cooling water in each channel. In this work, the temperature of the inflow water was set to 25ºC, and the volumetric flow rate of cooling water was fixed at 0.15L/min.
2.2. Experimental procedure

To investigate the effect of tilting configurations on the thermal performance of the vapour chamber, we tested the tilting orientations and angles in this liquid cooling system. Before the test, the vapour chamber was vacuumed and filled with acetone as working fluid. To reduce experimental heat loss, the setup was wrapped up with insulated cotton, which was secured by two stainless steel plates and placed on an adjustable workbench, as shown in Figure 4. The tilting angle of the workbench can be adjusted on the basis of an electronic inclinometer. A DC power supply and a float flowmeter control the heat load of metal ceramics heaters and flowing rate of one-through cooling plate, respectively. In this study, the specific tilting angles and orientations of ±10°/±20° were tested as the urban and rural road environment to investigate the thermal performance of vapour chamber. Table 1 lists the test conditions of the experiment.

![Experimental setup with an adjustable workbench.](image)

**Figure 4.** Experimental setup with an adjustable workbench.

| Parameters     | Value   | Unit | Measurement            |
|----------------|---------|------|------------------------|
| Heat load      | 40      | W    | DC power supply        |
| Flow rate      | 0.15    | L/min| Float flowmeter        |
| Filling ratio  | 20–50   | %    | Sample injector        |
| Tilting Angle  | ±10°/±20| °    | Electronic inclinometer|

2.3. Definitions
According to the heat load \( (Q) \) of the DC power and the average temperatures on the heating surface and cooling surface \( (T_{h-avg}, T_{c-avg}) \), the thermal resistance \( (R) \) of the vapour chamber can be calculated by:

\[
R = \frac{(T_{h-avg} - T_{c-avg})}{Q} \tag{1}
\]

The temperature difference \( (\Delta T_h) \) of heating surface can be expressed as:

\[
\Delta T_h = \text{max}(T_{h1-5}) - \text{min}(T_{h1-5}) \tag{2}
\]

Where \( \text{max}(T_{h1-5}) \) and \( \text{min}(T_{h1-5}) \) represent the maximum and minimum temperatures of five temperatures on the heating surface, respectively.

Based on the recommended methods from reference \[15\], the uncertainty of the thermal resistance can be estimated within 9.23\%, which could be deduced from:

\[
\frac{\Delta R}{R} = \left\{ \left[ \frac{\Delta T}{(T_h - T_c)} \right]^2 + \left( \frac{\Delta Q}{Q} \right)^2 \right\}^{1/2} \tag{3}
\]

Where \( \text{min}(T_h - T_c) \) means the minimum temperature difference between the heating and cooling surface. \( \Delta T \) and \( \Delta Q \) represent the measured deviation of temperature and heat load.

3. Results and discussion

In the liquid cooling system, the large temperature rise of the coolant can decrease the temperature uniformity of the heating surface. If there is no vapour chamber used in this liquid cooling system, the temperature of the heating surface varies synchronously with the temperature of the cooling water, which means the temperature of the heating surface increases along the direction of the cooling water flowing. According to the calculation of the heat transfer in one-through cooling plate:

\[
Q = C_p \times m \times \Delta T \tag{4}
\]

Where \( C_p \) and \( m \) represent the specific heat and mass flow rate of the water, and \( \Delta T \) means the temperature rise of the coolant. The temperature rise of the coolant can be up to 3.8\(^\circ\)C, and the maximum temperature difference of the heating surface can be nearly to 4.3\(^\circ\)C, which indicates that the one-through cooling plate results in a poor temperature uniformity on the heating surface. However, with the effect of the vapour chamber, the temperature rise of coolant can be suppressed through the heat and mass transfer during the phase change process inside vapour chamber.

In this study, the tilting configuration was investigated on the thermal performance of the grooved vapour chamber. For easy describing the different tilting orientations of the vapour chamber, the tilting position is defined as a positive tilting configuration when the inlet of cooling plate is at a higher position, as shown in figure 5. Due to the effect of non-isothermal heat sink in this liquid cooling system, there is a hotspot on the heating surface near the outlet. And the direction of the vapour transport would be opposite to the direction of cooling water flowing, which is affected by the bouncy force.

![Figure 5. Schematic of vapour chamber at a positive angle.](image-url)
On the contrary, the negative tilting configuration is the position when the outlet of cooling plate is at a higher place, as shown in figure 6. And the direction of the vapour transport is parallel to the direction of cooling water flowing.

![Figure 6. Schematic of vapour chamber at a negative angle.](image)

3.1. Thermal resistance
Figure 7 shows the thermal resistance in different tilting configurations. It can be seen that, thermal resistance is on a rising trend with the increase in tilting angle. Moreover, the thermal resistance of the vapour chamber shows an obvious difference between different tilting orientations. The reason is that the partial surface of the evaporator may dry out in a large tilting angle, and the coolant flowing directions is related with the heat transfer of phases inside vapour chamber. As shown in figure 7, the thermal resistance at a positive tilting angle is smaller than that at the same angle in negative tilting orientation. For example, the vapour chamber at 20% filling ratio has the best thermal performance in the positive tilting configuration, which has the minimum thermal resistance below 0.075°C/W. However, there is a large sharp rise of the thermal resistance when the vapour chamber is in the negative tilting configuration, the maximum thermal resistance could be over 0.12°C/W. The mass transport of the vapour and liquid medium, which is affected by gravity, is relative to the heat transfer inside the vapour chamber in this liquid cooling system.

![Figure 7. Thermal resistance in different tilting configurations.](image)

The temperature distribution of the vapour chamber is influenced by the temperature rise of the cooling water in this liquid cooling system. The hotspot on the heating surface is near the outlet of the cooling plate. At a positive tilting angle, as shown in figure 5, the liquid medium inside the vapour chamber congregates at the lower place due to the effect of gravity, which makes the hotspot on the evaporator immersed in liquid medium. The heat, accumulated near the outlet, could be mitigated effectively. Meanwhile, due to the effect of the bouncy force, the pressure difference delivers the heat of vapour to the higher position, which warms the surface of the condenser near the inlet. Thus, the heat transfer can be improved through the mass transport of phases inside the vapour chamber, which may make a smaller thermal resistance in positive tilting configurations compared with that in negative tilting configurations. In other words, when the generated vapour transport is in an opposite
direction to the cooling water flowing, the heat transfer could have a certain compensation inside vapour chamber. On the contrary, at a negative tilting angle, the hotspot was totally exposed to the vapour, which made the heat transfer deteriorated in the phase change process. In general, the results indicate that the tilting configurations can decrease the thermal performance of the vapour chamber, it is obviously seen that the vapour chamber at negative angles has a higher thermal resistance than that at positive angles in this liquid cooling system.

Moreover, it also can be seen in figure 7 that the vapour chamber at 20% filling ratio has the smallest thermal resistance. The overfilling liquid may block the transport of the vapour, and the thermal resistance increases with the increase in filling ratio.

3.2. Temperature uniformity
Figure 8 shows the temperature difference of the heating surface in different tilting configurations. It can be seen that, the thermal uniformity of the vapour chamber becomes worse under the tilting conditions due to the partial dried-out evaporator. Despite the temperature rise of the cooling water up to 3.8°C, the temperature distribution of the heating surface is fairly uniform in the positive tilting configuration. The vapour chamber at 30% filling ratio can keep the temperature uniformity of the heating surface within 1°C, which indicates that the temperature rise of cooling water can be suppressed by vapour chamber in the positive tilting configurations. However, the temperature difference increases sharply when the vapour chamber is in the negative tilting configuration, especially at 20%~30% filling ratio. This is because the hotspot of the evaporator cannot be effectively immersed into the liquid medium, as shown in figure 6, which results in the phase change process deteriorated. With the increase in filling ratio, the temperature non-uniformity on the surface can be mitigated because of the heat conduction process, which shows a better temperature uniformity on the heating surface at large filling ratio. The results indicate that the tilting configurations can decrease the thermal uniformity of the vapour chamber, especially the vapour chamber under negative tilting angles at small filling ratio.

4. Conclusions
The temperature rise of the coolant and tilting configurations are main factors influencing the temperature uniformity of the heating surface. To develop a simplified and efficient liquid cooling system for the BTMS to keep the temperature of heating surface uniform, the tilting configurations of an aluminium grooved vapour chamber were investigated on the thermal performance with a one-through cooling plate. In this study. The minimum temperature difference of the heating surface could be kept within 1°C and the minimum thermal resistance of vapour chamber can be kept within 0.075°C/W at horizontal conditions, which could suppress the temperature rise of the cooling water. The tilting configurations can result the deterioration of the thermal performance of the vapour chamber.
Different tilting orientations and angles result in different thermal performance in this liquid cooling system, which indicates that the configurations at negative tilting angles in this liquid cooling system need to be avoided in actual road environment especially. Moreover, the vapour chamber at 20%–30% filling ratio can homogenize the temperature distribution well on the heating surface, which is an appropriate filling ratio range of the vapour chamber.

5. References

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Acknowledgments

This work was supported by the National Key R&D Program of China (2018YFB0104502).