ENHANCED BATTERY THERMAL REGULATION USING WATER–ETHANOL-BASED OSCILLATING HEAT PIPES: AN EXPERIMENTAL INVESTIGATION

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ABSTRACT

Effective thermal management of lithium-ion batteries is crucial to ensure their performance, safety, and lifespan, particularly under high-load operating conditions. In this study, a lithium-ion battery is experimentally investigated, incorporating circular shaped oscillating heat pipe (OHP). The heat pipe was filled with a mixture of water and ethanol and was used to emulate thermal behavior under rapid discharge and thermal runaway scenarios. Experiments were conducted by varying the volume ratio (VR) and filling ratio (FR). Among the tested compositions, OHP with 50% FR and 40-60 VR of water and ethanol mixture exhibited better heat transfer performance. The temperature drops to 47.7^{0}C which is below the desired limit of 50^{0}C. Compared to the system with a 0% filling ratio, a temperature reduction of 42.5°C was observed. This significant improvement highlights the effectiveness of using a water-ethanol mixture in pulsating heat pipes for cooling lithium-ion batteries. Such a setup presents a viable and efficient solution for managing battery temperatures in electric vehicles, contributing to improved thermal stability and overall performance.

Keywords - Lithium-ion battery; Ethanol, Oscillating heat pipe; Battery Discharging

INTRODUCTION

As concerns about greenhouse gas emissions from fossil fuels continue to rise, substantial attention has been directed toward the development of electric vehicles (EVs). Among the various battery technologies used in EVs, lithium-ion batteries stand out as the most promising, owing to their high energy density, extended lifecycle, and absence of memory effect [1]. However, to maintain optimal performance and ensure safety, the operating temperature of these batteries must be carefully regulated [2].

During both charging and discharging cycles, lithium-ion cells generate a considerable amount of heat due to internal resistance and electrochemical reactions. This makes a Battery Thermal Management System (BTMS) essential for maintaining the battery within a safe operating temperature between 25°C and 50°C [3,4]. An efficient BTMS not only ensures battery reliability and performance but also extends the overall lifespan of the system.

BTMS approaches are generally categorized into three types: active, passive, and hybrid systems. Active systems require external energy input, such as forced air or liquid cooling to dissipate heat[5]. In contrast, passive systems rely on natural heat transfer mechanisms like convection, conduction through heat pipes, or the use of phase change materials (PCMs) and operate without consuming additional energy. Hybrid systems combine elements of both to leverage the strengths of each approach.[6,7]

Park et al. [8] introduced a one-dimensional thermal model of a cylindrical battery to analyze temperature profiles and operating conditions. Their study included both air-based and liquid-based BTMS models. The findings suggested that compact battery modules with minimal spacing between cells are more suitable for liquid cooling. Moreover, their analysis showed that liquid-based systems are generally more energy-efficient than air-based ones.

Furthering this research, Mahamud et al. [9] proposed a strategy utilizing reciprocating airflow in cylindrical lithium-ion cells, modeled with two-dimensional computational fluid dynamics. Their simulations demonstrated that this technique could reduce the temperature gradient within the battery by about 4°C and lower the peak cell temperature by approximately 1.5°C, especially with a 120 second reciprocation cycle.

In another study, Chen et al. [10] optimized the spacing between battery cells for air-cooled systems. Their numerical simulations revealed that strategically adjusting the inter-cell distance can significantly improve the cooling efficiency. Park [11] emphasized that forced air cooling remains a practical solution for electric vehicle. He noted, however, that consistent airflow distribution is crucial for uniform heat dissipation across multiple battery cells. Given air relatively low thermal conductivity [12], a high flow rate is usually required to cool the cells effectively.

Yang et al. [13] explored air as a cooling medium in lithium-ion battery packs. Their results indicated that while increasing airflow enhances temperature uniformity, it also raises power consumption, ultimately reducing system efficiency. Moreover, under high-stress conditions such as rapid discharge or elevated ambient temperatures (above 40°C) air cooling alone often fails to maintain a uniform or sufficiently low battery temperature.

Chacko and Charmer [14] evaluated an indirect liquid cooling method and concluded that it offers a highly reliable approach for battery thermal management. Complementing this, Panchal et al. [15] carried out both experimental and numerical studies on cold plates with narrow channels. Their results showed that higher discharge rates and operating temperatures directly lead to increased cold plate temperatures. Similarly, Basu et al. [16] proposed a liquid-cooled model. Their system employed aluminum components to thermally connect the cells, enhancing overall heat dissipation and system stability.

In the present paper, A 60V, 40Ah lithium-ion battery pack with OHP is experimentally evaluated by using water and ethanol mixture as base fluid at different FR and VR. The volume concentration of water and ethanol mixture is varied as 40-60, 50-50 and 60-40. Also the filling ratio is varied as 30%, 40%, 50% and 60% respectively.

DESIGN AND FABRICATION OF OHP

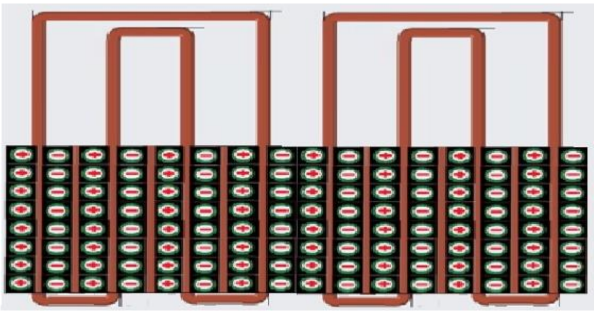


Fig.1 System layout of OHP assisted battery cooling system

Fig. 1 presents the experimental setup, featuring the battery pack integrated with a circular-shaped OHP made from copper tubing. To enhance thermal management efficiency, the system employs two independent OHP units. Each unit consists of a copper tube with an outer diameter of 3 mm and an inner diameter of 2.5 mm. The total length of each OHP is 749 mm, which includes a 600 mm evaporator section and a 300 mm condenser section. The tubes are arranged with a center-to-center spacing of 42 mm, resulting in an overall OHP module width of 138 mm.

The battery system is composed of standard cylindrical lithium-ion cells, each with a physical dimension of 65 mm in length and 18 mm in diameter. Each cell delivers a nominal voltage of 3.7 V and has a rated capacity of 5 Ah. The complete battery pack consists of 128 cells, organized into two identical modules. Each module features an 8×8 matrix configuration, comprising 8 rows and 8 columns of cells.

EXPERIMENTAL SETUP

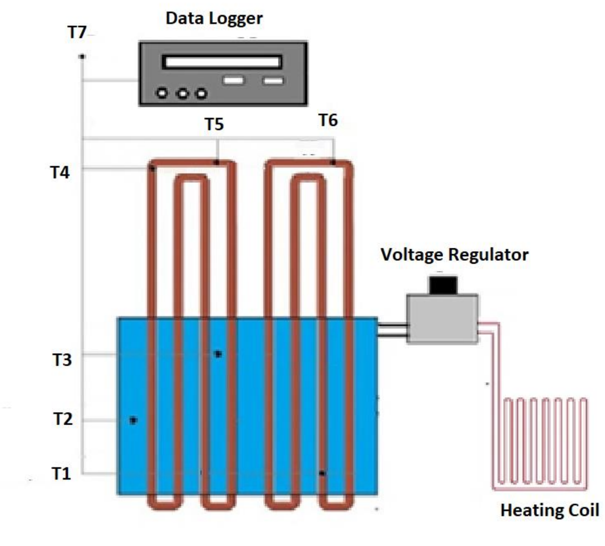


Fig. 2. Setup schematic diagram

The battery pack integrated with a circular OHP, along with a voltage regulator, a heating coil, and a data acquisition system for real-time temperature monitoring is depicted in Figure 2. Temperature measurements were conducted using T-type thermocouples with a wire diameter of 0.1 mm. Thermocouple T7 was designated to monitor ambient temperature. Three thermocouples (T1–T3) were installed along the condenser section, while an additional three thermocouples (T4–T6) were strategically positioned within the evaporator section and across the battery pack to capture temperature distribution. All measurements were continuously recorded using a dedicated data logger. The condenser section of the heat pipe was passively cooled through natural convection.

RESULTS AND DISCUSSION

Fig. 3 presents the temperature profile of the OHP under dry conditions, tested at a 0% filling ratio (FR), meaning no working fluid was present. As time progressed, the temperature within the battery pack steadily increased, eventually peaking at 90.2°C, which is significantly higher than the ambient temperature. In the absence of a working fluid, heat transfer within the OHP occurred primarily through conduction along the copper tube. At the condenser section, the limited heat dissipation that did occur was mainly due to natural convection and thermal radiation, resulting in inefficient cooling performance.

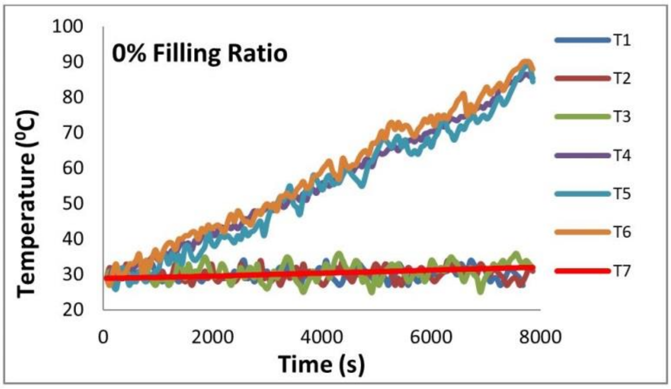
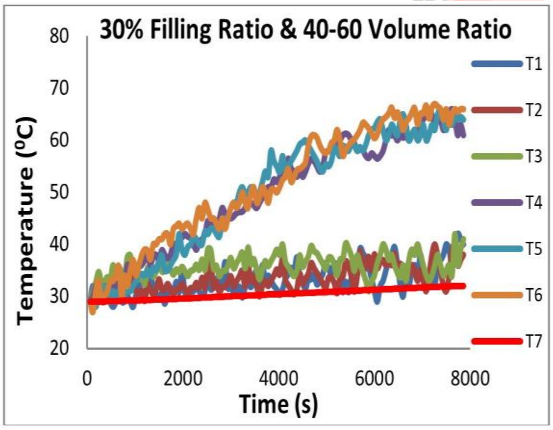
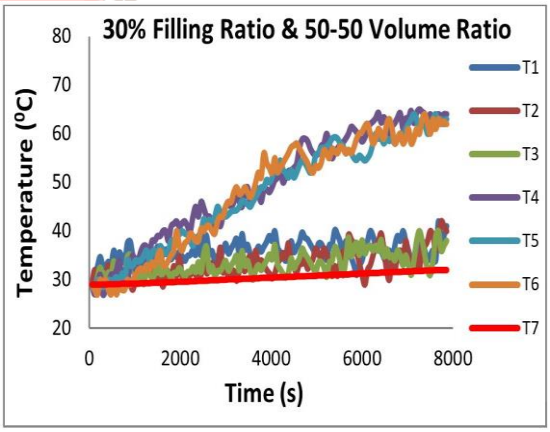


Fig. 3. Temperature profile of OHP over time for 0% FR.

The transient temperature response of the OHP using water–ethanol mixtures at volume ratios of 40:60, 50:50, and 60:40, with a FR of 30% is illustrated in Fig. 4. The results indicate that the introduction of these binary working fluids led to a noticeable improvement in thermal performance compared to the empty OHP condition. Although the temperature within the OHP still increased over time, the rise was significantly lower than that observed in the absence of a working fluid. This suggests that even at a relatively low filling ratio of 30%, the water–ethanol mixtures enhanced the heat transfer characteristics of the system.





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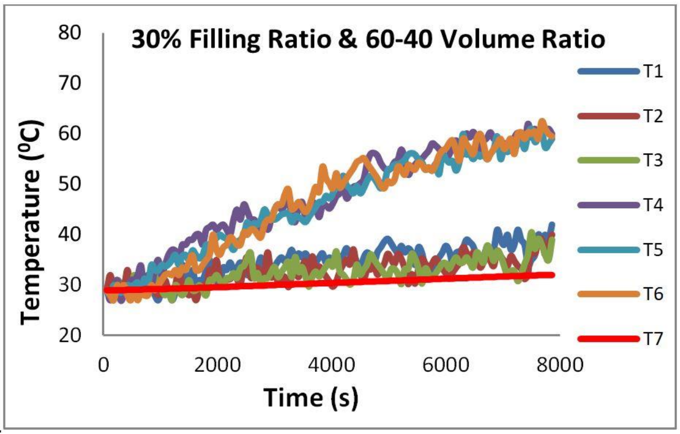

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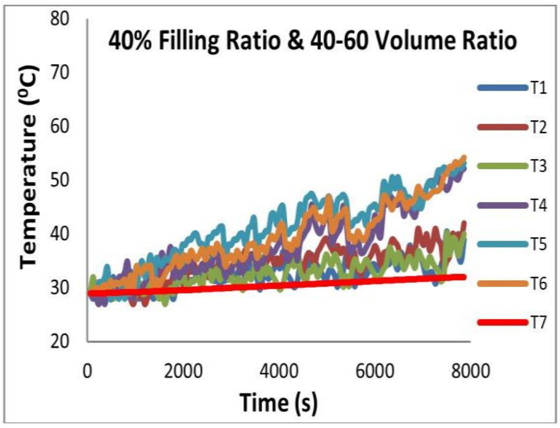
Fig. 4. Temperature profile of OHP over time at 30% FR for Various Water–Ethanol Mixtures *(a) 40:60, (b) 50:50, (c) 60:40 VR*



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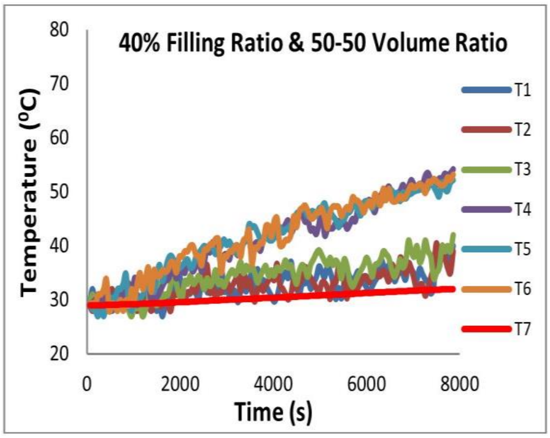

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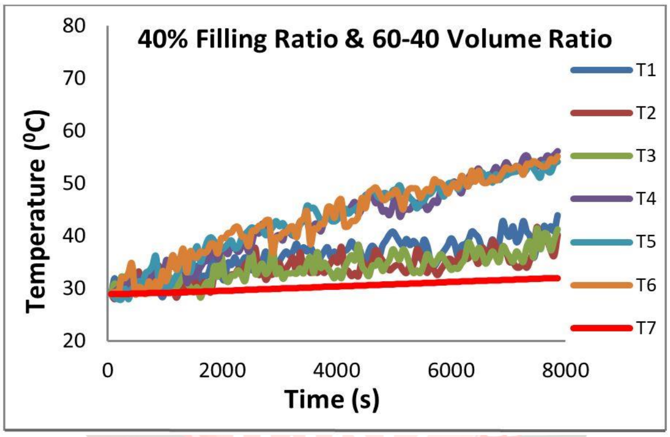

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Fig. 5. Temperature profile of OHP over time at 40% FR for Various Water–Ethanol Mixtures (a) 40:60, (b) 50:50, (c) 60:40 VR

Initially, the base fluid does not reach its boiling point due to insufficient heat generation within the system. However, as heat accumulates over time, vapor bubbles begin to form in the evaporator region, initiating oscillatory motion within the OHP. This pulsating action significantly enhances heat transfer, leading to improved thermal performance as the experiment progresses. As a result, the temperature of the battery pack decreases from an initial peak of 89.9°C observed in the dry condition to approximately 65.8°C when using the working fluid. Furthermore, increasing the ethanol concentration in the water–ethanol mixture leads to better activation of the OHP, enhancing its overall cooling effectiveness. With higher ethanol content, the battery pack temperature drops even further, reaching 64.1°C and 61.2°C for the respective volume ratios, indicating a clear correlation between ethanol concentration and improved thermal regulation.

Fig. 5 compares the temperature profiles of OHP charged with water–ethanol mixtures at various volume ratios (60:40, 50:50, and 40:60) under a 40% filling ratio. The results clearly indicate that the mixture with a 40:60 water-to-ethanol volume ratio delivered superior cooling performance compared to the other combinations. As the ethanol content increased, the battery pack temperature decreased more effectively, attributed to the lower boiling point and improved volatility of ethanol. The consistent and prolonged temperature oscillations observed in the condenser section further enhanced heat transfer. The highest temperatures in the evaporator section were recorded as 53.9°C, 53.1°C, and 51.8°C for the 60:40, 50:50, and 40:60 volume ratios, respectively.

Figure 6 shows the transient temperature behavior of the OHP using the same water–ethanol mixtures, but with an increased FR of 50%. With this higher FR, the thermal performance further improved, and the battery pack temperatures decreased to 47.7°C, 49.9°C, and 51.5°C for the 40:60, 50:50, and 60:40 mixtures, respectively. This improvement is attributed to more efficient fluid oscillation and enhanced suggesting phase-change activity within the evaporator section. The condenser temperature showed only a marginal rise compared to the ambient temperature, indicating effective heat rejection.

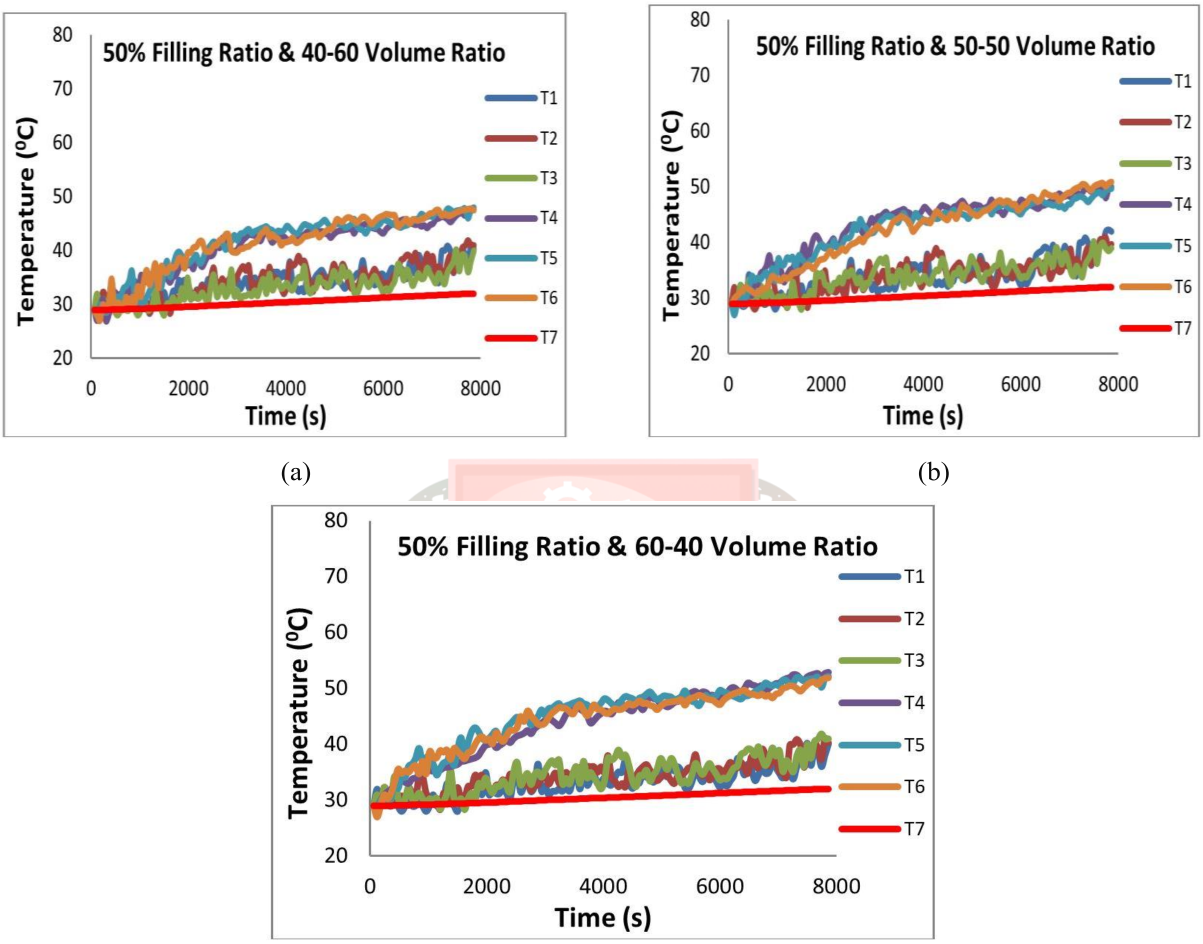

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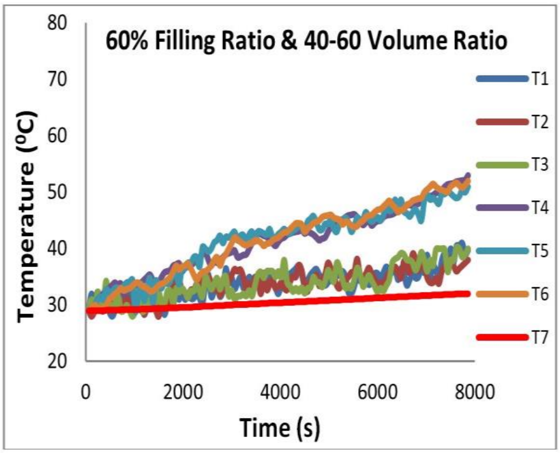
Fig. 6. Temperature profile of OHP over time at 50% FR for Various Water–Ethanol Mixtures *(a) 40:60, (b) 50:50, (c) 60:40 VR*

Fig. 7 compares the thermal performance at a 60% filling ratio for the same fluid mixtures. Interestingly, further increasing the filling ratio resulted in higher battery pack temperatures, a decline in cooling performance.



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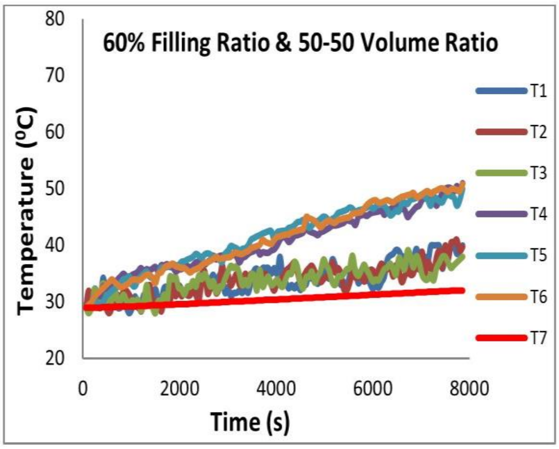

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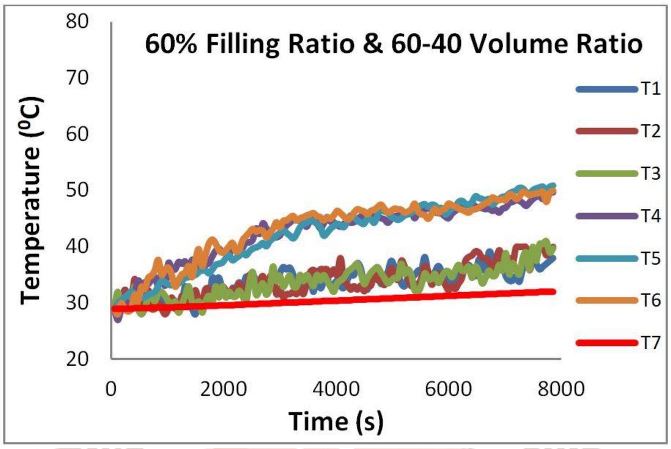

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Fig. 7. Temperature profile of OHP over time at 60% FR for Various Water–Ethanol Mixtures *(a) 40:60, (b) 50:50, (c) 60:40 VR*

The measured temperatures rose to 49.3°C, 50.9°C, and 52.8°C for the 40:60, 50:50, and 60:40 ratios, respectively. This reduction in efficiency is likely due to limited space for bubble formation in the evaporator section at higher liquid volumes. The suppressed nucleation and reduced oscillation impair the fluid motion within the OHP, thereby diminishing the effectiveness of heat transfer from the evaporator to the condenser The filling ratio and volume ratio of the working fluid play a crucial role in influencing the transient thermal behaviour of the system. Under optimal conditions specifically, a 50% filling ratio combined with a 40:60 water–ethanol volume ratio the system achieved the lowest initiation temperature of 47.7°C, indicating the most effective thermal response.

Conclusion

In this experimental investigation an OHP was tested using water–ethanol mixtures as the working fluid, with volume ratios of 40:60, 50:50, and 60:40, and filling ratios of 30%, 40%, 50%, and 60%. The results were compared against a dry OHP condition (0% filling ratio). It was observed that even a 30% filling ratio significantly improved heat transfer performance. Under these conditions, the battery pack temperature dropped from 90.2°C (dry case) to 66.0°C, and further declined to 64.1°C and 61.2°C with varying volume ratios (60:40, 50:50, and 40:60, respectively). This demonstrates that both FR and VR have a substantial influence on OHP performance.

When the FR was increased to 50%, further enhancement in thermal performance was observed. The battery pack temperatures were reduced to 51.5°C, 49.9°C and a minimum of 47.7°C for the 60:40, 50:50, and 40:60 mixtures, respectively. The lowest recorded temperature, 47.7°C occurred at a 50% filling ratio with a 40:60 water–ethanol mixture representing a temperature reduction of 42.5°C compared to the dry condition. This clearly highlights the importance of optimizing both fluid composition and FR for effective thermal management using OHPs

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