Visualization Experiment of Immersion Cooling of the Battery Thermal Management System using Mineral Oil and Aluminum Nitride Nanofluids

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With the improvement of the performance of electric vehicles, the heat generation of the battery increases, and the battery thermal management system becomes very important. Immersion cooling has become an important thermal solution, exposing the battery directly to the liquid to improve heat dissipation efficiency. Adding nano-aluminum nitride to the fluid can increase the thermal conductivity of the fluid. In this study, the concentration of the aluminum nitride nanofluids in mineral oil ranged from 0 to 3.0 wt%. According to the viscosity test, it is found that the viscosity of aluminum nitride nanofluids is greatly affected by temperature. In addition, the experimental state and test temperature data are captured by a visualization testing platform to study the feasibility of nano-aluminum nitride in immersion cooling.

NOMENCLATURE

C = the charge and discharge current of the battery (-)
H = the measurement range on the TSI (-)
h = the measurement height per 20μm on the TSI (-)
I = current (A)
i = the number of scans on the TSI (-)
q = the battery heating rate per unit volume (W/m^3)
T = temperature (°C)
T_1–T_8 = thermocouples (-)
U = the test voltage of the battery cell (V)
U_0 = open circuit voltage of the battery cell (V)
V_b = effective calculated volume of the battery cell (m^3)

1. Introduction

Net-zero carbon emission is the global consensus on environmental development, and countries strive to develop electric vehicles [1] to achieve the goal of net-zero carbon emission. As the power density of electric vehicle batteries increases a year than a year, the heat generated by the batteries increases accordingly. If the temperature of the battery exceeds 45 °C, the performance of charge and discharge will be damaged [2]. Excessive temperature will cause the battery to catch fire, seriously endangering the safety of personnel. Therefore, how to quickly and massively conduct heat away from the battery for effective heat dissipation has become an important research topic. Currently, the heat dissipation of electric vehicle batteries divides into air cooling and liquid cooling. The advantage of air cooling is that the heat dissipation module is lighter, but the disadvantage is that the heat dissipation ability is worse than that of liquid cooling. Therefore, commercial electric vehicles, electric buses, and so forth choose liquid cooling to dissipate heat from the battery. The immersion cooling system is direct liquid cooling. The advantage is that the cooling liquid directly contacts the battery without using thermal interface materials, which reduces thermal resistance and improves heat exchange [3] and can improve the temperature uniformity of the space, save heat dissipation energy, and save heat dissipation costs. Charlotte Roe et al. [4] reviewed the literature on immersion cooling for lithium batteries, including the advantages of immersion cooling for batteries, which can achieve a more uniform temperature and improve the battery's healthy life. In this study, in order to make further improvements in the heat exchange performance of immersion cooling, nano-aluminum nitride (AlN) was introduced into mineral oil, and various heat transfer and fluid performance analyzes were carried out.

The introduction of nanofluids into the field of heat dissipation originated from the publication of the General Theory of Electromagnetism by Maxwell [5]. In addition to integrating the theory of electromagnetic properties, it also brought a new concept of a two-phase flow of particles mixed in fluids. Although it was impossible to make nanofluids in the early 20th century, Maxwell used a theory to predict that adding round particles to the suspended liquid would improve the thermal conductivity. In the middle of the 20th century, Hamilton and Crosser [6] believed that heat transfer should occur on the particle surface, so they controlled the shape and surface area of the particle, corrected the Maxwell model, and further increased the thermal conductivity. In 1975, Ahuja [7] studied the effect of particle volume, size, and flow rate on heat conduction. However, at that time, nanoparticles and suitable suspending agents could not be produced, and nanoparticles could not be properly separated from the fluid. Only in the working fluid, adding micron- and millimeter-sized particles to the experiment showed an increase in thermal conductivity, verifying that Maxwell's theoretical predictions were correct. Unfortunately, due to the large particles, the experiment eventually blocked the pipeline and even caused pipeline wear.

At the end of the 20th century, nanotechnology gradually matured. Choi [8] was the first to use copper oxide nanofluids and titanium dioxide nanofluids to explore the thermal conductivity in nanofluids and improve the lack of previous micro-particles and millimeter-particles. Luo [9] used nano-silicon carbide to add oil to perform immersion cooling on the data center to study its optimal heat dissipation. The results of the study found that the addition of nano-silicon carbide can increase the heat transfer capability of the immersion cooling liquid because the suspended nano-powder can achieve good heat exchange when the fluid flows. Wong et al. [10,11] used a visualized flat heat pipe and observed the heating condition of the evaporation area in the case of pure water, acetone and methanol in nano-alumina fluid and nano-copper powder fluid. It was found that the maximum heat transfer rate of nanofluids was 20% higher than that of pure water, resulting in a little boiling. Ho et al. [12-14] studied nanoparticle doped in mineral oil and pure water. It is analyzed the cooling of electric vehicle batteries. They found that graphene and nanoparticle doped in mineral oil or pure water can effectively reduce the temperature. Moreover, they designed machine learning to optimize the parameters of nanofluids. Therefore, it cannot be doped with too high a concentration, so that the improvement of heat exchange is limited. Therefore, this article studies the high thermal conductivity nano-AlN, mixed with mineral oil, uses the experimental platform to verify the temperature of the model battery at different charges and discharges, and discusses the experimental results of the nano- AlN on the battery thermal management system.

2. Experimental Methods

2.1 Battery heat

Huang et al. [15] studied the heat generation of batteries during discharge. The heat generation rate of a single battery during discharge can be calculated through the Bernadi equation, as shown in equation (1). The battery heating rate q (W/m^3) per unit time and unit volume can be expressed as:

$$q = \frac{1}{V_b}\left[I^2 R_0 + IT\frac{dU_0}{dT}\right] \quad (1)$$

I is the current through the battery, which is positive when charging and negative when discharging. V_b is the effective-calculated volume of a single battery cell. U and U_0 are the test voltage and open circuit voltage of the battery cell, respectively. T is the current battery temperature. TdU_0/dT is a parameter related to the electrochemical reaction, called the temperature coefficient. The internal resistance can be set to 0.04 Ω, and TdU_0/dT can be set to 0.01116 V. The heat generation rate under different discharge conditions can then be calculated as a constant value. According to the research of Sato [16] and Bernardi et al. [17], calculate the heating rate of a single 18650 battery under discharge, and the 1C discharge current is 1.35 A.

A single 18650 battery has a diameter of 18 mm and a height of 65 mm, so the volume V_b is 1.654×10^{-5} m^3. Assuming that the inner group is 0.04 Ω and TdU_0/dT is 0.01116 V, the heating rate q per unit volume of a single battery is 0.088 W. For example, calculate the heat generation rate of a single 18650 battery under discharge, and the 2C discharge current is 2.70 A, then the heat generation rate q of a single battery unit volume is 0.322 W as Table 1.

Table 1. Heat generation of 18650 battery during different discharge

Discharge rate	Current of the cell	Heat generation rate (W)
1C	1.35A	0.088 W
2C	2.70A	0.322W

2.2 Viscosity

The viscosity coefficient affects the flow rate of the immersion cooling fluid. A low viscosity coefficient will allow for smooth fluid flow and improved heat transfer. On the contrary, high-viscosity fluids tend to accumulate heat in the heat dissipation system and cannot be cooled smoothly. Adding nano-AlN will increase the thermal conductivity, but it will affect the viscosity coefficient. Therefore, it is necessary to find the appropriate parameters to achieve the best heat exchange. In this study, we used a sine wave vibratory viscometer (SV-10) from A&D Co., Ltd., with a test viscosity range of 0.3 mPa·s-10_mPa·s. The dispersant used in the experiment is sodium dodecyl benzene sulfonate (SDBS). In the experiment, the concentration of SDBS was fixed at 0.5 wt%, and the amount of mineral oil was 40 g. The ambient temperature of the experiment was 25.0±1.0 °C, 45.0±1.0 °C and 65.0±1.0 °C. The measurement temperature was measured with a k-type 1 mm diameter stainless steel sheath probe (Omega, Inc.), and the temperature error was 0.1 °C. As shown in Figure 1.

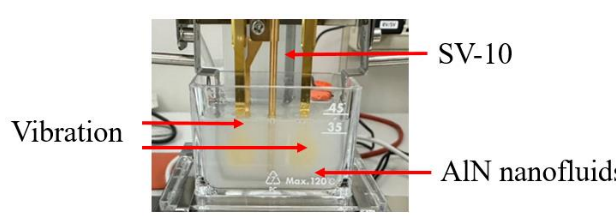

Figure 1. Viscosity measurement experiment platform

For one experiment, the amount of mineral oil was 40 g, the concentration of AlN was varied from 0.1 wt% to 3.0 wt%, and the concentration of SDBS was fixed at 0.5 wt%. In another experiment, the amount of mineral oil was 40 g, the concentration of AlN was fixed at 0.5 wt%, and the concentration of SDBS was from 0.1 wt% to 3.0 wt%. Both experiments were tested at three different ambient temperatures.

2.3 Suspension

The suspending ability of nanofluids affects the heat transfer performance of immersion cooling. Due to the poor concentration configuration of SDBS and AlN, nanoparticles will cluster in the fluid due to Brownian motion, and subsequent precipitation will reduce the heat transfer performance of immersion cooling and may block the pump. This experiment utilizes the principle of multiple light scattering to measure the dispersion state and time-dependent changes of various graphene nanofluids. The equipment used is Turbiscan, and the applicable range of nanoparticle size is 5 nm~1,000 μm. The measurement method is to measure the sample from the bottom up and display the total stability index (TSI) in real time. The larger the TSI value, the more unstable the dispersion; the smaller the TSI value, the more stable the dispersion.

$$TSI = \sum_i \frac{\sum_h |scan_i - scan_{i-1}|}{H} \qquad (2)$$

H is the measurement range, h is the measurement height per 20_μm, and i is the number of scans. There are four bottles of test samples: 0.5 wt% AlN in mineral oil, add 0.5 wt% SDBS; 0.5 wt% AlN in mineral oil, add 2.0 wt% SDBS; 2.0 wt% AlN in mineral oil, add 0.5_wt% SDBS; 2.0 wt% AlN in mineral oil, add 2.0 wt% SDBS.

If the TSI is less than 3, it means destabilization phenomenon and most likely not visible; if the TSI index falls between 3 and 10, it means important destabilization and can be visible; if the TSI index is greater than 10, it means high destabilization and surely visible.

In order to prevent the various experiments from being affected by precipitation, we will use an electromagnetic stirrer for 2 hours of nanofluids disturbance before each experiment, and use an ultrasonic oscillator for 4 hours of fluid shock. As shown in Figure 2.

Figure 2. Electromagnetic stirrer (left) and ultrasonic oscillator (right)

2.4 Experiment platform

The experimental design refers to the previous research [12]. We use red copper to make a battery model with a diameter of 18.0 mm and a height of 65 mm. A heating rod with a diameter of 6.5 mm and a height of 50 mm is placed in the center. And arrange thermocouples, these thermocouples, K-type 1 mm-diameter (Omega, Inc.), are denoted by T1-T4, respectively. T1 monitors the temperature change of the heating rod and uses thermal interface material (TIM) to reduce the air thermal resistance of the heating rod, thermocouples, and the inner wall of the battery model. The thermal conductivity of TIM is 1.0 W/m-K. T2 detects the surface temperature of the battery model, T3 observes the temperature change of the immersion fluid, and T4 monitors the ambient temperature, as shown in Figure 3. The overall experimental structure, in which the immersion cooling chamber is installed, adopts a four-sided transparent design for visualization research. There is another cavity under the transparent cavity, with a built-in pump, which can transport the cold fluid below to the right side of the upper transparent cavity, and the flow channel is designed on the left side of the transparent cavity, allowing the heated fluid to flow back from the top to the bottom by gravity for cooling, as shown in Figure 4.

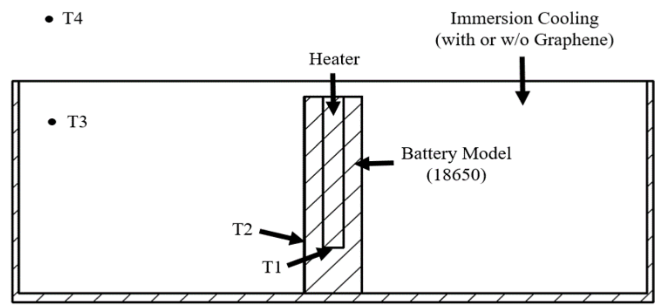

Figure 3. Thermocouple positions

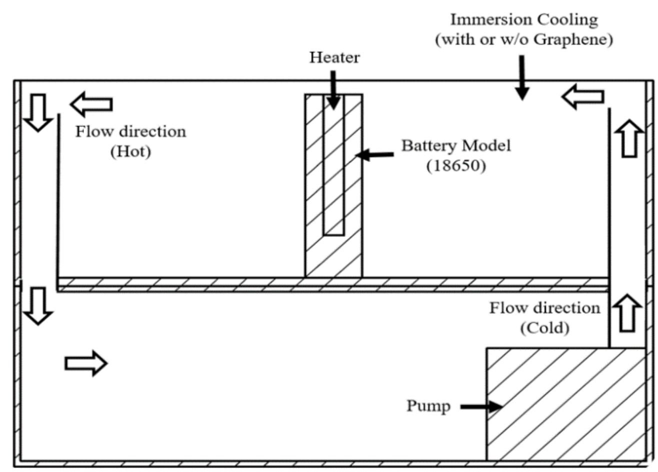

Figure 4. Experiment platform

3. Experimental Results

We used 40 g of mineral oil, SDBS concentration of 0.5 wt%, AlN concentration of 0.1 wt% to 3.0 wt%, and temperatures of 25 °C, 45 °C, and 65 °C to observe the viscosity change. As shown in Figure 5, the higher the concentration, the greater the viscosity change, and the changes of the three temperatures have a greater influence on the viscosity than the change of the concentration. It can be seen from the experiment that if the temperature is 25 °C, the viscosity of 2.5 wt% AlN concentration is twice that of 0.25 wt% AlN concentration, but if the concentration of 2.5 wt AlN is 25 °C, the viscosity is 5 times that of 65 °C. As the temperature rises, the viscosity will drop significantly. Therefore, when the battery is dissipated, the temperature will rise and the viscosity will drop after the nano- AlN immersion cooling liquid contacts the battery. A decrease in viscosity represents a decrease in flow resistance, which can increase the rate of heat exchange. The AlN concentration used in the battery immersion cooling experiments was 1.0 wt%.

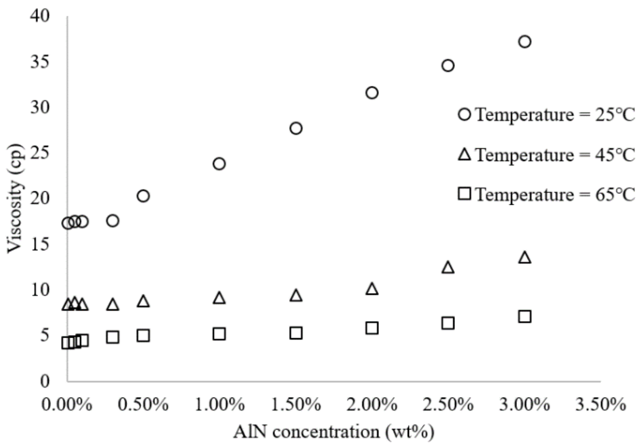

Figure 5. AlN concentration and viscosity

We use 40 g of mineral oil, the concentration of AlN is 0.5 wt%, the concentration of SDBS is 0.1 wt% to 3.0 wt%, and the ambient temperature is 25 °C, 45 °C, and 65 °C. As shown in Figure 6, when the SDBS concentration is below 3.0 wt%, the viscosity does not change much, but the viscosity will obviously decrease as the temperature rises. When the ambient temperature is 25 °C, the viscosity is four times that of the ambient temperature 65 °C. Therefore, it is speculated that when the temperature of the battery is raised, the temperature of the AlN nanofluids increases, and the viscosity will decrease, resulting in a decrease in flow resistance. Therefore, the SDBS concentration is selected to be 0.5 wt%.

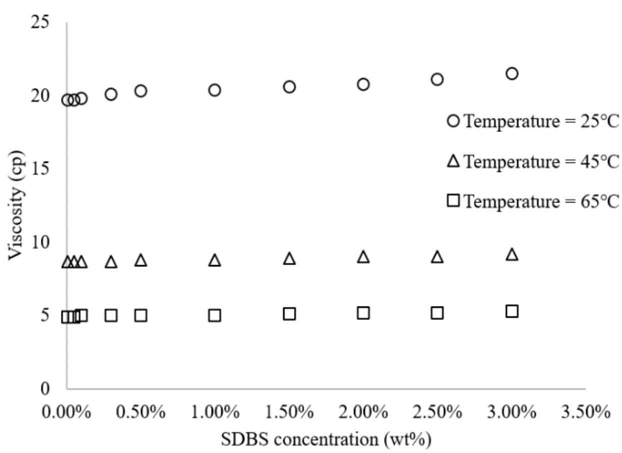

Figure 6. SDBS concentration and viscosity

There are four bottles of test samples: AlN concentration is 0.5 wt%, SDBS concentration is 0.5 wt%; AlN concentration is 0.5 wt%, SDBS concentration is 2.0 wt%; AlN concentration is 2.0 wt%, SDBS concentration is 0.5 wt%; AlN concentration is 2.0 wt%, SDBS concentration is 2.0 wt%. The results are shown in Table 2. After 7 days of suspension experiments, the TSI values of the four bottles were all above 10, and no obvious precipitation occurred. Therefore, it is deduced that the concentration of AlN is between 0.5 wt% and 2.0 wt%, the concentration of SDBS is between 0.5 wt% and 2.0 wt%, and the nano-suspension force for one week will not be affected. According to this result and the results of the viscosity experiment, it is reasonable for us to adopt an AlN concentration of 1.0 wt% and add SDBS concentration of 0.5 wt% for subsequent cooling experiments of the battery under heating at 1C and 2C.

Table 2. Suspension test results

Item	AlN concentration (wt%)	SDBS concentration (wt%)	TSI
1	0.5	0.5	14.5
2	0.5	2.0	13.8
3	2.0	0.5	13.6
4	2.0	2.0	14.2

In the actual measurement, we give the heating rate per unit volume of the battery as 0.088 W and 0.322 W. The corresponding battery charge and discharge are 1C and 2C. The temperature of the battery model immersion cooling was compared using pure mineral oil and mineral oil added with 1.0 wt% nano-AlN and 0.5 wt% SDBS. The test time is 20 minutes, and the temperature change of the battery model is recorded every 5 minutes. It is observed from the experimental results that the temperature of the battery model will enter a steady state after about 15 minutes. Because the viscosity experiment shows that temperature has a great influence on the viscosity, the ambient temperature of 25 °C and 45 °C is used for the experiment. As shown in Figure 7, when the ambient temperature is 25 °C and the battery is charged and discharged at 1C and 2C, pure mineral oil immersion cooling can keep the battery at about 27.3 °C and 27.5 °C, while the introduction of nano-AlN mineral oil can make the battery cool down by about 0.3 °C at 1C and 2C. Adding nano-AlN to mineral oil, when the ambient temperature is 25 °C, although the experimental results have made the surface temperature of the battery drop, it only drops 0.3 °C, and the effect of heat transfer is not obvious.

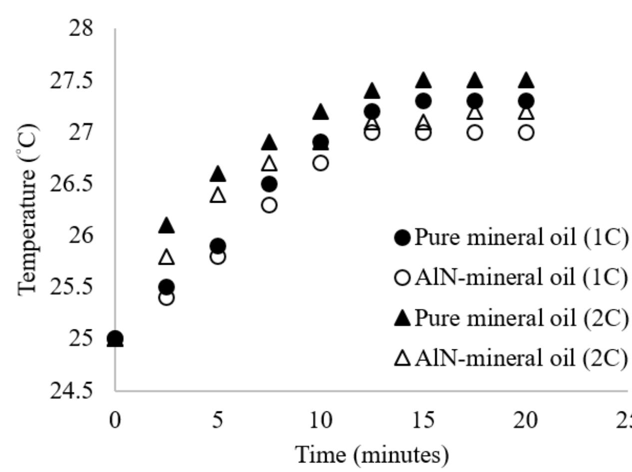

Figure 7. Test results when the ambient temperature is 25 °C

However, when the ambient temperature was raised to 45 °C in the experiment, such as in a real desert environment or summer. For batteries 1C and 2C, we still give 0.088 W and 0.322 W heating. The experiment time is 20 minutes, which is the same as when the ambient temperature is 25 °C, and the temperature of the battery appears stable in approximately 15 minutes. The experimental results show that pure mineral oil immersion cooling can keep the battery at 28.5 °C and 29 °C. Mineral oil containing nano-AlN can maintain the battery at 27.8 °C and 28.2 °C. The overall temperature dropped by about 0.7 to 0.8°C. As shown in Figure 8. The cooling effect when the ambient temperature is 45 °C is significantly better than that when the ambient temperature is 25 °C.

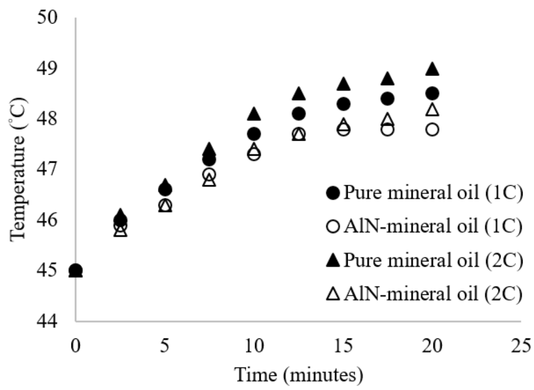

Figure 8. Test results when the ambient temperature is 45 °C

4. Conclusions

This experiment uses a viscometer to test the viscosity experiment of adding different nano-AlN to mineral oil and fixing the concentration of SDBS. As well as viscosity experiments testing a fixed concentration of AlN added to mineral oil and varying the concentration of SDBS. Both experiments used different ambient temperatures: 25 °C, 45 °C, and 65 °C. In addition, the suspension test was used to ensure that the experimental concentrations of AlN and SDBS were not precipitated to avoid experimental inaccuracies.

Experiments have found that when the concentration of nano-AlN is below 3.0 wt%, and the concentration of SDBS is below 3.0 wt%, the influence of ambient temperature is greater than the concentration change of nanofluids or SDBS. Therefore, in the cooling experiment of the battery model, we use 25 °C and 45 °C tests. It was found that the addition of nano- AlN can effectively improve heat exchange and reduce the surface temperature of the battery.

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