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Battery Thermal Management Using Phase Change Process

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ABSTRACT

In an era of escalating resource depletion and environmental concerns, the exploration of non-conventional resources has become a global imperative. These alternative resources offer a multifaceted solution, allowing for sustainable energy storage, reducing pollutant emissions, and mitigating resource scarcity. Central to this energy storage paradigm are batteries, which play a pivotal role in various applications, including electric vehicles and hybrid electric vehicles. Among the battery types, lithium-ion batteries have emerged as preferred choices due to their attributes of lightweight design, extended lifespan, high energy density, and adequate power output. However, prolonged and demanding usage scenarios, particularly in the context of electric vehicles, can lead to substantial temperature differentials within battery packs, posing significant challenges to battery performance and longevity. This present work delves into the critical importance of battery thermal management systems in sustaining the efficiency and durability of energy storage systems. In this context, nanofluid two-phase change process (boiling) have garnered considerable attention as an efficient solution. Nanofluids possess a unique set of attributes, including a high latent heat capacity, non-toxicity, and other advantageous characteristics. By integrating nanofluids into battery systems, these materials exhibit the capacity to maintain optimal operating temperatures with high heat removal rate, significantly enhancing the overall performance and longevity of batteries. A two-phase pool boiling experimental setup is developed to explore the effectiveness of phase change heat transfer process for cooling devices. The two-phase heat transfer experiments are conducted with different volumetric percentage (0.025 to 0.10) of alumina-water nanofluid. The alumina-water nanofluids are significantly improved the heat transfer performance with lower surface superheat temperature. The maximum heat transfer performance is achieved with 0.1% volumetric of alumina-water nanofluid.

Keywords: Phase-transition, Lithium-ion battery, Utilization, Efficiency, Sustainability, Nanofluids.

INTRODUCTION

The world faces a pressing issue of the excessive use of conventional resources is rapidly depleting them, leading to a scarcity that could occur within a few years. This has prompted a global search for alternative, non-conventional resources. These resources not only address the scarcity problem but also offer a unique opportunity to store energy in batteries, a crucial aspect of modern life. By harnessing non-conventional resources, we can significantly reduce pollutants and harmful emissions, contributing to a cleaner environment. However, a challenge arises when we rely on batteries for continuous energy usage, especially in applications like electric vehicles and hybrid electric vehicles, where lithium-ion batteries are commonly used due to their lightweight nature, long lifespan, high energy density, and reasonable power output. Continuous usage of these batteries can lead to temperature spikes within battery packs. This elevated temperature can negatively impact the battery's capacity and overall lifespan. Hence, it becomes essential to implement a thermal management system for these battery packs. One effective solution for battery thermal management is the use of Phase Change process with Nanofluids. Nanofluids while going through Phase Change Process possess remarkable properties such as high latent heat capacity, non-toxicity, and more. When integrated into battery systems, Nanofluids play a critical role in maintaining optimal operating temperatures. Researchers have found that adjusting the composition of Nanoparticles in a Nanofluid can significantly reduce battery temperatures, leading to a decrease in energy loss rates. To keep our reliance on non-conventional resources sustainable and our environment clean, it is vital to tackle the overheating issue in batteries. Utilizing Nanofluid based cooling systems is a promising strategy, as they not only ensure the efficient operation of batteries but also contribute to the broader goal of reducing our dependence on conventional resources while minimizing the impact on our planet's well-being Optimizing the generation and transmission of energy in industrial processes is crucial for economic sustainability. Industries like petrochemical and refineries consume energy for heating and cooling. A significant portion of this energy comes from burning fossil fuels, which is harmful to the environment and costly.

The development of electric vehicles (EVs) has undergone major breakthroughs over the last decade. Further improvement of EVs can be found in increased battery performance and more efficient energy schemes. Because the battery-pack durability and life also affect the cost and reliability of the vehicle, any parameter that affects this battery lifetime must be optimized. Temperature (range and uniformity) has a strong influence on the battery (pack) lifetime and thus on the overall performance of EVs. Comparable thermal issues in high-end electronics are faced with advanced thermal management schemes based on boiling heat-transfer. That is, thermal homogenization as well as cooling is attained very effectively by heat exchange of the device with a boiling medium. Boiling heat-transfer namely affords cooling capacities substantially beyond that of conventional methods. It furthermore, allows for thermal homogenization very effectively as it, irrespective of heat fluxes, happens at a fixed temperature for a given pressure. cool boiling may serve as physical representation for heat transfer applications based on boiling heat-transfer. In thermal management schemes based on pool boiling, it is of importance to keep the system in the desired boiling mode. Due to fluctuating and uncertain heat-transfer demands this is a challenging task. Therefore, the boiling process in these thermal management schemes must be regulated. Controllers that achieve this are to be developed using theoretical models describing the dynamics of these systems. Pool boiling may serve as physical representation for thermal conditioning applications based on boiling heat-transfer. Such systems consist of a heater to supply heat to the liquid in the pool.

1. EXPERIMENTAL SETUP AND PROCEDURE

1.1 Components

1.1.1 Copper Block

Copper is a highly conductive and ductile metal with a reddish-brown color. It has excellent thermal and electrical conductivity, making it essential in electrical wiring, electronics, and heat exchangers. Certain machining operations such as facing, turning, step turning, drilling has been performed on the copper block as per the requirement for the experimental setup Initially the diameter and height of the copper block is 4.5cm and height of 16 cm which was further reduced to the height of 9.5cm with diameter 4.5cm, second step of 3 cm diameter and height of 2.5 cm finally in third step turning reduced to a height of 3.5 cm height and 1.2 cm diameter. The final machined copper block is shown in Fig.1.

Fig.1 copper block

1.1.2 Thermocouple

J-type thermocouples are temperature sensors composed of iron and constantan. They offer a broad temperature range (-210°C to 1,200°C) with moderate sensitivity. These sensors are highly durable, suitable for harsh environments, and widely used in industries like food processing and pharmaceuticals. Their accuracy varies and may require periodic recalibration. Proper color coding (black) helps in easy identification. J-type thermocouples as shown in below Fig.2 are essential tools for measuring temperature in various applications due to their reliability and cost-effectiveness. In these experimental setups the thermocouple is used to measure the temperature of the copper block and the temperature of the phase change material in the Teflon block to analyze the changes occurred in the liquid.

Fig.2 J-Type Thermocouple

1.1.3 Teflon Block

Teflon, also known as polytetrafluoroethylene (PTFE), is a remarkable synthetic material renowned for its non-stick and low-friction properties. In the form of a block, Teflon exhibits excellent chemical resistance, electrical insulation, and a wide temperature tolerance, ranging from -200°C to 260°C (-328°F to 500°FTeflon blocks are favored for their versatility, non-toxic nature, and ability to reduce friction and wear. Some of the machining operations such as a hole of about 8 cm was made at the front face of it, a hole of 2.7 cm was made on the top of the block for the reflexive condenser and a hole of 1.2 cm is made at the bottom for the contact of Teflon block. The final machined Teflon Block is shown in Fig.3.

(a) (b)

Fig.3 Teflon Block: before machining (a), after machining (b)

1.1.4 Cartridge Heater

A cartridge heater, shown in Fig.4, whether it's 1.2 cm and 9.5 cm in height, is a versatile electric heating element used in various industrial applications. It consists of a cylindrical metal tube with a resistive heating element inside. These heaters are designed for efficient and uniform heat transfer, making them suitable for heating liquids, gases, or solid materials. The smaller 1.2 cm diameter cartridge heaters are commonly used in precision equipment, while the larger 9.5 cm diameter heaters find applications in industrial processes, including plastics molding and extrusion, metalworking, and packaging machinery. This cartridge heater is inserted into the hole that is made to the copper block at the bottom surface to heat the copper block.

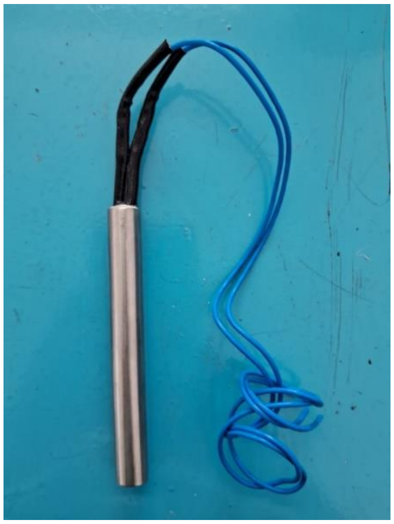


Fig.4 Cartridge Heater

1.1.5 Reflex condenser

A reflexive condenser, often referred to as a reflex condenser, is an essential component in laboratory apparatus used for distillation and reflux processes. It consists of a vertical glass tube with an inner coiled tube. The coiled portion allows vapor to rise and condense, while the liquid then flows back into the original flask or reaction vessel. This design effectively prevents the loss of valuable compounds during distillation, ensuring a more efficient and controlled process. Reflex condensers as shown in Fig.5, are vital tools in chemistry laboratories, providing a means to separate and purify substances through distillation techniques.

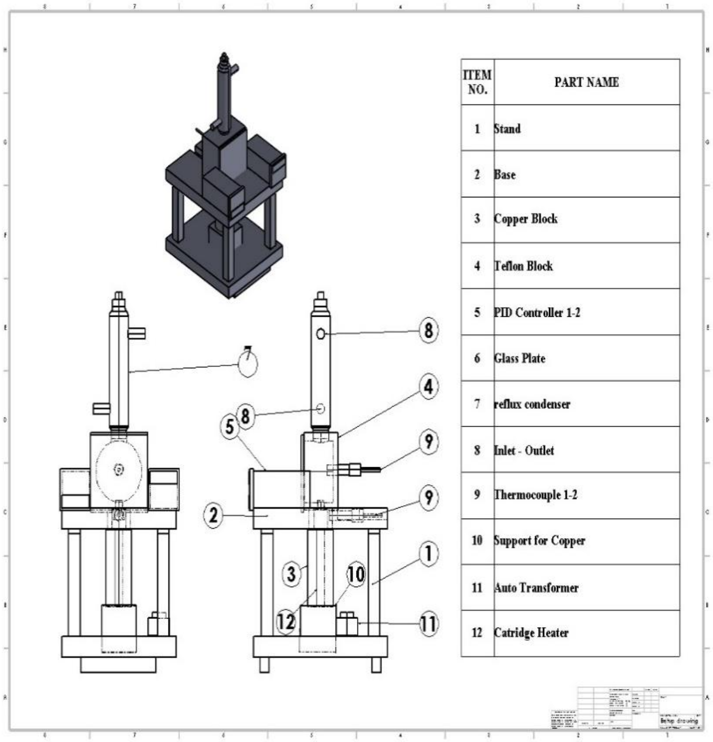
Fig.5. Reflex Condenser

1.1.6 PID Controller

A PID (Proportional-Integral-Derivative) controller as shown in Fig.6, is an essential device in control systems engineering. It regulates processes by continuously adjusting an output based on the difference between a desired setpoint and a measured process variable. The proportional term responds to the current error, the integral term corrects accumulated past errors, and the derivative term anticipates future errors. This combination of actions provides precise and stable control in various applications, such as industrial automation, temperature regulation, and robotics, enhancing system performance and accuracy.

Fig.6. PID Controller

EXPERIMENTAL SETUP



ITEM NO.	PART NAME
1	Stand
2	Base
3	Copper Block
4	Teflon Block
5	PID Controller 1-2
6	Glass Plate
7	reflux condenser
8	Inlet - Outlet
9	Thermocouple 1-2
10	Support for Copper
11	Auto Transformer
12	Catridge Heater

Experimentation

In this experiment, the process of boiling has been analyzed. Here, a special experimental setup is fabricated. A rectangular block made of PTFE-Teflon. This block holds the test area. The one side of Teflon block is drilled and fitted the fiber glass with the help of screws so that observation can be happened through this side. And moreover, Teflon is provided with three holes, such as bottom hole for copper block, rear face hole for J-type thermocouple and top hole for reflux condenser. Initially, the analysis takes place with pure water and then move into Nanofluids. The copper block is arranged in such a way that, the tip of the block is inserted into the bottom hole of the Teflon block. Copper block is insulated for uniform, heat flow. The copper block is heated by cartridge heater and the heat input of heater can be controlled through the auto transformer. Auto transformer helps in control the voltage which is directly related to heat input. And current can be measured by ammeter. To measure the temperature of liquid, thermocouple is placed at the rear face in such a way that thermocouple must in contact with liquid and it is connected to the digital scanner so that readings can be observed. As the heat passes through copper block to liquid so that temperature of the liquid raises and attains steady state after sometime. After liquid attains steady state, due to continuous heat supply phase change of the liquid takes place. The converted steam is passes through reflux condenser and converts into liquid in condenser due to continuous flow of water through inlet and outlet of the condenser. Another thermocouple is fitted to the surface of copper block at a distance of 10 mm from the tip of the copper block and connected to the another PID controller.

Following our experiment, we utilize two fundamental laws of heat transfer: Fourier's Law of Conduction and Newton's Law of Cooling. Initially, Fourier's Law is employed to determine the temperature at the tip of the copper block where it makes contact with the Teflon block. This helps to understand how heat spreads within our materials. Subsequently, Newton's Law of Cooling is applied to calculate a parameter known as the heat transfer coefficient. This coefficient deals with how effectively heat moves between the copper and liquid.

Preparation of Nanofluids

Mainly the process used in this preparation of the phase change materials is firstly the magnetic stirring and then the sonication. The solutions prepared are:

- The solution volumetric percentage is 0.025% (0.05 grams of alumina nano powder for 200ml of water).

Magnetic stirring

Magnetic stirring is a fundamental technique employed in various scientific and industrial contexts to achieve thorough and uniform mixing of substances in solution. By focusing on the controlled mixing of water and alumina nano powder, operating the magnetic stirrer at a constant speed of 1000 revolutions per minute (rpm). The magnetic bar, powered by a rotating magnetic field beneath the container, parts a swirling motion to the magnetic bar, creating turbulence within the solution. This motion enables the effective dispersion and integration of solid particles, such as alumina nano powder, into the liquid medium, in this case, water.

Fig.7 Magnetic Stirring

Ultra Sonication

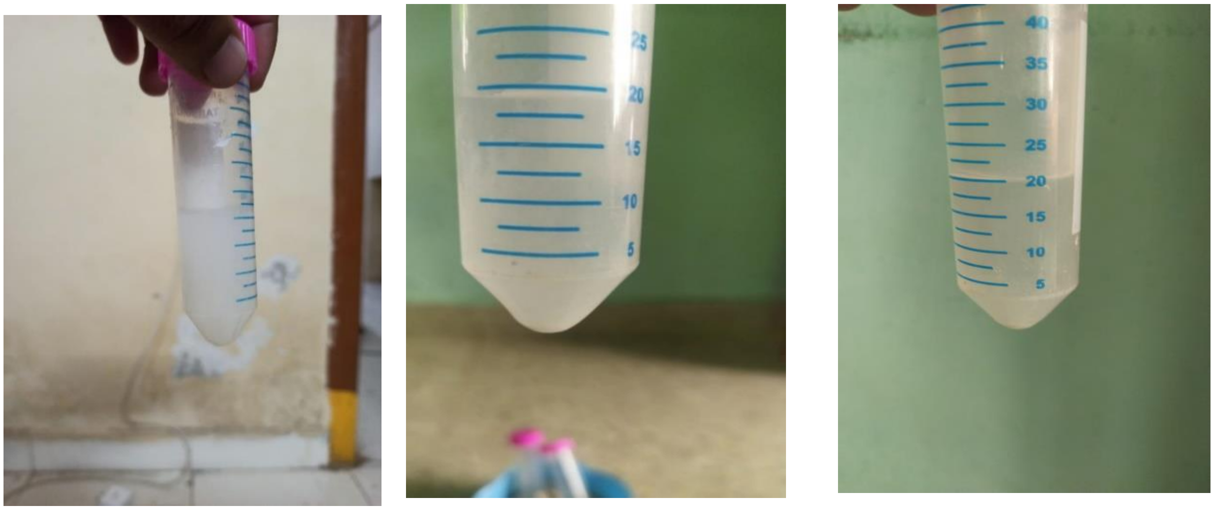
Ultrasonication, often referred to as sonication, is a transformative technique employed in a wide range of scientific, industrial, and medical applications. At its core, ultrasonication utilizes high-frequency sound waves, here at 20kHz, to create powerful mechanical forces within a liquid medium. These forces, generated by a process known as cavitation, drive various processes with exceptional precision and efficiency. Cavitation is the formation, growth, and collapse of tiny vapor-filled bubbles (cavities) within the liquid subjected to ultrasonic waves. During the rarefaction phase of the sound wave, pressure decreases, causing these bubbles to form. Fig.8 shows the process of Ultra sonication.

Fig.8 Ultra sonication

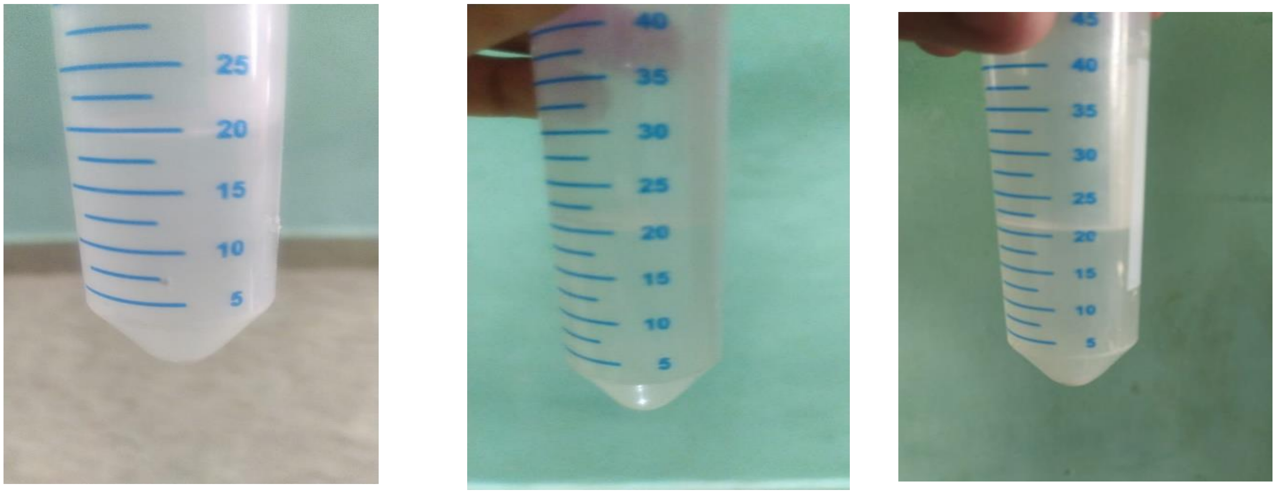
RESULTS AND DISCUSSIONS

Observations from the stability analysis of Nanofluids

0.025Vol% of alumina nanoparticles solution



(a) (b) (c)



(d) (e) (f)

Fig.9 Sedimentation of 0.025Vol% Nanofluid on (a) 1st day, (b) 2nd day, (c) 3rd day, (d) 4th day, (e) 5th day, (f) 6th day

The magnetic stirring was conducted for the solution of 0.05 grams of alumina and 200ml of water for two hours for the correct mixture of the particles the solution the after the solution was kept for the sonication as alumina particles are of small sizes were dissolved and the mixture was formed correctly this solution was observed for six days to test the stability of the solution. The observations are shown in Fig.9.

Two-phase heat transfer analysis of prepared nanofluid

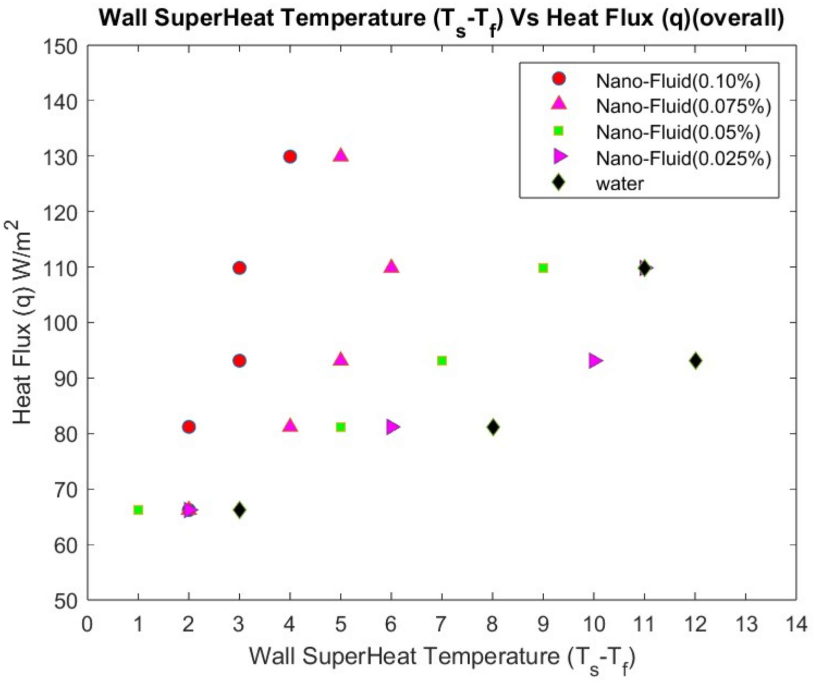


Fig.10 Wall Superheat Temperature (T_s – T_f) Vs Heat Flux(q)

The heat transfer characteristics of the pool boiling using a unique working fluid that is nanofluid, which is constituted of water with alumina Nano-particles at atmospheric pressure, were examined. By volume, several diluted volumetric percentages ranging from 0.025 % to 0.1 % were acquired to prepare the nanofluids. The pool boiling curve, which is shown in Fig.10 for the nanofluids and water, is the relationship among the wall superheat temperatures and applied heat flux. It should be noted that the boiling characteristics graphs for nanofluids were moved to the left of the pure water pool boiling characteristics graphs at the equivalent heat flux for all volume percentages. This indicates that, compared to the base situation of water, the effectiveness of pool boiling performance was increased for present nanofluids. However, compared to the lower percentages (i.e., 0.025 % and 0.050 %) employed in this experiment, the improvement in the boiling curve was obtained better at larger volume percentages (i.e., 0.10 % and 0.075 %). In addition to the development of bubbles at the bottom of the mixture, the nanoparticles deposition with varied particle sizes at high volume percentage triggered the nucleation spots, increasing surface roughness and forming a nano porous layer across the flat surface. In addition, the nanoparticles deposition created a highly conductive Alumina nano porous coating at the high heat flux, which enhanced the heat transfer from the boiling surface to the bulk working liquid.

CONCLUSION

The characteristics of Al_2O_3-water nanofluids that transmit heat during pool boiling are reported in the current work. In this test, several volume percentages (0.025 % to 0.1 %) were experimentally explored. This experimental study intends to assess the boiling performance of nanofluids on a horizontal copper cylindrical surface. The pool boiling characteristics graphs of water from a bare copper surface with a primary roughness of 0.08 µm were plotted and compared with the expected correlation in the literature, and the acquired findings match a fair agreement. These nanofluids enhanced the efficiency of boiling heat transmission, as shown by decreasing the wall superheat at a specific heat flux for all volume percentages causes the pool boiling profiles for nanofluids to move to the left. With a reduction in surface contact angle, nanofluids become more wettable and capillary. Pool boiling heat transmission and critical heat flux in nanofluids are improved by the developments in wettability and capillarity. The accumulation of nanoparticles on the heating surface is the cause of surface roughness improved with particle addition. Higher volume fractions cause the increase in roughness to be more noticeable, which improves pool boiling performance. This was the main cause of the pool boiling improvement throughout the moderate levels of heat supplied with a variety of volume percentages utilized in the current study.

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