Experimental Investigation of Liquid Metal Droplet on the Heat Transfer Performance in an Oscillating Heat Pipe

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An oscillating heat pipe (OHP) charged with a hybrid fluid is investigated. This hybrid fluid uses an emulsion-based mixture of liquid metal gallium microdroplets suspended in an ethanol solution. The gallium microdroplets are fabricated using an ultrasonication technique. The OHP is fabricated from a copper plate and contains a six-turn channel with a 3×3 mm^2 cross section. The heat transfer performance of the OHP was investigated experimentally with different concentrations of gallium at a 50% filling ratio. Steady-state oscillating motion was achieved with weight concentrations of gallium up to 20%. The experimental results show that using gallium-in-ethanol hybrid fluid emulsion as the working fluid can increase the heat transfer performance of the OHP by up to 7.8% over pure ethanol at 300 W. The mass of gallium needed to achieve this magnitude of heat transfer improvement is drastically reduced compared to previous research.
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Keywords: heat pipes, oscillating heat pipes, phase change heat transfer

Introduction

An oscillating heat pipe (OHP) is a heat transfer device [1,2] that consists of closed interconnected tubing that uses the pressure difference produced by the temperature difference to drive a train of liquid plugs and vapor bubbles and produces the oscillating motion. The evaporation in the evaporator section and the condensation in the condenser section plus the oscillating motion can effectively transport heat in an OHP. The oscillating motion is caused by the pressure imbalances resulting from the volume expansion and contraction of the vapor plugs during phase change. The synthesis of phase-change heat transfer and oscillating motion of the working fluid results in extremely high effective thermal conductivity [3]. In comparison to conventional heat pipes, OHPs can effectively transfer heat at a wider range of power inputs [3–7] and can be manufactured with different materials [7,8], sizes, and shapes [9–11]. As modern electronics require higher power demands, increasing attention to the development and improvement of thermal management technologies is necessary to eliminate high heat fluxes. OHPs will play an integral part in meeting increasing power demands well into the future.

The OHP heat transfer performance depends on the physical and thermal properties of an OHP including the shell material from which an OHP is fabricated, channel inner diameter, channel length, channel shape, turn number, filling ratio, surface wetting characteristics, thermal conductivity, viscosity, and latent heat of vaporization. To form liquid slugs and vapor plugs, the inner hydraulic diameter of the OHP channel must be smaller than the maximum hydraulic diameter (MHD). The MHD can be predicted by [1]

$$D_h \leq 1.84\sqrt{\frac{\sigma}{g(\rho_l - \rho_v)}} \tag{1}$$

where σ is the surface tension between liquid and vapor, ρ_l and ρ_v are the density of the liquid and vapor respectively, and g is the acceleration due to gravity. Chu et al. [12] fabricated a copper OHP with eight turns and a 6-millimeter inner diameter to study the heat transfer performance. Two working fluids, deionized water and ethanol, were used to charge the OHP where the hydraulic diameter of the OHP exceeded the MHD by 19.6% and 91.6%, respectively. It was found that the OHP could function well even with the hydraulic diameter exceeding the MHD by 91.6%.

Working fluids with a high $(\partial P/\partial T)_{sat}$, the slope of the vapor–liquid saturation line, and a low latent heat have been shown to facilitate the easier start-up of OHPs at lower temperatures and heat inputs [13]. Low latent heat allows for the fluid to quickly evaporate and condensate with relatively little heat input. A steep slope of the vapor–liquid saturation line means that small changes in temperature result in high-pressure changes when the fluid is in a saturated state. These properties enable a high driving force of the liquid slugs. Binary mixtures have been investigated to improve the effective thermal conductivity of OHPs [14]. Hao et al. [14] investigated the heat transfer performance of an OHP using a water and erythritol mixture. Erythritol's high heat of fusion allows it to absorb and release large amounts of energy during its phase change, absorbing heat as it melts in the evaporator and releasing heat as it solidifies in the condenser. A six-turn copper OHP was fabricated and tested with varying concentrations of erythritol. It was found that low concentrations of erythritol (1–5 wt%) improved the thermal performance of the OHP by up to 10%. The low thermal conductivity and high viscosity of the erythritol solution produced a negative effect on the OHP's performance at higher concentrations.

Liquid metal has been proposed as a working fluid because it has the properties of both metal and fluid. Liquid metals have high thermal conductivity and exist in a liquid state at or around room temperature. Thermal devices that use pure liquid metal need an external energy source to provide the necessary driving force for operation. For use in OHPs, liquid metals need to be supplemented with other phase-change liquids in order to operate with no external

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source. Hao et al. [15] investigated the performance of a six-turn copper OHP charged with water–galinstan hybrid fluids of varying concentrations of galinstan. It was found that galinstan increased the performance of the OHP at heat inputs above 260 W. The thermal resistance of the OHP saw a 13% reduction at an 8 g galinstan concentration at 420 W. At the highest concentration of galinstan (8 g, 10.7 wt%), the start-up power increased from 140 W to 180 W. Galinstan is an alloy of gallium which has a thermal conductivity of 16.5 W/(m · K), almost 30 times higher than that of water. It is a non-toxic substance that exists in a liquid state near room temperature. These qualities suggest that gallium and its alloys are ideal working fluids for an efficient cooling device. However, galinstan has a high density and viscosity compared to conventional working fluids. A greater driving force is needed to start up the oscillations of the hybrid fluid. At low heat inputs, higher concentrations of galinstan are not beneficial to the oscillation of the water slugs. Ethanol and acetone have latent heats of vaporization of 109 kJ/kg and 518 kJ/kg, respectively, both significantly lower than water. Due to their low latent heat of vaporization, Ethanol and Acetone are good candidates for a phase-change liquid that will be able to provide the driving force for higher concentrations of galinstan with relatively low heat input as compared to water. Hao et al. [16] investigated the heat transfer performance of a six-turn polytetrafluoroethylene OHP charged with water, ethanol, and acetone. The results showed that the acetone-filled OHP provided the best thermal performance. With acetone, the temperature oscillated with the highest frequency and the time for the start-up was the shortest, signaling a higher driving force and faster slug oscillations. The overall thermal resistance of the acetone-filled OHP was reduced by 30–63% compared to the water-filled OHP.

Mixtures of nanoparticles that are suspended in a base fluid are called nanofluids. They both increase the thermal conductivity of the working fluid and reduce the effective thermal resistance of an OHP with concentrations as low as 1 wt% [17,18]. The emulsion of liquid metal in a fluid medium can be seen as similar to a nanofluid. Kumano et al. [19] found that heat transfer was improved using an emulsion of high-viscosity oil as compared to low-viscosity oil. Trinh and Xu [20] found an up to 70% increase in the heat transfer coefficient using an ethanol/polyalphaolefin (PAO) nanoemulsion flowing through a microchannel as compared to pure PAO under flow boiling conditions. Further studies are needed to further understand the mechanisms behind improved heat transfer of liquid–liquid emulsions.

In this investigation, the effect of liquid metal/phase-change fluid emulsions on the heat transfer performance of an OHP is analyzed. Gallium microdroplets are fabricated using an ultrasonication process and mixed into ethanol solutions with various concentrations. An experimental setup is developed for the hybrid fluid OHP (HFOHP), which will be tested against an OHP using pure ethanol as its working fluid. An analysis of the experimental data is conducted to determine whether using liquid metal microdroplet hybrid fluid improves the heat transfer performance over using pure ethanol by calculating the thermal conductance of the OHP.

Experimental Description

Experimental Setup. The schematic drawing of the experimental setup is shown in Fig. 1. The setup mainly includes a copper flat-plate OHP, a heating plate, a power supply, a cold plate, a cooling bath, insulation material, a data acquisition system, a computer, and thermocouples. The DC power supply provides current to the cartridge heaters, which in turn provide power to the OHPs via joule heating. The cold plate is a 115×37 mm^2 aluminum block with integrated tubes that connect to a cooling bath that pumps water at a constant temperature of 15 °C. The heater block is made from a 59×50 mm^2 aluminum block with four inserted cartridge heaters that provide up to 600 W of power. The heater block and cold plate are fastened to the OHP with bolts, with a thin layer of

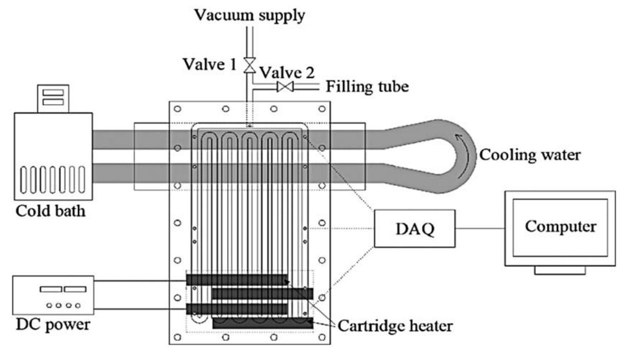

Fig. 1 Schematic drawing of experimental setup

OMEGATHERM™201 silicone grease applied between the surfaces to reduce thermal resistance. The OHP's dimensions are shown in Fig. 2. The OHP total length is 130 mm, with an evaporation section length of 59 mm, an adiabatic section length of 10 mm, and a condensation section length of 37 mm. The complete OHP assembly is a copper base with a 3×3 mm^2 cross-section channel machined into it bolted onto a transparent polycarbonate cover plate, with a 0.5 mm thick high-temperature silicone rubber sheet lying between. Insulation material covers the entire OHP to prevent heat loss to the outside environment.

The back-filling charging method [1] was employed for charging the working fluid. The OHP was evacuated before it was charged, and a Varian DS 602 vacuum pump was employed for this process. After a vacuum of $\sim 3 \times 10^{-1}$ torr was achieved, the OHP was fully charged with ethanol that is then boiled out to ensure minimal air is left in the OHP. The OHP was then charged to a 50% filling ratio with varying concentrations of ethanol-in-gallium hybrid fluid emulsion. The gallium concentrations by weight fractions are 1%, 5%, 10%, and 20%. This converts to 0.048 g, 0.25 g, 0.52 g, and 1.14 g of gallium respectively inside the OHP when charged to a filling ratio of 50%. Eight T-type thermocouples were implemented into the system to track the temperature. Six thermocouples were inserted into the OHP thermocouple holes to measure the temperature variations: two in the condenser section, two in the adiabatic section, and two in the evaporator section. The remaining two thermocouples are inserted into the inlet and outlet of the condenser block. The temperature data are collected by a Measurement Computing™ USB-2408 at a rate of 5 Hz with the maximum uncertainty of ±0.2 °C. The heating input was provided by a VARIAC transformer (Model No: TDGC-2KM) with a voltage resolution of 0.5% and a current resolution of 1.0% and varies from 100 W to 300 W with 50 W increments, with 5 min being given to allow the OHP to reach steady state at each heat input. The thermal conductance of the OHP is calculated by

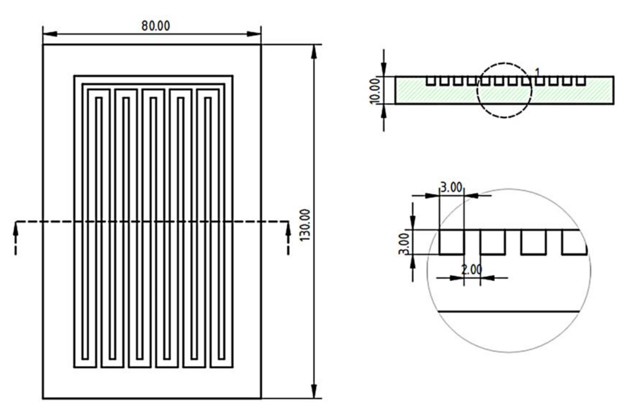

Fig. 2 Dimensions of the OHP (unit: mm)

$$C = \frac{Q_e}{\bar{T}_e - \bar{T}_c} \quad (2)$$

where Q_e is the power input into the evaporator via the cartridge heaters, T_e is the area-averaged temperature of the evaporator, and T_c is the area-averaged temperature of the condenser. The uncertainty of the thermal conductance can be calculated by

$$\frac{\delta C}{C} = \sqrt{\left(\frac{\delta T_e}{T_e - T_c}\right)^2 + \left(\frac{\delta T_c}{T_e - T_c}\right)^2 + \left(\frac{\delta Q}{Q_e}\right)^2} \quad (3)$$

where the uncertainty of the heat input can be found by

$$\frac{\delta Q}{Q_e} = \sqrt{\left(\frac{\delta U}{U}\right)^2 + \left(\frac{\delta I}{I}\right)^2} + \frac{\delta Q_{loss}}{Q_e} \quad (4)$$

where U is the voltage output from the DC power supply, I is the current, and δQ_{loss} is the heat loss which was determined by the heat input on the evaporator compared to the heat output from the condenser, which was less than 4.5%. The heat loss depended on the heat input. The maximum experimental uncertainty of the heat input is less than 4.8%.

Properties of Working Fluids

Gallium is one of five naturally occurring liquid metals. Gallium has a useful combination of properties that are similar to both a liquid and a metal. Due to this, gallium has been chosen as the liquid metal for this research. As a pure gallium OHP would require an external driving force to operate, another fluid needs to be implemented for a self-actuating OHP device to be feasible. Ethanol has been studied extensively in previous research. Ethanol's low density, boiling point, and latent heat of vaporization make it a good candidate for a phase-change fluid that can provide a driving force strong enough to oscillate the gallium. Table 1 shows the thermophysical properties of gallium and ethanol.

Emulsion Production of Liquid Metal Microdroplets

Finding efficient and easily repeatable ways to create liquid metal microdroplets in large amounts has been a recent area of interest. Gallium microdroplets have been suggested for use in a variety of applications ranging from flexible electronics, composites, and creating 3D structures [22]. Various methods are used to manufacture these microdroplets, such as ultrasonication, flow-focusing microfluidics, and submerged electrodispersion [22–24]. Ultrasonication has been chosen as the method of choice for this work because of the capability to produce gallium microdroplets both in bulk and in a wide range of working fluids that can be used as the continuous phase. Ultrasonication involves permeating a liquid sample with frequencies of more than 20 kHz to agitate particles in the sample. These high energy waves cause cavitation to occur, a process that involves small vacuum pockets in the fluid collapsing on themselves. This causes shockwaves that contain enough force to break up particles immersed in the fluid into smaller pieces. Liquid–liquid emulsions can be quickly and consistently produced in bulk quantities using this technique.

A Cole-Parmer Ultrasonic Cleaner is used to create the emulsion of gallium-in-ethanol solution. After the water bath contained in the device is warmed to 50 °C, containers containing different weight concentrations of gallium-in-ethanol solution, ranging from 1% to 20%, are placed inside. The samples are then subjected to sound waves with a frequency of 40 kHz for 70 min. Figure 3 shows the output of the solution after ultrasonication. The gallium particles are uniformly dispersed in the ethanol in the form of near-spherical microdroplets. The gallium microdroplets almost immediately begin to sediment to the bottom of the container, but when given a light shake, they are dispersed back into the solution of ethanol. The gallium microdroplets do not coalesce back together and have formed permanent particles.

A sample of the gallium microdroplets viewed from a Nikon Eclipse LV150 is shown in Fig. 4. The microscope is set to an M-10× microscope objective, providing a 100× magnification. The gallium particles range in size from ∼1 to 50 μm in diameter. The size distribution of a sample of the gallium microdroplets was determined by using ImageJ. The number of gallium particles in the sample was determined by adjusting the color threshold of the image to black and white, and then using the "Analyze Particles" feature to count the number of particle locations. Over 80% of the 2425 gallium microdroplets analyzed are under 2 μm in radius, and the average diameter is found 3 μm. Figure 5 shows the results of the analysis.

Results and Discussion

The OHP was charged and tested with weight concentrations of gallium of 1.0%, 5.0%, 10.0%, and 20.0% using the experimental setup described. The OHP was able to start with a minimum heat input of 100 W when charged with ethanol and various concentrations of hybrid fluids. Vapor nucleation sites formed at the walls of the evaporator section of the OHP, producing small vapor bubbles that grew larger and began to detach from the wall. Vapor bubbles would rise from the evaporator section with increasing frequency until distinct vapor plugs and liquid slugs were formed and oscillation began. No dry-out was observed during testing with a heat input of up to 400 W.

Temperature data from the thermocouples placed in the evaporator, adiabatic, and condenser sections of the OHP was collected and analyzed. Figure 6 shows the temperature readings of the thermocouples distributed across the OHP throughout the duration of testing. The OHP exhibited similar behavior for each working fluid tested; an initial rise in temperature at each heat input until a steady-state temperature was reached. The thermal conductance was calculated using Eqs. (2) and (3). Between 150 W and 200 W, the temperature difference between the evaporator and

Table 1 Thermophysical properties of ethanol and gallium [21]

Properties	Ethanol	Gallium
Density/kg · m^{-3}	789.2 at 20 °C	6095 at 29.8 °C (liquid)
Melting point/°C	−114.1 °C at 1 atm	29.78 °C at 1 atm
Boiling point/°C	78 °C at .987 atm	2400 °C at 1 atm
Thermal conductivity/W · m^{-1} °C^{-1}	0.179 at 25 °C	29
Specific heat/kJ · kg^{-1}°C^{-1}	2.4 at 20 °C	0.370
Viscosity/Pa · s	0.001074 at 25 °C	0.00189 at 32 °C
Vapor pressure/mmHg	750.1 at 78 °C	7.5×10^{-3} at 1037 °C
Latent heat of vaporization/kJ · kg^{-1}	920 at 25 °C	3643
Thermal diffusivity/m^2 · s^{-1}	1.43×10^{-7} at 20 °C	1.29×10^{-5}

Fig. 3 From left to right: 5% wt., 10% wt., and 20% wt. gallium-in-ethanol emulsions.

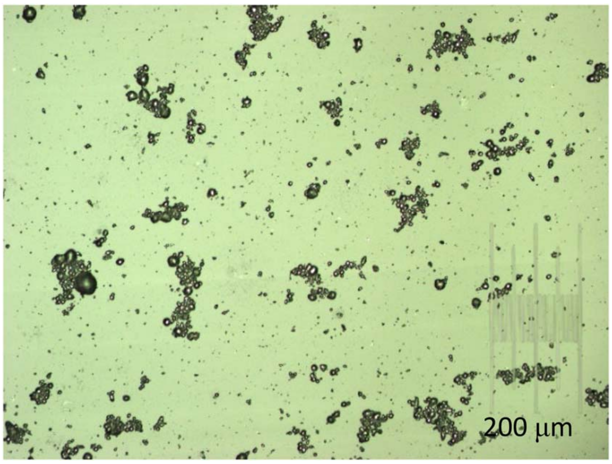

Fig. 4 Gallium microdroplets

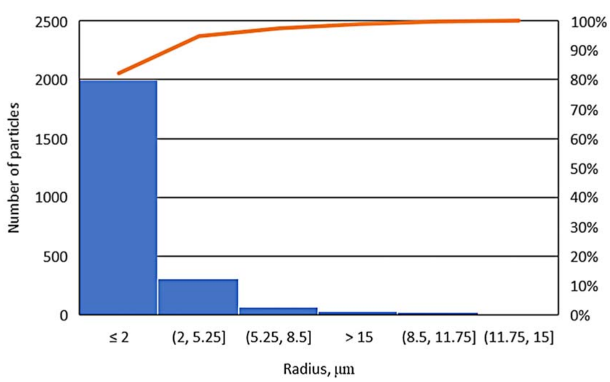

Fig. 5 Radius distribution of a sample of gallium microdroplets

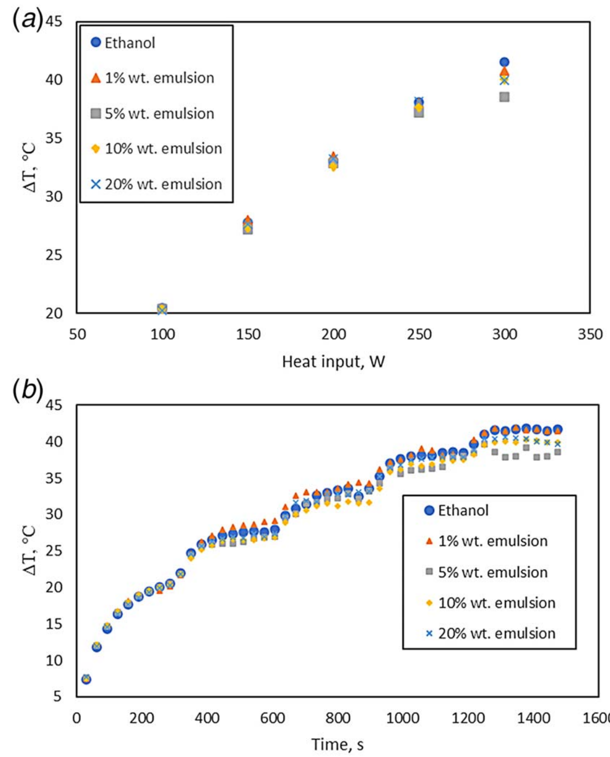

Fig. 6 ΔT Versus: (a) heat input and (b) time

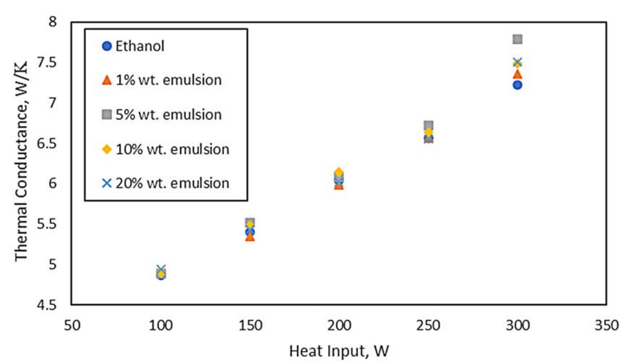

Fig. 7 Thermal conductance versus heat input

condenser shows little to no dependence on the gallium concentration of the working fluid. Figure 7 shows the calculated thermal conductance with respect to the heat input. A linear relationship is observed between C and the power input under 250 W, which then diverges as the heat input approaches 300 W. The various emulsions begin to noticeably increase the performance of the OHP between 250 W and 300 W. At 300 W, the 5% gallium-in-ethanol emulsion performs the best, resulting in the OHP attaining a thermal conductance of 7.79 W/K. The 10% and 20% wt. gallium-in-ethanol emulsions perform similarly well, producing a thermal conductance of 7.48 and 7.5 W/K, respectively. The 1% wt. gallium-in-ethanol emulsion shows the least improvement in heat transfer over the control, with a thermal conductance of 7.35 W/m·K.

Table 2 shows the percentage change in thermal conductance of the OHP charged with the different emulsions compared to pure ethanol. At 100 W, there is a slight positive correlation between the gallium weight concentration and heat transfer improvement, with the 20% wt. concentration performing the best and increasing the thermal conductance by 1.30%. Between 250 W and 300 W, the 5% wt. gallium-in-ethanol emulsion produced an increase in heat transfer of 2.42–7.81% over pure ethanol. The 5% and 10% concentrations improved the heat transfer performance of the OHP at all heat inputs, while the 1% and 20% concentrations saw a reduction in thermal conductance between 150–200 W and 200–250 W, respectively.

Table 2 Percent change in thermal conductance compared with ethanol control

	Weight concentration of gallium in ethanol				
Heat Input Qe (W)	0%	1%	5%	10%	20%
100	0.00%	0.42%	0.38%	0.57%	1.30%
150	0.00%	−0.90%	2.17%	1.61%	0.59%
200	0.00%	−0.91%	0.74%	1.71%	−0.28%
250	0.00%	0.21%	2.42%	1.19%	−0.13%
300	0.00%	1.84%	7.81%	3.64%	3.89%

Conclusions

An experimental investigation of a hybrid fluid oscillating heat pipe charged with gallium-in-ethanol emulsions was conducted to study the effects on the thermal performance of the OHP. An emulsion technique, called ultrasonication, was utilized to produce varying concentrations of gallium microdroplets in an ethanol solution. Four concentrations of gallium-in-ethanol emulsion were fabricated and tested against a control of pure ethanol: 1%, 5%, 10%, and 20%. Between 250 W and 300 W, all the concentrations of gallium-in-ethanol emulsion enhanced the heat transfer capability of the OHP over pure ethanol. The 5% wt. gallium-in-ethanol was found to perform the best, increasing the thermal conductance by 2.42–7.81%. Through the development of an emulsion-based hybrid fluid, the quantity of gallium needed to reproduce similar heat transfer enhancement was drastically reduced compared to previous investigations; with only 0.25 g of gallium needed to produce a 7.81% increase in the thermal conductance. It can be concluded that a gallium-in-ethanol emulsion-based hybrid fluid with a given charging ratio can improve the heat transfer performance of an OHP.

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Conflict of Interest

There are no conflicts of interest.

Data Availability Statement

The data sets generated and supporting the findings of this article are obtainable from the corresponding author upon reasonable request.

Nomenclature

d = distance (m)
g = gravitational constant (m/s^2)
k = thermal conductivity (W/m-K)
u = velocity (m/s)
A = area (m^2)
C = conductance (W/K)
D = diameter (m)
I = current (A)
P = pressure (Pa)
T = temperature (°C)
Q = heat transfer (W)

Greek Symbols

Δ = increment
∂ = partial differential
μ = viscosity (Pa s)
ρ = density (kg/m^3)
σ = surface tension (N/m)

Subscripts

c = condenser
$crit$ = critical
e = evaporator
eff = effective
l = liquid
$loss$ = loss
sat = saturation
v = vapor

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