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Performance enhancement of a two-phase closed thermosiphon with a thin porous copper coating

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ABSTRACT

In this study, the heat transfer augmentation of a two-phase closed thermosiphon (TPCT) with a thin, porous copper coating is studied and compared with an uncoated TPCT. The inner surface of the TPCT is coated using an electrochemical deposition process. The coated and uncoated TPCTs are filled with deionised water and tested with a heat input of 50 to 250 W. The heat transfer coefficient in the evaporator and condenser is assessed and compared with the thermal resistance of coated and uncoated TPCTs. The effects of the inclination angle, power input and thin copper coating on the performance of the TPCTs are explored. The heat transfer coefficient of the evaporator is found to be enhanced up to 44% at a heat flux of 10 W/m^2 for an inclination angle of 45°. TPCTs with an oxide coating are also compared to those with a metallic coating and the metal-coated TPCT was found to perform better than the oxide-coated TPCT. The effect of non-dimensional numbers, such as Bond (Bo), Webber (We), Kutateladze (Ku) and condensation (Co) numbers, with the variation of heat flux, is also investigated.

1. Introduction

A two-phase closed thermosiphon (TPCT) is a passive heat transfer device that operates on the basis of phase conversion heat transfer by means of boiling and condensation. As the heat is realised in the evaporator section, the working fluid absorbs the latent heat and becomes vapour. The vapour then moves towards the condenser section and becomes liquid by releasing its latent heat during the condensation process. The condensed liquid slides through the TPCT wall and reaches the evaporator section through gravity. These TPCTs are simple in construction and transfer a considerable amount of heat over a long distance with a minimum temperature drop.

Hence, TPCTs are used in many industrial applications, such as electronic cooling, heat recovery systems, solar collectors and energy storage systems [1–5]. As miniaturisation technology grows faster than ever, the need for efficient cooling devices is also growing. To meet this requirement, heat transfer devices have to be enhanced in order to operate efficiently at small sizes. The performance of TPCTs mainly depends on the type of working fluid, inclination angle and geometry of the enclosure material. The boiling characteristics of the working fluids and the nature of the evaporator surface also play a major role in TPCT performance. Hence, several investigations have been performed to access the heat transfer enhancement of TPCTs with various working fluids [6–18]. This includes traditional fluids such as water, ammonia and acetone [6]. Over the past few decades, nanofluids have been receiving much attention due to the enhancement in thermophysical properties.

Hence, thermosiphons have been tested with working nanofluids like Al_2O_3-water and CuO-water [7], as well as carbon nanotube (CNT) nanofluids [8,9], and it was found that the performance of the TPCTs is enhanced by the nanofluid. Liu, Yang and Guo [8] and Liu, Yang, Wang and Guo [9] investigated the open thermosiphon to identify the optimum mass of nanoparticle concentration to attain the peak heat transfer. In this study, CuO-water and CNT-water nanofluids are used as heat transfer fluids. It was found that the required mass concentration for nanoparticles to attain the highest heat transfer capability was 1.0 and 2 wt% for CuO-water and CNT-water nanofluids [8,9] respectively. Sarafraz et al. [10] studied the thermal performance of a thermosyphon with biologically eco-friendly silver nanofluids. The nanofluid was prepared by green synthesis method with silver nitrate solution and fresh tea leaf extract. Their results showed that the use of nanoparticles in the thermosyphon reduces the evaporator temperature and also it enhances the thermal performance of thermosyphon. Yang and Liu [11] conducted a number of studies to understand the effects of surface

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Nomenclature

A	area (m^2)
ΔA	change in area (m^2)
Bo	Bond number
D	diameter (m)
g	acceleration due to gravity (m/s^2)
h	heat transfer coefficient (W/m^2-K)
h	heat transfer coefficient (W/m^2-K)
h_{fg}	heat of vaporization (J/kg-K)
Δh	change in heat transfer coefficient (W/m^2-K)
k	thermal conductivity (W/m-K)
Ku	Kutateladze number
l	length (m)
$\dot{Q}$	heat input (W)
ΔQ	change in heat transfer (W)
q	heat flux (W/m^2)
Δq	change in heat flux (W/m^2)
R	resistance (C/W)
r	radius (m)
T	temperature (°C)
We	Webber number
μ	viscosity (Ns/m^2)
ρ	density (kg/m^3)
σ	surface tension (N/m)

Subscripts

c	condenser
e	evaporator
hp	heat pipe
t	total
l	liquid
v	vapour

functionalised nanofluids and conventional nanofluids on the heat transfer characteristics of the TPCT. A thin, porous coating layer was found at the inner wall of the evaporating section of a TPCT with conventional nanofluid. However, no porous layer was found in the TPCT with surface-functionalised nanofluids. Noie et al. [12] observed an improvement in the thermal efficiency of a TPCT with a mixture of alumina nanoparticles and water. Parametthanuwat, Rittidech and Pattiya [13] and Paramatthanuwat, Boothaisong, Rittidech and Booddachan [14] analysed the thermal performance of a TPCT with silver nanofluids. Huminic et al. [15] analysed the heat transfer performance of a TPCT with Fe_2O_3-water nanofluids. All the abovementioned studies [8–15] show that the thermophysical properties of the working fluid play a major part in the heat transfer enhancement of TPCT.

Recent literature [16–19] reveals that the surface structure formed through the operation of a TPCT is the key to enhancing the performance of a TPCT when nanoparticles are suspended in the base fluid. However, in recent years, better pool-boiling characteristics were obtained with a uniform thin porous coating [20–22]. Several researchers investigated the effect of a nanoporous coating on the heat transfer characteristics of the pool-boiling system. These coatings were prepared by the deposition of thin metallic oxides, such as CuO, Al_2O_3 and TiO_2, and pure metals, such as copper, gold and silver. Vemuri and Kim [20] prepared a nanoporous Al_2O_3 coating with an anodising technique and investigated the pool-boiling characteristics of a nanoporous surface with a saturated dielectric fluid (FC-72) as the working fluid. Chen et al. [21] prepared a hydrophilic surface with a TiO_2 coating on a flat surface and studied the pool-boiling heat transfer. El-Genk and Ali [22] found that nucleate boiling heat transfer enhancement was achieved with a copper microporous surface that is prepared on a copper substrate. In this study, an electrochemical process is used to develop a coating. Kunugi et al. [23] presented a heat transfer enhancement through a nanoporous surface that was prepared by the chemical etching method. All these studies with improved surface properties on the device wall showed a significant improvement in heat transfer. Current experimental studies [24,25] reveal that when a thin oxide coating develops on the inner side of the TPCT enclosure, the heat transfer is enhanced significantly. Generally, the oxide coatings have poorer thermal conductivity when compared to metallic coatings (see Table 1). Hence, metallic coatings have attracted more interest in the areas of electronic cooling and compact heat exchangers. Therefore, Yong et al. [26] conducted a pool-boiling experiment and found that the heat transfer was enhanced using a novel metallic nanoporous surface.

In recent times, the use of a metallic porous coating has been extended to many applications, such as heat exchangers, heat sinks, heat pipes and thermosiphons. Hanlon and Ma [27] showed that the thin-film evaporation, which occurs as a result of the sintered porous media, plays an important role in enhancing the evaporation heat transfer coefficient. Lee et al. [28] reported that the evaporation heat transfer enhancement of the heat exchanger with a sintered porous copper coating is twice as good as the plain uncoated heat exchanger. They recorded that this enhancement is mainly due to the thin spreading characteristics of the working fluid in the porous coating. Sun et al. [29] explained the mechanisms involved in the heat transfer enhancement in a porous layer. It was concluded that the microbubbles in the porous layer work like a pump in which they suck the working fluid into the porous layer for the bubble contraction and expel the fluid for expansion. From the abovementioned studies [27–29], it is clear that the heat transfer coefficient in the evaporation process is enhanced with the use of thin, porous coatings. Not only is the evaporation heat transfer enhanced, but the condensation heat transfer is also enhanced with the use of a thin, porous coating. Wang et al. [30] noticed a heat transfer enhancement in the film condensation process in a vertical fluted tube with a thin porous coating.

Lee et al. [31] developed a micro-nanoporous coating with polyphenylene sulphide (PPS) and polytetrafluoroethylene (PTFE), which enhances the drop-wise condensation. Furthermore, Chien and Chang [32] investigated the effect of particle size and the porous surface's coating thickness on the evaporator thermal resistance of the flat thermosyphon. The porous coating consists of a sintered copper particle with two different thicknesses and particle sizes. The testing was done with two different saturation temperatures of 60 and 70 °C, and found that the best boiling surface has a thickness of 1 mm with 247 μm particles. Vasilieve et al. [33,34] also studied the performance of the grooved heat pipe with thin, porous deposited evaporators, and found that the heat transfer coefficient is enhanced to a factor of 1.5 to 2. Rahimi et al. [35] studied the thermal characteristics of a thermosiphon with a resurfaced evaporator and condenser. The evaporator surface was coated with SiO_2 particles 154 μm in size to make the surface more hydrophilic. The condenser section was coated with $(C_6H_5)_2SiO_n$ to make the surface more hydrophobic. By employing the above surface modifications, the thermal resistance of the resurfaced thermosiphon was 2.5 times lower than that of a traditional thermosiphon.

Table 1
Thermal conductivities of metals and metallic oxides.

S·No	Material	Thermal conductivity (W/m-K)
1	Copper	400
2	Titanium	22
3	Aluminium	205
4	Zinc	116
5	Copper oxide	110
6	Titanium oxide	8
7	Aluminium oxide	30
8	Zinc oxide	21