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# Heat transfer performance of a lubricant-infused thermosyphon at various filling ratios

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ABSTRACT

The effect of the filling ratio ($25\% \leq FR \leq 98\%$) on the heat transfer performance of a novel two-phase closed thermosyphon (TPCT) combined with a superhydrophilic (SHi) evaporator and slippery lubricant-infused porous surface (SLIPS) condenser (TPCT-SHiSL) is systematically investigated in the present study. On the evaporator side, experimental results show that a different evaporation mechanism takes place dependent on the filling ratio, which has a strong impact on the overall heat transfer performance. Film evaporation plays a dominant role at the filling ratio of 25% and at the filling ratios of 40% and 70% at low heat flux. Nonetheless, film evaporation is gradually reduced and pool boiling becomes important at the filling ratios of 40% and 70% for moderate and high heat fluxes. Finally, pool boiling plays a dominant role for the TPCT-SHiSL at the filling ratio of 98%. In the case of the condenser, the condensation heat transfer of the SLIPS is reduced with increasing filling ratio. Balancing between the thermal resistance and heat transfer capacity, the TPCT-SHiSL at the filling ratio of 40% shows the best heat transfer performance.

## 1. Introduction

The thermal management of high-performance electronic devices such as CPUs, GPUs and insulated gate bipolar transistors (IGBTs) is becoming a tremendous challenge due to the rapid increase in power and in heat generation of these devices. To meet this great heat dissipation demand, two-phase closed thermosyphons (TPCTs) with different evaporator and condenser configurations were designed and implemented to cool high heat flux devices. The phase change processes of the working liquid taking place inside the TPCT absorb a large amount of heat while the temperature remains fairly constant, and the heat transfer performance may also be further enhanced by the different evaporator and condenser configurations.

Designs to improve the performance of the condenser have mainly focused on the promotion of dropwise condensation due to the fact that its heat transfer coefficient (HTC) is approximately 10 times higher than that of filmwise condensation [1,2]. In particular, superhydrophobic surface (SHS), which consists of a combination of micro- and/or the nano-cavities and a hydrophobic polymeric coating, was reported to exhibit great dropwise heat transfer potential [3]. However, a large amount of liquid droplet embryos are formed between the nanostructures of SHS, which grow into condensate droplets that are completely pinned to the SHS [4,5]. Moreover, at subcooling degrees greater than 1.2 °C, the droplets remain attached to the surface rather than jumping off after coalescence [6–8]. Since in the practical applications the subcooling degree is typically much higher than 1.2 °C, dropwise condensation eventually deteriorates into filmwise, inhibiting the heat transfer performance of the SHS [5,8–10]. Lastly, the SHS also shows poor stability and reliability, which further inhibits their application in the TPCTs [8,11].

To alleviate the above issues, slippery lubricant-infused porous surfaces (SLIPSs) have been recently proposed [12] and were found to exhibit great HTC [3,4,13]. In particular, the micro- and nano-cavities of the porous surface are infused with a low-surface-tension lubricant, which confers the surfaces with extreme water repellency and in turn leads to greater dropwise condensation heat transfer. In addition, the SLIPS is capable of sustaining stable dropwise condensation under vacuum condition in many cooling applications [3,4].

In a previous work, the SLIPS was incorporated into the condenser part of a TPCT and the results demonstrated that in fact the SLIPS accelerated the removal of small condensate droplets refreshing the condenser area for re-nucleation [14]. However,

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## Nomenclature

| | |
|---|---|
| $A_H$ | the hamaker constant (J) |
| $D$ | diameter (m) |
| $h$ | heat transfer coefficient (W/(m$^2$ K)) |
| $I$ | current (A) |
| $L$ | length (m) |
| $P$ | pressure (Pa) |
| $Q$ | power (W) |
| $R$ | thermal resistance (K/W) or radius (m) |
| $S$ | spreading coefficient (mN/m) |
| $T$ | temperature (°C) |
| $U$ | voltage (V) |
| $V$ | volume (m$^3$) |

*Greek symbols*

| | |
|---|---|
| $\Delta$ | uncertainty (–) |
| – | average (–) |
| $\gamma_l$ | the surface tension of the lubricant (mN/m) |
| $\delta_l$ | the cloaking film thickness (m) |
| $\lambda$ | thermal conductivity (W/(m K)) |
| $\Phi$ | ratio of thermal resistance (–) |

*Subscripts*

| | |
|---|---|
| *be* | before |
| *c* | condenser |
| *cond* | conductivity |
| *cop* | copper |
| *e* | evaporator |
| *eff* | effective |
| *elec* | electricity |
| *i* | inner |
| *l* | lubricant |
| *NCG* | non-condensable gas |
| *net* | net |
| *o* | outer |
| *w* | water |
| *sat* | saturated |
| *SHi* | superhydrophilic surface |
| *SHS* | superhydrophobic surface |
| *SLIPS* | slippery lubricant-infused porous surface |
| *FR* | filling ratio |
| *t* | total |

the condensed droplets were cloaked with a thin lubricant film, which was shed with the drops from the condenser with the assistance of the gravity. In turn, the lubricant contaminated the evaporator surface and resulted in deterioration of the boiling heat transfer performance of the evaporator [15]. The contamination of the evaporator surface by the lubricant may be alleviated by introducing a superhydrophilic surface (SHi) as the evaporator due to its oil-repellency property when submerged in water [16]. Combining a SHi evaporator and a SLIPS condenser into a TPCT, namely the TPCT-SHiSL, led to great performance improvement over a conventional TPCT [14]. The performance enhancement potential of such an innovative TPCT-SHiSL design is still not clear and merits a further investigation.

For a conventional TPCT, the heat transfer is significantly affected by the inclination angle, geometry, thermo-physical properties of the working fluid and filling ratio [17]. Among them, the filling ratio (*FR*) is one of the most important factors that directly determine the overall heat transfer performance of the TPCT. The filling ratio is generally defined as the ratio of the volume of the working fluid to the volume of the evaporator. The introduction of the low surface tension lubricant in the SLIPS condenser is expected to mix with the working fluid and play an important role dependent on the filling ratio, which may lead to different boiling and condensation heat transfer performances.

From the above discussion, it becomes readily apparent that the boiling/evaporation and condensation mechanisms taking place inside a conventional TPCT and a TPCT-SHiSL could completely differ, and one of the most important parameters is the filling ratio. Typically, deterioration of boiling occurs at low filling ratios because of not enough working fluid, leading to dry-out; whereas condensation heat transfer is inhibited at high filling ratios because of flooding in the condenser which implies that there is an optimal filling ratio that achieves the best heat transfer performance [17–19]. The influence of the filling ratio on the thermal resistance of the TPCT was investigated by Solomon et al. [20], and it was reported that the thermal resistance of the TPCT increased with increasing filling ratio, due to the evaporator being flooded by the excess liquid supplied to the evaporator. The thermal characteristics of a TPCT at different filling ratios were investigated through numerical simulation by Shabgard et al. [18]. Results showed that dry-out of the TPCT was easily triggered at low filling ratios, whereas the thermal resistance of the TPCT increased at high filling ratio. At high filling ratios, the heat transfer rate of the liquid pool is lower when compared to film evaporation at low filling ratios. The influence of the filling ratio on the heat transfer performance of a TPCT was also investigated by Long and Zhang [21], and the results indicated that the dry-out limit occurred not only at low filling ratios but also at high filling ratios. The heat transfer limit rose with increasing filling ratio at $FR < 1.0$, and then the heat transfer performance remained nearly unchanged at $FR > 1.0$. It was then demonstrated that the heat transfer mechanisms of the TPCTs are significantly affected by the filling ratio. The dry-out limit easily occurs when the filling ratio is low, and the boiling limit may occur at high filling ratios. Since the filling ratio is paramount to the conventional TPCT designs, it should be at least equally important in a TPCT-SHiSL.

From the discussion mentioned above, it can be reasonably postulated that the filling ratio might play a significant role in the TPCT-SHiSL because the TPCT-SHiSL involves the SHi and contamination of lubricant from the SLIPS condenser. The wettability of the SHi evaporator is more easily affected by residual lubricant at low filling ratio at high heat flux, but the wettability does not change at high filling ratio. Therefore, variation of wettability at different filling ratios further influences the heat transfer of the evaporator. The dropwise condensation on the SLIPS condenser is accelerated at low filling ratio, but it is inhibited at high filling ratio. The lubricant of the SLIPS condenser at different filling ratios affects the boiling/evaporation heat transfer of the SHi evaporator; therefore, the effect of the filling ratio on heat transfer is worth investigating.

In the present study, the TPCTs with different evaporator/condenser configurations, i.e., the pristine surface/pristine surface system (TPCT-PP), the pristine surface/SLIPS system (TPCT-PSL), the SHi/SHS system (TPCT-SHiS) and the SHi/SLIPS system (TPCT-SHiSL), are studied, and the effect of the filling ratio on the heat transfer performance of the TPCT is evaluated. The experiments demonstrate that the boiling and condensation heat transfer characteristics of the TPCT-SHiS and the TPCT-SHiSL are heavily