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Research paper

Role of nanofluid fouling on thermal performance of a thermosyphon: Are nanofluids reliable working fluid?

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HIGHLIGHTS

- Application of TiO_2 water based nanofluid in a thermosyphon is studied.
- Fouling resistance causes deterioration in thermal performance.
- By using nanofluids, evaporator depreciation in a transient study is seen.
- In steady state study, nanofluids enhance the thermal performance of heat pipe.

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ABSTRACT

This paper focuses on fouling formation of nanofluid in a gravity-assisted thermosyphon equipped with a mesh screen wick. A transient study has been established on the fouling resistance of water-based TiO_2 nanofluids at different operating conditions comprising the applied heat flux, mass concentration and inclination of thermosyphon. Nanofluids were prepared using prolonged sonication, stirring, and pH control. Triton X-100 was utilized as a dispersant. The thermosyphon is a copper made tube, which is dimensionally 10.7 mm and 12 mm for inner and outer pipe diameters respectively and total length of 280 mm. Transient results over the extended time reveal a considerable deterioration of heat transfer coefficient and thermal performance as a result of fouling formation inside the wick at evaporator section. According to the results, rate of fouling can be enhanced by increasing the nanofluid mass concentration. Intensification of fouling on wick structure and internal wall of evaporator causes instabilities in thermal performance of thermosyphon over the time, which eventually causes the thermosyphon failure. This point has been ignored by most of previous researchers, which has a considerably negative impact on thermal performance of thermosyphon at longer operating time and higher heat loads. Therefore, a new fouling resistance model has been re-developed combining the microfluidic typical models. This model can predict the fouling resistance of nanofluid inside the thermosyphon with approximate deviation of 30%.

1. Introduction

Generally, heat pipes and thermosyphons are two-phase passive heat transfer devices with energy-saving capability and promising solutions for removing large quantities of heat without consumption of any external energies. These devices are particularly suitable for cooling applications such as electronic devices (for heat pipes) and cooling cycles in reactors (for thermosyphons) where reliability and safety are of paramount importance. For a thermosyphon equipped with mesh wick, condensed working fluid can be easily transferred to the evaporator section using capillary forces provided by metal mesh screen wick twisted close to the inner wall of the thermosyphon and by means of gravitational force (in gravity-assisted ones). Nanofluids, as introduced by Choi [1], are an engineered colloid, which are known for their outstanding thermo-physical features, particularly their superior thermal conductivity. Many efforts have been made to investigate the advantages of using nanofluids in thermal

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engineering systems. Although thermal conductivity of nanofluids is the outstanding feature, deposition of nanoparticles inside the heat transfer media has been an indispensable challenge among the researchers. Despite the fouling formation of nanofluids, many investigators have conducted experiments on the possible application of nanofluid on enhancement of thermal performance of heat pipes [2–10] and thermosyphons [11–18]. Following literature represents some of the recent works on application of nanofluids in heat pipes and thermosyphon.

For heat pipes, recently, effect of nanofluids on thermal performance of heat pipe has experimentally been investigated by Do et al. [19]. The testing heat pipe was a circular screen mesh wick working with water-based alumina nanofluids. They reported that, thermal resistance of heat pipe can be decreased to about 40% in evaporator section, which is due to the fouling formation of nanoparticles on the wick structure. This can enhance the wettability and capillary action in wick structure. However, their studies was not over the time and fouling formation of nanoparticles did not reported over the time. Kole et al. [20] experimented on a mesh screen heat pipe and investigated the influence of angular position and Cu/water nanofluid concentration on thermal resistance of heat pipe. A layer of copper nanoparticles on the mesh structure was formed, which resulted in reduction of thermal resistance of heat pipe to 27%. No specific information about operating time and its role was found in their study, although impact of time on fouling formation was trivially found to be important. Putra et al. [21] determined the role of concentration and the type of nanofluids that can enhance the thermal performance of screen mesh wick heat pipes. Also, they investigated the effect of coatings on the structure of the screen mesh wick after using nanofluids as the working fluid. For alumina and titana, they concluded that the formation of a thin coating layer on the screen mesh surface leads to the reduction in thermal resistance. Also, the thin coating promotes good capillary structure and higher thermal performance of a thermosyphon charged with nanofluids. This reveals the potential of nanofluids as a substitute for conventional working fluids. However, no exact information about time of fouling on wick structure, rate of fouling and fouling resistance was reported. In another experimental study, heat transfer mechanisms in condenser and evaporator sections of a copper-water wicked heat pipe with 3 layers of screen mesh were investigated by Kempers et al. [22]. . The heat pipe was mounted horizontally and boiling was observed in evaporator section. They investigated on the dominant mechanism in a heat pipe and found out that heat transfer inside the condenser section is by conduction, while for evaporator, conduction and boiling heat transfer are the main dominant mechanisms. The transition between the two modes was found to be dependent on the vapor pressure and applied heat fluxes. In terms of thermal resistance, results showed that the main heat transfer resistance was related to the evaporator section, but they did not report any information about fouling and scale formation inside the evaporator. Finally, they correlated the experimental data by means of nucleation site predicting models. The proposed model was a composite heat transfer model for the heat pipe that considers both conduction and boiling heat transfer in the evaporator. All in all, fouling was seen in their studies and boiling heat transfer was dominant mechanism which enhances the heat transfer coefficient at higher applied heats. A study on operating of mesh wick heat pipe was performed by Wong et al. [23]. Experimental results showed that under a smaller filling ratio of working fluid, boiling heat transfer can be the dominant mechanism with a partial dry-out sub-phenomenon in evaporator. However, they did not consider the influence of dry-out, hotspot and fouling on the performance of heat pipe, while they represented visual evidences about these sub-phenomena.

For thermosyphons, Chen et al. [24] conducted experiments on thermal performance of a thermosyphon working a with new water-based SiO_2 functionalized nanofluid. This functionalized nanofluid can have unique dispersing ability without fouling formation on heated surfaces. The flow evaporating heat transfer characteristics of functionalized nanofluid in a thermosyphon were investigated to understand the sole effect of thermal properties of nanofluid on the heat transfer characteristics of the thermosyphon, Results show that: functionalized nanofluid deteriorates both the evaporating heat transfer coefficient and the maximum heat flux of the thermosyphon. The changes in the thermal properties of functionalized nanofluid mainly result in the heat transfer deterioration. No especial nano-scale effect or fouling was found in the present study. In another research, a two-phase closed thermosyphon (TPCT) was investigated by Noie and his co-workers [25]. As a working fluid, nanofluid of aqueous alumina nano-suspensions were prepared at different volume concentration (1–3%) and used in a TPCT. Experimental results showed that for different input powers, efficiency of the TPCT increases up to 14.7%, when alumina/water nanofluid was used instead of pure water. Temperature distributions on TPCT confirmed these results too. In this work, role of particulate fouling was not carefully considered or reported. In a study performed by Huminic et al. [26], a thermosyphon heat pipe was investigated in terms of temperature distribution and heat transfer rate of the thermosyphon heat pipe working with nanofluid and with DI-water. The concentration level of nanoparticles was 0%, 2%, and 5.3%. Results showed that the addition of 5.3% (by volume) of iron oxide nanoparticles in water presented improved thermal performance in comparison with the case that thermosyphon is operating with DI-water. Effect of electric field on thermal performance of two-phase thermosyphon as external modifications has experimentally investigated by Heris et al. [27]. In their study, internal modifications were applied by using two different alumina and CuO water based nanofluids as working fluids. Results show that the thermal performance, and the Nusselt number gradually increase by increasing the intensity of electric field and amount of nanofluid concentration. These values decrease by increasing the applied heat. Results also showed that alumina/water nanofluid can improve the thermal performance of thermosyphon more than CuO/water nanofluid. Also, the experimental results indicated that the effect of nanoparticles on thermosyphon thermal performance was higher than the electric field. Maximum enhancement of Nusselt number was about 43% that observed at power of 60°W and volume fraction of 2.5% under 20 V electrical field strength. Enhancement value was 39% for CuO/water nanofluid. During the experiments, deposition of nanoparticles inside the thermosyphon was neglected and role of electric field on deposition was not studied.

According to the literature, some studies discuss the positive perspectives on application of nanofluid such that using nanofluid in heat pipes/thermosyphons can create a deposited layer on wick structure or internal wall of heat pipes/thermosyphons, which apparently decreases the thermal resistance due to the increase in capillary force and bubble formation in evaporator. To the best of our knowledge, however fouling as a challenge has not been considered over the extended time in heat pipes and thermosyphons, meaning that, role of fouling over the time has not been determined or studied. In the present work, we have conducted steady-state and transient experiments, in which thermal fouling resistance of a thermosyphon is experimentally measured over the time. Due to the particulate fouling, fouling resistance become a paramount parameter, which increases the thermal resistance of thermosyphon during operation. This can also have negative impact on the heat transfer coefficient of evaporator and create a massive depreciation in evaporator section, especially for higher