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Operation performance of thermosyphons employing titania and gold nanofluids

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A B S T R A C T

Experimental investigations with four large thermosyphons identical in construction operated with titanium dioxide and gold nanofluids and deionized-water as reference fluid are carried out. It is experimentally shown that the thermal resistance can be lowered by employing nanofluids only at small values of heat flow rates provided at the evaporator. The best results are achieved with a gold nanofluid at heat flow rates between 50 W and 150 W. The lowering of the thermal resistance is here about 20%. Accompanying distillation experiments clearly indicate that only some per mill of the nanoparticles originally suspended in the nanofluid are torn out of the working fluid and transported by the vapour phase. Beside descriptive explanations and diagrammatical representations of the experimental results three videos are provided. These videos allow for the first time *in situ* observations of the thermosyphons interior when operated with nanofluids in real time.

1. Introduction

Energy is one of the key motifs of our era. Despite the focus being mostly on saving of electrical energy, effective transfer and saving of thermal energy is of comparable importance. Heat transfer is mostly enhanced by passive and active augmentation techniques (Dewan et al. [1], Bergles [2]). Corrugated walls, swirl flow devices, and dimples are examples for the first; surface vibration, injection, and suction are examples for the second strategy. An alternative approach – the enhancement of thermal conductivity by adding nanoparticles to a basefluid – has emerged with new technologies allowing the production of nanometer sized particles. One of the first papers on the so-called nanofluids written by Choi and Eastman [3] caused an avalanche of experimental and numerical investigations. Overviews (Sergis and Hardalupas [4], Thomas and Sobhan [5]) reviewing the current state of the art of nanofluid research indicate that indeed heat transfer can be significantly enhanced when classical heat carriers like water are replaced by water based nanofluids. Moreover, the application of nanofluids in thermosyphons, heat pipes, and oscillating heat pipes has shown early promising results (Liu and Li [6], Buschmann [7]). However, while for heat transfer and especially heat conduction the increase of thermal conductivity is most important for thermal processes with phase changes other physical processes are relevant.

The present study is focused on closed two-phase thermosyphons operated with nanofluids. Due to the phase change which the working fluid undergoes, these devices of passive heat transfer are highly efficient. Textbooks by Reay and Kew [8] and Faghri [9] discuss design, operation principle, and thermal performance. Basically, thermosyphons consist of an evaporator, an adiabatic zone, and a condenser. In the lower part of the thermosyphon the working fluid is evaporated. Natural convection is then utilised to carry the vapour to the condenser region. Here cooling forces the vapour to condensate on the inner wall of the thermosyphon. Eventually the down flowing condensate joins the liquid part of the working fluid again.

In the case of nanofluids being employed as working fluid, the situation changes significantly. Thermodynamical and fluid mechanical processes taking place within the thermosyphon can no longer be referred to as two-phase. Due to the fact that nanofluids themselves have a two-phase character (liquid/solid), rather three-phase problems arise. The consequences are far reaching in the sense that nanoparticles are segregated from the liquid phase and form porous layers on parts of the inner surface of the thermosyphon [6,7]. Transport of nanoparticles by the vapour phase would lead to a deposition of nanoparticles on the condenser surface. The presented study investigates these processes in detail.

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Nomenclature

D	non-dimensional temperature difference, –
d_i	inner diameter of thermosyphon, mm
Δh_p	latent heat of vaporisation enthalpy of evaporation, J/g
k	thermal conductivity, W/m-K
Nu	Nusselt number, –
P	provided heat at evaporator, W
Pr	Prandtl number, –
R_Q	thermal resistance, K/W
T_c	condenser temperature, °C
T_e	evaporator temperature, °C

Greek symbols

ϕ	concentration, vol. %, wt. %, ppb
η	dynamic viscosity, kg/m-s
Θ	non-dimensional ratio of temperatures, –

Abbreviations

Au	gold
DI	deionized
HC	heating cartridge
NF	nanofluid
TiO_2	titanium dioxide
TS	thermosyphon

2. Objective of study and organisation of the paper

Main goal of the study is to investigate the effects of nanofluids on the thermal performance of thermosyphons in a most representative form. The objective of the study is to answer several questions with respect to the use of nanofluids in thermosyphons raised especially in the survey by Buschmann [7]. The three main questions are as follows:

(1) What is the major mechanism for the often observed enhancement of heat transfer in thermosyphons when nanofluids are employed as working liquids?
(2) Is this effect stable in the long-term or not?
(3) Are nanoparticles transported by the vapour phase, and if yes, do these nanoparticles change the heat transfer mechanism on the condenser surface?

These questions are mainly answered by experimental determination of the heat transferred by four thermosyphons (TS) but also by carrying out additional experiments with respect to certain physical effects such as the evaporation of nanofluids. The temperature range between 20 °C and 60 °C at which thermosyphons are operated is mainly dictated by the available thermophysical properties especially thermal conductivity of the used nanofluids but also by practical considerations.

Besides photos and scanning-electron-microscope (SEM) images, experimental results are mainly presented in diagrams. The symbols employed are compiled in Table 1. All diagrams show differently grey shaded areas which represent different coolant volumetric flow rates. Data points clustered within one of these grey areas are taken at one and the same coolant flow rate. Note that these areas appear in different forms for dimensional and non-dimensional representations of the results. However, in all cases the same grey intensity indicates the same coolant volumetric flow rate, which is also indicated in the diagrams with its numerical value. Plots of working fluid temperature and of thermal resistances indicate the uncertainties of these parameters through error bars.

Nanofluid experiments carried out in a first step are denominated experiments of the first series, while repetitions are denoted as experiments of the second series. After the first series of measurements, the nanofluids are not replaced so that both experimental series are carried out with the same charges of working fluid.

3. Experiments

3.1. Test rig and data reduction

The test rig consists of four thermosyphons identical in construction (Figs. 1 and 2). The centre piece of each thermosyphon is a stainless steel pipe with a length of 1440 mm and an inner diameter of 108 mm. The upper ends of the pipes are closed with inspection windows. They are heated to avoid condensation so that video cameras mounted on top of each thermosyphon can record their interior. Special care is taken to clean the inner walls of the TS. First the pipes are purged with a solution made from one percent Alconox precision cleaner (Alconox, Inc., USA) and water. In a second step the pipes are completely filled with the same solution for 24 h, after which the pipes are emptied and purged again. To avoid contamination the pipes are then filled with nitrogen during the assembling process. After completing installation of all measurement equipment the pipes are finally evacuated and filled with the working fluid. The amount of working fluid is in all cases 1500 ml. All TSs are wrapped with a 50 mm thick insulation made of ASGLAVLIES® (ASGLAWO technofibre GmbH, Germany), a mechanically consolidated needle non-woven with aluminium laminated exterior.

Before filling with the working fluid, all TSs are evacuated employing a vacuum pump RV12 (EDWARDS GmbH, Germany). The pressure established is 1.0 Pa, which is permanently controlled to ensure vacuum conditions employing a Piezo/Pirani transmitter (PT R32 130, Pfeiffer Vacuum GmbH, Germany).

The working fluid of each thermosyphon is heated with three cylindrical heating cartridges (HC) made of stainless steel, which act as evaporators (Fig. 3). Each of them is 40 mm long and has an outer diameter of 16 mm. To obtain a certain heating power, the supply voltage is adjusted by means of a current transformer according to the known ohmic resistance of each HC-triple. All HCs are grit blasted to remove any corrosion products, to give them a comparable surface structure, and to increase the number of nucleation sites. The averaged surface roughness of the fresh HCs is $R_a = 2.6$ μm and the distance between highest peak and lowest

Table 1
Symbols employed for diagrams.

Thermosyphon	DI-water	Nanofluid		
		Nanofluid	First series	Second series
TS01	■	NF01	■	■
TS02	◆	NF02	◆	◆
TS03	▲	NF03	▲	▲
TS04	▼	NF04	▼	▼