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Experimental investigation of the thermal performance of a two-phase closed thermosyphon at different operating conditions

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ABSTRACT

In this study, the thermal performance of a two-phase, closed thermosyphon (TPCT) was investigated experimentally. In the experiments, we used water, ethanol, and ethylene glycol as the working fluids and considered different operating conditions, such as inclination angles (30, 60, and 90°), heat inputs (200, 400, and 600 W), and flow rates of cooling water (10, 20, and 30 L/h). Initially, an experimental test rig was designed and built, and, then, a series of rigorous tests was conducted on the TPCT. In the experiments, the temperature distribution on the wickless heat pipe or the thermosyphon's surface and the temperature differences of the cooling water were measured. The data were used to calculate the thermal resistance and efficiency of the TPCT, and the results are presented graphically and discussed in detail. The efficiency of the TPCT for each working fluid at different operating conditions varied between averages of 30 and 95%, which was in good agreement with published results. The results indicated that water was the best working fluid when the heat inputs were 200 W and the flow rates of the cooling water were 10 L/h. Ethylene glycol was the best working fluid when the heat inputs were 200 W and the flow rates of the cooling water were 30 L/h. Ethanol was the best working fluid when the heat inputs were 600 W and the flow rates of the cooling water were 10 L/h. In addition, it was found that the inclination angle and heat inputs had significant effects on the efficiency of the TPCT.

1. Introduction

Because heat transfer is an integral part of many industrial processes, these processes perform more efficiently when the heat transfer rates are appropriate for the intended application. The increasing rate of energy consumption in today's world has caused engineers and scientists to focus more attention and effort on developing new energy technologies and thermal management systems. Thus, the efficient use of existing energy technologies has become an important and serious issue. However, large quantities of energy are being lost by thermal systems, and heat exchanger devices are being used to recover this energy and put it to beneficial use in heating and cooling processes. Among these devices, the heat pipe which can transport relatively a large quantity of energy over a small temperature gradient between its ends is preferred in thermal systems [1].

A heat pipe is a two-phase, heat-transfer device that is vacuumed a closed volume, and it can have a cylindrical shape or various other shapes. Due to their excellent heat transfer capabilities [2], heat pipes are superior heat exchangers, and they are used extensively in various industrial applications, such as adsorption, refrigeration, computer systems, water heater systems, seawater desalination, ground source heat pumps, and space applications [3]. Some types of heat pipes that are in general use were described in [4,5] as follows, i.e., (i) variable conductance heat pipes, (ii) thermal diodes, (iii) oscillating heat pipes (OHPs), (iv) loop heat pipes (LHPs) and capillary pumped loops (CPLs), (v) micro heat pipes, (vi) heat pipes that use electrokinetic force, (vii) rotating heat pipes, miscellaneous types-sorption heat pipe (SHP), (viii) magnetic fluid heat pipes, and (ix) two-phase, closed-thermosyphon (TPCT) or wickless heat pipes. Heat pipes that work under gravity with the condenser above the evaporator do not require external power or capillary action to return the working fluid from the condenser to the evaporator. Such heat pipes are known as thermosyphons or wickless heat pipes [6]. Condensation of the working fluid occurs due to gravity, so the evaporator must be positioned at a lower position than the condenser. Due to their simple structure, stable operating conditions, and extensive range of operating temperatures, thermosyphons are in many industrial applications [7].

TPCT heat pipes consist of three parts, i.e., the evaporator, adiabatic section, and condenser section. The evaporator section of the thermosyphon is always at the bottom so the condensate can return

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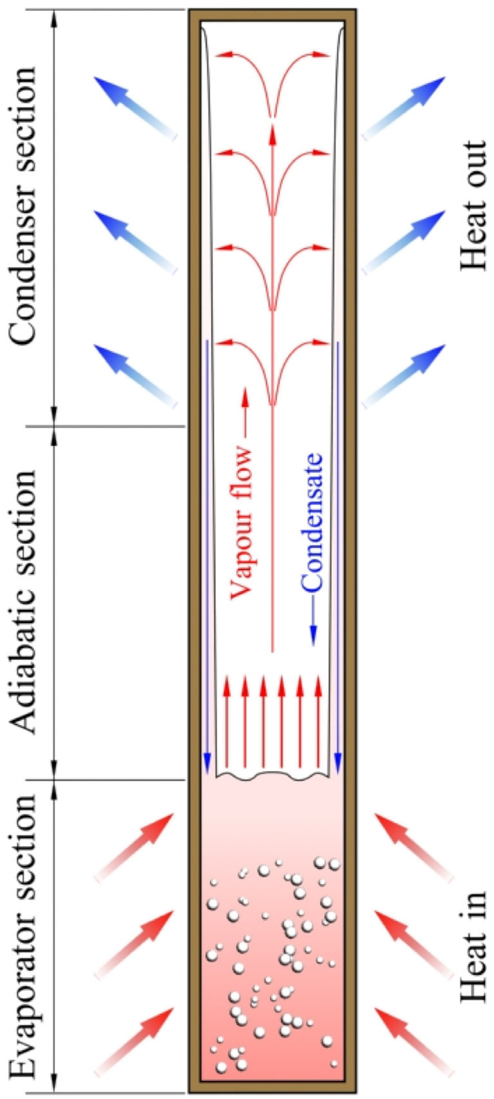

Fig. 1. Schematic view of the working principle of the TPCT.

to this section by gravity flow. The operating process begins at the evaporator section, which is filled with a certain amount of working fluid. The working fluid is a saturated liquid, which is heated by a heat source, such as a hot bath or electrical heating element. Then, the saturated liquid changes to a vapor and moves up to the condenser section. After that, the vapor in the condenser section transfers the heat to a heat sink, such as cool water. As a result, the vapor condenses to a liquid and flows down to the evaporator section [8]. Fig. 1 shows a schematic view of the working principle of the TPCT.

Since the first basic heat pipe concept was proposed by Gaugler [10], several investigations [9] have been conducted with the goals of enhancing the thermal performance of the thermosyphon and understanding the effects of various parameters and operating conditions on its performance. These are categorized mainly into three approaches in [11], i.e., (1) use of an efficient working fluid, (2) mechanical and surface modifications, and (3) mathematical and computational modelling.

Elmosbahi et al. [1] investigated the effect of the working fluid inventory on the performance of the gravity-assisted solar heat pipe. The results indicated that the optimum performance occurred when the evaporator's volume was two-thirds filled with methanol. There are basic parameters that influence the thermal performance of the TPCT, such as the working fluids, inclination angle, heat input, and filling ratio. Fadhl et al. [12] investigated the performance of a water-filled thermosyphon. They conducted experiments in which they studied the effects of the difference in the temperatures of the cooling water at the inlet and at the outlet, the temperature of the wall of the thermosyphon, and flowrate of the cooling water. The thermosyphon was made of a copper material, and it had an outer diameter of 22 mm and a wall thickness of 0.9 mm. The overall length of thermosyphon was 500 mm, consisting of a 200-mm evaporator, a 100-mm adiabatic section, and a 200-mm condenser. The performance of the thermosyphon was studied numerically using the volume of fluid (VOF) method that is commercially available in ANYSYS Fluent computational fluid dynamics software. The results that were obtained from the experimental and numerical studies were compared, and they indicated in their paper that there was good agreement between them.

Depending on the working conditions, different working fluids have been used in thermosyphons. Kannan et al. [7] investigated the effect of operating parameters on the heat transport capability of TPCT using water, methanol, ethanol, and acetone as the working fluids. These working fluids were evaluated based on some critical features, such as boiling point, their heat of evaporation, compatibility with other materials, thermal conductivity, wettability, vapor pressure, thermal stability, kinematic viscosity, coefficient of surface tension, and freezing point. A high latent heat of vaporization is desirable for a working fluid, as are high surface tension, low viscosity, and thermal stability. The most-preferred working fluids in TPCT are water [13], methanol, ammonia, and other refrigerants [14,15]. Jouhara and Robinson [16] investigated the performance of thermosyphons charged with water as well as the dielectric heat transfer liquids, i.e., FC-84, FC-77, and FC-3283. Payakaruk et al. [17] investigated the heat transfer characteristic of a gravity-assisted, two phase, closed thermosyphon charged with R22, R123, R134a, ethanol, and water as the working fluids with varying angles of inclination. Esen and Esen [18] investigated the thermal performance of a two-phase, closed thermosyphon solar collector using R-134a, R407C, and R410A refrigerants. Sundaram et al. [19] experimentally investigated a two-phase, closed thermosyphon for telecommunication shelters in tropical and desert regions. Working fluids that had low global warming potential were investigated by MacGregor et al., for a closed, two-phase thermosyphon [20]. The results of their experimental work showed that a 95/5% water/ethylene glycol mixture was a suitable replacement fluid, although, under certain conditions, its performance was less than that of R134a.

The effect of filling ratio on the heat transfer characteristics of TPCT was investigated by Park et al. [21] and Ong et al. [22]. The effect of the inclination angle on the thermal performance of a two-phase, closed thermosyphon using copper tubes with filling ratios of 15, 22, and 30% was investigated experimentally by Noie et al. [23]. In their study, they used a copper thermosyphon with an outside diameter of 16 mm, an inside diameter of 14.5 mm, and a length of 1000 mm, and they used distilled water as the working fluid. They concluded that the two-phase, closed thermosyphon had its best thermal performance at inclination angles in the range of 15°–60° and a filling ratio of 30% or greater. Emami et al. [24] experimentally studied the effects of aspect ratio and filling ratio on the thermal performance of an inclined, two-phase, closed thermosyphon. The filling ratio was varied from 20 to 60% for the working fluid, which was distilled water in their study. The best thermal performance of the inclined thermosyphon was reported for an inclination angle of 60° and a filling ratio of 45%.

In recent years, many researchers [25–27] have focused on nanofluids, which are rapidly emerging as alternatives to conventional heat transfer fluids. Khandekar et al. [28] investigated the