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Heat transfer characteristics of a two-phase thermosyphon heat exchanger

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HIGHLIGHTS

► A prototype two-phase thermosyphon heat exchanger (TPTHEx) was proposed.
► Performance of the TPTHEx was improved by the enhanced boiling tubes application.
► Calculation algorithm of heat flux transferred in TPTHEx was proposed.

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ABSTRACT

In this paper, a special design for a two-phase thermosyphon heat exchanger is proposed. This design features an evaporator tube bundle consisting of smooth, corrugated or porous coated tubes. The prototype heat exchanger consists of two horizontal cylindrical vessels connected by two risers and a downcomer. Tube bundles placed in the lower and upper cylinder function as an evaporator and a condenser. The operation of a two-phase thermosyphon is determined primarily by the evaporator's performance. Therefore, an experimental investigation was conducted to determine the effects of the evaporator tube pitch (1.7*d* and 2.0d), the liquid head and fluid type on heat transfer in this two-phase thermosyphon heat exchanger. The investigation concerned six prototype heat exchangers operating in a heat flux range of 5–70 kW/m^2. As working fluids, distilled water, methanol and refrigerant R-141b were utilised. The tested two-phase thermosyphon heat exchanger operates in a vacuum, and therefore the working liquids boiled in temperatures ranging from 24 °C to 62 °C. The obtained results indicate that the two-phase thermosyphon heat exchanger performs more effectively with an evaporator bundle comprising of porous coated tubes than with corrugated or smooth tubes. The evaporation heat transfer coefficient is strongly dependent on the liquid level above the top tube row (5 mm, 15 mm and 20 mm).

1. Introduction

Two-phase thermosyphon heat exchangers (TPTHExs) are recuperators with an intermediate working fluid. This type of heat exchanger is used in a variety of heat transfer applications, but the heat transfer process mechanism in shell-side boiling and condensation heat exchangers is far from well-understood [1].

The TPTHEx is chiefly used for heat recovery from sewage or exhaust gases through the vaporisation of liquids at low temperatures. The TPTHEx protects installations against corrosion during the combustion of sulphured fuels because it is possible to select a working fluid and pressure such that the boiling temperature of the working fluid will always be higher than that of the exhaust gas's dew point. In other words, if the temperature of the exhaust gases is lower than the temperature of the dew point, the TPTHEx operation stops. Used in heat recovery from sewage, the TPTHEx stops sewage from freezing at the evaporator outlet and, due to its double wall design, protects the heating installation from contamination. The TPTHEx can serve as a preheater and vaporiser of liquids at low temperatures, with vapour serving as the heating medium. Special care is required to prevent the freezing of the condensate, which flows inside the tubes of the evaporator. It is possible to select a working fluid and pressure inside the shell such that the boiling temperature of the working fluid will always be higher than the freezing temperature of the condensate.

The two-phase thermosyphon (TPT) operates as follows: heat is supplied to the heating zone; the working fluid starts boiling and produces vapour, which moves to the condensing zone, where it loses heat; lastly, due to gravity, the condensate returns to the

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evaporator such the evaporation–condensation heat transfer cycle may be repeated. A characteristic feature of the TPT is that it operates as a thermal diode. This property means that the heat can be transported only in one direction – from the evaporator to the condenser. Two-phase thermosyphons can be divided into two main groups: those with single tubes for a countercurrent flow of liquid and vapour [2–4] and those with two-phase loops in which the evaporator is connected to the condenser (always above the evaporator) by a riser and a downcomer [5,6]. In vapour-dynamic thermosyphons [7], vapour and liquid flows are separated by a wall, and heat transfer is realised in the gap between an inner and an outer tube. Vapour-dynamic thermosyphons and loop heat pipes [8] can provide the coupling between topping and bottoming sorption cycles [7]. In a thermosyphon tube, the heat flux is limited by the counter flows of vapour and condensate [9]. In a two-phase loop, the heat flux is limited by critical heat flux in two-phase flow [10,11].

The simplest thermosyphon consists of a vertical tube, which is heated and cooled from the outside. This design is a case of lateral heating and cooling of the casing. In another type of TPT the condenser can be situated within the casing, and lateral heating is applied to the casing [12]. In another type of thermosyphon tube, both the condenser and evaporator are placed within the casing. Such a solution allows for the utilisation of enhanced surfaces in the design of condensers and evaporators, such as the proposed TPTHEx.

Recent studies concern miniature thermosyphons used in cooling applications for electronic components and higher heat duty heat exchangers for energy saving or heat recovery.

With regard to the miniature thermosyphons, Jouhara and Robinson [13] tested a short (200 mm), small-diameter (6 mm) thermosyphon with water and three Fluorinert liquids. They established that water outperformed the Fluorinert liquids. Additionally, they found that their calculations of the evaporator section heat transfer coefficient compared well with experimental data, as well as with pool boiling correlations commonly accepted in literature.

Tsoi et al. [14] proposed a new design of a two-phase loop thermosyphon (TPLT) in the form of a thin (200 mm × 200 mm × 3 mm) plate. This TPLT operates horizontally and vertically at sub-atmospheric pressure. The authors proposed a set of correlations for the overall thermal resistance prediction.

Filippeschi [15] tested the operation of a miniature periodic two-phase thermosyphon (PTPT) with the same condenser and accumulator and two evaporator geometries of different internal volume (20×10^{-6} m^3 and 5×10^{-6} m^3). A PTPT is a wickless device that can operate opposite gravity. Filippeschi showed that the thermal resistance of a PPT is similar to that of a miniature LHP and during steady state operation equals 0.55 K/W with a heat load of 110 W.

Firouzfar et al. [16] studied thermosyphons that are high heat duty heat exchangers. The authors established that the application of methanol-silver nanofluid as the working fluid in a TPTHEx saves energy by 9–31% for cooling and 18–100% for reheating the air supply stream in an air conditioning system.

Considerations for designing thermosyphons include prediction and control for oscillations encountered during different heat loads. Recently, Khazaee et al. [17] conducted experiments with two 1000 mm copper pipes with 15 and 25 mm inside diameters using methanol as the working fluid to study geyser boiling in a two-phase closed thermosyphon. Their results show that the period of geyser boiling can be decreased by increasing the heat load and aspect ratio and increased by increasing the filling ratio.

Khodabandeh and Furberg [18] examined instabilities in a miniature two-phase loop thermosyphon. The authors established that flow and thermal instability increases as channel height decreases.

The purpose of this paper is to examine the effect of the evaporator tube bundle geometry, the type of tube in the tube bundle (smooth, corrugated and porous coated) and the liquid level above the top tube row and the type of liquid (water, methanol or R-141b) on the overall performance of a TPTHEx.

2. Experiment

2.1. Experimental setup

The test stand consists of three main systems: the prototype TPTHEx, the heating loop and the cooling water loop. The test facility is capable of determining an overall heat transfer coefficient of the TPTHEx. A diagram of the test stand is shown in Fig. 1. The heating and cooling water loops each contain a centrifugal pump, a flowmeter and a vent tank. A district heating network and a cooling tower are used as a heat source and heat sink, respectively. Heating and cooling water flow rates are controlled by a regulating valve and are measured by a Danfoss MAG 3100 magnetic flowmeter, which is accurate to ±0.25%. The average temperatures of the heating and cooling water at the inlets and outlets of the TPTHEx evaporator and condenser tube bundles are measured using the Pt100 resistance temperature gauging device with an accuracy of ±0.1 °C.

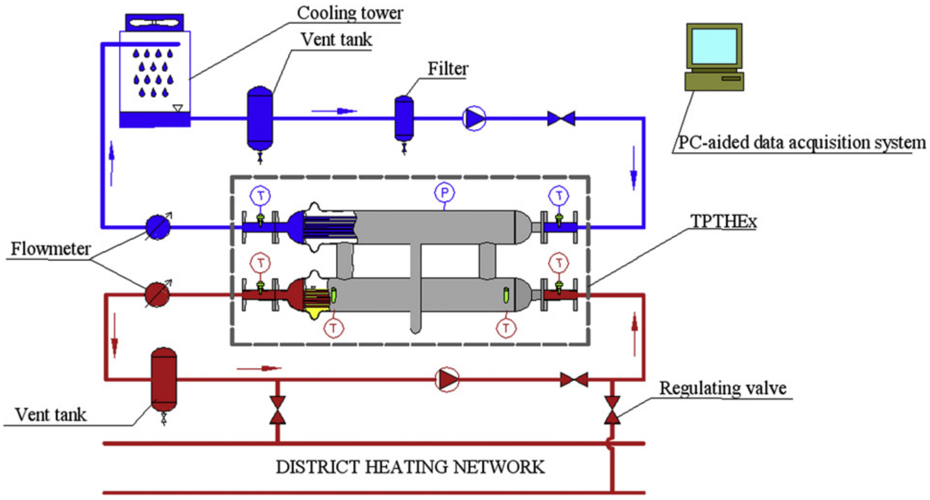

Fig. 1. Schematic view of the experimental setup.