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Research Paper

Numerical and experimental investigation of a counter-current two-phase thermosyphon with cascading pools

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HIGHLIGHTS

- An innovative counter-current two-phase thermosyphon is presented.
- The thermosyphon features multiple pools cascaded along the evaporator section.
- Liquid accumulates in the pools until they overflow to spread the working fluid.
- A numerical control volume model and experimental validation are discussed.
- The paper includes an interactive 3D model and a video of the working prototype.

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ABSTRACT

An innovative design of a counter-current two-phase thermosyphon is investigated for the in-plane cooling of flat product structures. The thermosyphon features multiple pools staggered along the entire evaporator section, in which liquid flowing toward the bottom of the thermosyphon can be stored. The pools are used to cascade the working fluid to the evaporator end cap. Liquid accumulates in the pools until they overflow, thereby spreading the working fluid across the entire evaporator length rather than creating one liquid pool at the bottom end cap. Multiple of such thermosyphons operating in parallel can be used for low-gradient planar cooling of vertically oriented surfaces. A numerical model using a control volume approach is developed to predict and to validate the experimental results of this innovative design. The main advantages of the control volume approach are the adaptability of the entire model and the fast computational speed in comparison to elaborate fluid dynamics models. Empirical correlations are used for the modeling of the heat transfer coefficients and friction factors of the counter-current flow. A proof of principle is given by observing a prototype that was milled into a copper bar. Next to logging temperature measurements, the prototype had a glass top plate to visually record the working fluid behavior. The model presented is well suitable for the early stages of thermosyphon design studies and for the impact evaluation of design changes.

1. Introduction

Heat transfer in cooling applications generally requires a low thermal resistance, which can be challenging using conventional forced convection methods. The physical phenomenon of phase transition and the ability to store energy as latent heat can be utilized to meet these low thermal resistance performance criteria. Thermosyphons are among other devices capable of transferring heat utilizing phase transition as the working principle. A common counter-current two-phase thermosyphon (alt. thermosiphon), as shown in Fig. 1a, is a closed tube with a working fluid inside. In this figure heat is supplied at the bottom of the thermosyphon where a pool of working fluid resides. The working fluid is circulating inside the tube due to phase changes caused by the heat transfer at the bottom (evaporator section) and at the top (condenser section). In the condenser section vaporized working fluid condenses as heat is extracted from the system and forms a liquid film along the thermosyphon wall. Gravitational forces (or centrifugal forces) are used to transport the condensed liquid back toward the evaporator section along the wall of the thermosyphon [1].

Because of their relative simple structure and low cost, thermosyphons are widely used as heat transfer devices (e.g. thermal management systems, heat exchangers and reboiling applications) in various applications [2]. The performance of the thermosyphon depends on the thermophysical properties of the working fluid, the fill ratio, the geometrical shape, the inclination angle and the operating conditions [3,4]. Various limitations regarding the working principle exist that can lead to rupturing or

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severe overheating of the thermosyphon. A major benefit compared to other heat transport devices is that no external power supply is needed for the migration of the working fluid other than a present heat source and gravitational field (or centrifugal forces). Liquid can also be transported using a wick structure, making it possible to function in any orientation. Such devices are commonly known as heat pipes.

1.1. Introduction to the new design

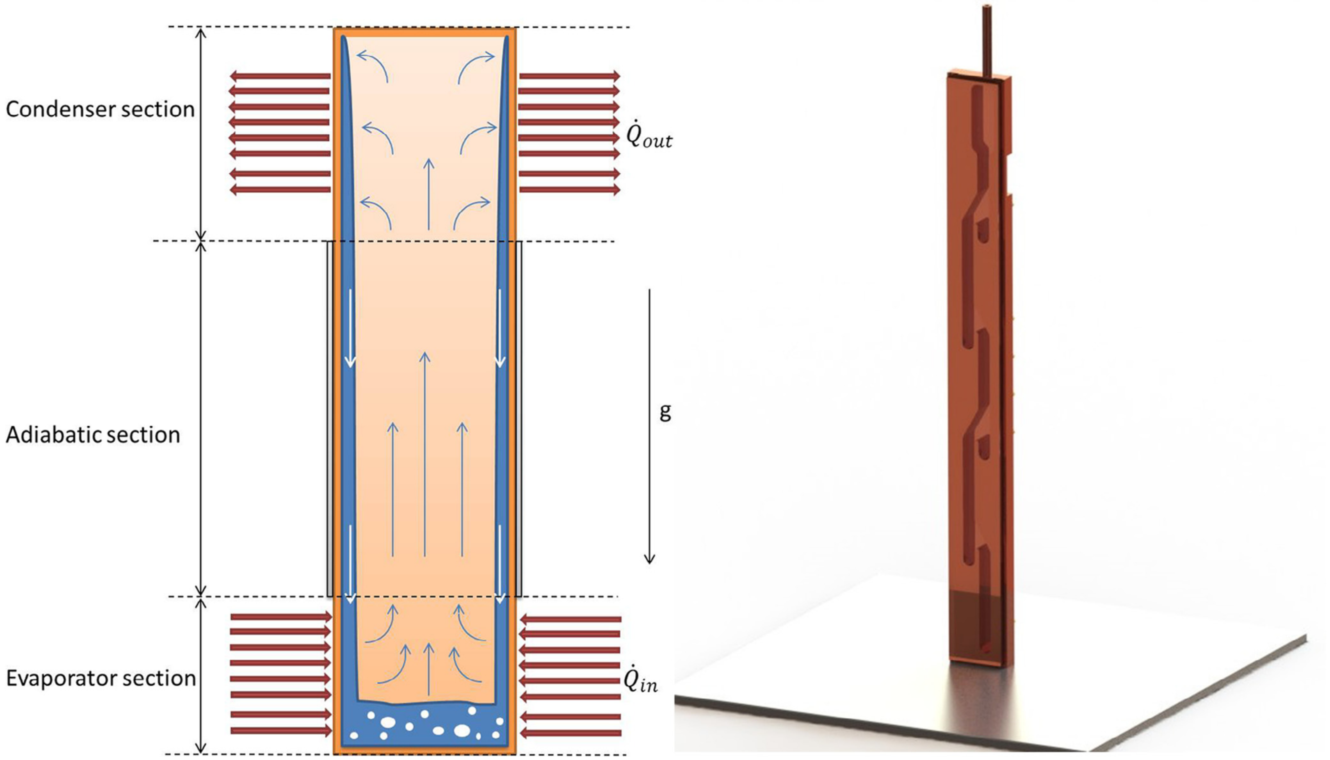
This paper presents an innovative design for a counter-current two-phase closed thermosyphon with cascading pools, as shown in Fig. 1b. This design focuses, in contrast to the classical thermosyphon design, on a relative long evaporator section in comparison to the adiabatic and condenser sections. The goal is to minimize the temperature gradient and temperature fluctuation along the entire length of the evaporator. This is done by having multiple cascading pools along the entire length of the thermosyphon's evaporator section. This enables the cooling of large planar surfaces in which space is a design constraint and heat needs to be dissipated effectively at an affordable cost. The design is further discussed in Section 2. An experimental apparatus was built based on a numerical model using a control volume approach. The experimental apparatus was used to gather both thermal measurement data and visual operations of the two-phase working principle to review the working principle and the performance. The numerical method focuses on good overall prediction, adaptability and computation speed. A comparison between the model and the experimental data is made and discussions about the findings are reported.

1.2. Literature review

The first tube with a two-phase cycle, called the Perkins tube, was patented by Jacob Perkins in 1836 [5]. Early research on counter-current two-phase closed thermosyphons was performed by Cohen and Bayley [6]. Most of the early research focused on specific phenomena, such as the heat transfer behavior in various sections and operation limitations [1]. The theoretical results were often compared with experimental data and empirical correlations were reported. Recent research surrounding this field seems to be more concentrated on the use of elaborate numerical optimization models [4,7], with the focus on accurate results.

1.2.1. Thermosyphon limitations

The operating limitations for thermosyphons describe the boundaries wherein the device should operate as designed. An important limitation is the flooding limitation. Shear on the liquid–vapor interface causes liquid to return to the condenser section when the shear forces are greater than the surface tension forces. Contributions for determining the flooding limitation were made by various researchers [8–12]. Other researchers contributed to the determination of correlations for the dry-out limitation [6,13,14]. Dry-out is reached when the amount of working fluid is small in comparison to the supplied heat, resulting in the entire vaporization of the liquid puddle at the bottom evaporator section. Finally, also the boiling limitation has been researched extensively [15,16]. This limit is encountered when the boiling regime changes from nucleate to film boiling, creating an insulating vapor layer between the wall and the liquid, causing the evaporator wall temperature to rise unacceptably.



(a) schematic drawing of a classical design (b) innovative design with cascading pools (3D model in PDF)

Fig. 1. Counter-current two-phase closed thermosyphon design.