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An experimental investigation on the evaporation and condensation heat transfer of two-phase closed thermosyphons

Davoud Jafari [a,*], Paolo Di Marco [b], Sauro Filippeschi [b], Alessandro Franco [b]

[a] *Faculty of Engineering Technology, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands*
[b] *Department of Energy Systems, Territory and Constructions Engineering (DESTEC), University of Pisa, Italy*

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ABSTRACT

Two-phase closed thermosyphons (TPCTs) are excellent thermal transfer devices that their integration into heat exchangers has been shown a strong potential for energy savings. The scope of this study is an experimental evaluation of the evaporation and condensation heat transfer of a TPCT for uniformly heated evaporator surface. Water as the working fluid is charged in a TPCT with a length of 500 mm and an inner diameter of 33 mm at different filling ratios (8–100%). The Thermosyphon heat transfer performances are compared with some predictive correlations of suppress the pool boiling insert uniquely and suppress the pool boiling combined with film evaporation for the evaporator section at different filling ratios. The experimentally obtained condensation heat transfer is also evaluated by available filmwise condensation model. Results show an agreement with the most of the selected correlations with tolerance ±30% and the appropriate set of correlations are introduced giving an accuracy within ±10%.

1. Introduction

A continuous cycle of the evaporation and the condensation processes is encountered in many energy and thermal processing applications. A two-phase closed thermosyphon (TPCT), i.e. a gravity assisted wickless heat pipe, is one of the two-phase passive devices which works on the mechanisms of evaporation and condensation to transfer large amounts of heat with a minimal temperature difference [1]. A TPCT starts operating when heat is applied to the evaporator section, causing evaporation of the working fluid. The vapor flows to the condenser section, where the fluid condenses. Then, the condensate returns to the evaporator section along the wall by the action of gravity, closing the cycle. Given the advantages of the TPCT, heat transfer predictions in its uniformly heated are of interest in many industrial and energy applications. Examples of these applications include heating, ventilation and air conditioning, residential and commercial refrigeration, data center cooling, solar water heating and geothermal energy recovery [2–6].

The prediction of heat transfer processes in these devices is very challenging. The heat and mass transfer processes inside a TPCT include convection, pool boiling, thin liquid film evaporation, countercurrent two-phase flow and filmwise condensation. In the evaporator section, the falling liquid film and the liquid pool in the bottom of the device give their contribution to the phase change and heat transfer simultaneously. As various heat transfer regimes can be observed in the evaporator section including natural convection, mixed convection and suppress the nucleate boiling (at high heat fluxes), the overall heat transfer mechanism is complex [7]. Recent studies considered the nucleate pool boiling regime to predict the heat transfer coefficient within the evaporator section: Rohsenow [8], Labuntsov [9], Imura et al. [10], Shiraishi et al. [11], Kutateladze [12] and Chowdhury et al. [13]. For a relatively small heat flux, Nusselt theory for filmwise evaporation is suggested [7,14] while Shiraishi et al. [11] suggested a modification of Nusselt theory when nucleate boiling within the liquid film is dominant. Among others, Kiatsiriroat et al. [15] reported the use of a modified Rohsenow [8] correlation to predict the boiling heat transfer coefficient inside the thermosyphon for different working fluid. Park et al. [16], Noie [17] and Guo and Nutter [18] showed a good agreement with the Imura [10] using FC-72, water and R134a as a working fluid, respectively. Jouhara and Robinson [14] experimentally investigated a thermosyphon charged with water at filling ratios of 50% and 160%. They compared the evaporation heat transfer with available predictive correlations and theories with a good agreement; however, they have not analyzed the combination of correlations in the case of low filling ratio.

A Nusselt analysis for filmwise condensation has been used to predict condensation heat transfer coefficient. To predict the

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* Corresponding author.
E-mail addresses: davoud.jafari@utwente.nl, j.davoud@yahoo.com (D. Jafari).

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Nomenclature

Bo	Bond number, d_i/L_b
c	specific heat (J kg^{-1} K^{-1})
D	diameter (m)
d_b	bubble departure diameter (m)
FR	filling ratio
g	gravitational acceleration (m s^{-2})
h	heat transfer coefficient (W m^{-2} K^{-1})
h_{fg}	heat of vaporization (J kg^{-1})
K	thermal conductivity (W m^{-1} K^{-1})
L	length (m)
L_b	bubble length scale (m), $[\sigma/g(\rho_l - \rho_v)]^{1/2}$
$\dot{m}$	mass flow rate (kg s^{-1})
Nu	Nusselt number, hL/k
P	pressure (Pa)
Pr	Prandtl number, υ/α
Q	heat transfer rate (W)
q	heat flux (W m^{-2})
R	thermal resistance (K W^{-1})
r	radius (m)
Re	Reynolds number, $4Q/\pi D h_{fg}\pi$
T	temperature (°K)

Greek symbols

υ	kinematic viscosity (m^2 s^{-1})
ρ	density (kg m^{-3})
μ	dynamic viscosity (Pa s)
σ	surface tension (N m^{-1})
θ	contact angle (°)

Subscripts

a	adiabatic
atm	atmospheric
c	condenser
e	evaporator
film	liquid film
i	inner
l	liquid
o	outer
p	pool
sat	saturation
t	total
v	vapor

filmwise condensation heat transfer, Rohsenow [8] modified Nusselt correlation which is applicable when Reynolds film number is in the range of 30–1600. Hashimoto and Kaminaga [19] provided a correlation considering the effect of entrainment, which was later modified by Jouhara and Robinson [14]. Different approaches for defining the condensation heat transfer are suggested by Wang and Ma [20] applicable for vertical and inclined TPCTs. Hussein et al. [21] presented a correlation to predict condensation heat transfer for a wide range of inclination angles. The majority of studies to analyze evaporation and condensation heat transfer have been recently discussed by Jafari et al. [2]. They have made a comparative analysis of the heat transfer correlations with the experimental data in the literature. They showed that the results appear to be dispersed both for condenser and evaporator sections.

The thermal characteristics of TPCTs have been investigated in recent years [22–25]. There still exists, however, uncertainty in the description of heat transfer characteristics. Previous studies on the investigation of evaporation heat transfer focused on pool boiling or film evaporation heat transfer. There is limited open literature on the combination of pool boiling and film evaporation heat transfer in TPCTs. The selection of appropriate heat transfer correlation would result in prediction of thermal performance of two-phase closed thermosyphon and, opening the way to their integration into lots of practical applications. The authors of present study [26], recently, experimentally and numerically investigated the transient behavior of TPCTs at different filling ratios. They showed that the Imura [10] correlation is able to accurately predict the pool boiling heat transfer as expected from the literature for high filling ratios (filling ratio of 135%), but a comparable agreement was observed at low filling ratios (filling ratio of 16% and 35%). Therefore, there is a need to evaluate the reported heat transfer correlations for thermosyphons to identify more accurate heat transfer correlations as well as appropriate combination.

This paper can be considered as the second part of a recently published paper [26]. The experimental data of a thermosyphon with 500 mm length and 33 mm internal diameter charging with water are presented. Water tests are performed with different filling ratios, ranging from 8% to 100% in order to have a combination of the liquid pool and liquid film region and also to have only pool boiling. The experimental measurements are compared with the prediction of a model based on existing correlations of the literature for evaporation and condensation heat transfer.

2. Methods for prediction of condensation and evaporation heat transfer in a TPCT

A TPCT is divided into three sections: an evaporator, an adiabatic region and a condenser, as shown in Fig. 1. The thermosyphon operates when heat is supplied to the evaporator section. The working fluid in the evaporator section is vaporized and conveys heat from the evaporator section (heat source) to the condenser section (heat sink), where condensation of the working fluid occurs. A countercurrent (the liquid and the vapor flow in opposite directions) thin liquid film flows back to the evaporator section under the gravitational force which the liquid is evenly distributed around the thermosyphon wall. The thermal resistances of a thermosyphon are illustrated in Fig. 1.

The two major contributors to the total thermal resistance of a thermosyphon are the thermal resistances in the liquid film in both the condenser (R_c) and the evaporator ($R_{e,film}$). The condensation thermal resistance of the thermosyphon is given by

$$R_c = \frac{1}{h_c A_c} \tag{1}$$

where h_c is the heat transfer coefficient of the liquid film in the condenser section, and A_c is the inner surface area of the liquid film. There are some parameters that affect the condensation heat transfer: thermal and hydrodynamic properties of the working fluid, local flow velocity, orientation and operating temperature. A Nusselt analysis for condensation on a vertical flat plate is the first basic approach commonly used to evaluate the condensation heat transfer coefficient, considering the filmwise condensation within the laminar regime, Eq. (3) (see Table 1). Where ρ_l and ρ_v are the density of the liquid and vapor, k_l is the thermal conductivity of the liquid, μ_l is the liquid viscosity. The film Reynolds number (Re_f) for this study is defined as