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Experimental investigation of a confined flat two-phase thermosyphon for electronics cooling

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A B S T R A C T

A novel type of two-phase heat spreader based on a flat confined thermosyphon is proposed for electronics cooling applications. Two wickless flat copper-water heat pipes with an inner thickness of 3 mm were experimentally investigated for two-phase flow visualizations and characterization of thermal performance. The effects of heat input, filling ratio, inclination, and saturation temperature were studied. Experimental results show that the confinement of the fluid inside the heat spreader induces confined boiling phenomenon with a strong coupling between condensation and boiling mechanisms. They also highlight an enhancement of heat transfer and interesting performance such as high heat transfer capability (tested up to 10 W/cm^2 with a corresponding thermal resistance around 0.07 K/W at an optimum filling ratio), low sensitivity to inclination and higher degree of freedom on heat sources location compared to a classical thermosyphon.

1. Introduction

Due to perpetual advances in electronic engineering with the pursuing of higher performance and device miniaturization, thermal management of electronic components requires to deal with continuously increasing heat fluxes and local temperatures: between the years 2000 and 2010, the associated heat fluxes were multiplied by more than ten, eventually reaching 120–150 W/cm^2 for some applications [1]. Since the lifetime and reliability of electronic components is sensitive to their operating temperature, these increasing demands on heat dissipation create a need for efficient devices with high heat transfer and heat spreading capabilities.

Heat pipes [2] and micro heat pipes [3] were first considered as an adequate solution for electronics cooling with their high effective thermal conductivity, passiveness, and performance for temperature control. However, today's requirements highlight their limitations in terms of heat transfer and temperature uniformity [1]. Two-phase thermosyphons, also known as wickless or gravity-assisted heat pipes, therefore emerged as an alternative for small-scale applications with better thermal performance [4–6].

The main physical mechanisms taking place in a classical two-phase closed thermosyphon (TPCT) are illustrated in Fig. 1a. A heat flux is supplied to the working fluid through the evaporator wall in the lower section of the device, causing the liquid contained in the cavity to start to evaporate. Vapor flows upwards in the pipe up to the condenser region where it condenses on the inner wall, forming a liquid film that is returned back to the evaporator by gravity.

Because of the significant latent heat of vaporization associated to phase change, a large amount of heat can be transferred from the evaporator section to the condenser section with a very small relative temperature difference. If the condensation area is larger than the evaporation area, the device also acts as a heat spreader, as illustrated in Fig. 1b where the heat is transferred from a power module to a larger heat sink consisting of fins.

TPCTs generally do not include wick structures, unlike conventional heat pipes: since gravity is the major driving force for condensate return, they exhibit neither a large flow resistance nor a low boiling limit inside the wick, which is of great interest for high heat flux applications where conventional heat pipes show limitations.

In addition to their high heat transfer and spreading capability, TPCTs have other interesting features for electronics cooling in challenging environments such as aeronautical environments: their geometry can easily be adapted to fit power modules or flat electronic components, or to meet space constraints; with the absence of wick, they are also simpler and cheaper to manufacture and do not raise the issue of frozen start-up in capillary structure.

However, TPCTs are constrained by other operating parameters since their thermohydraulic behavior is strongly affected by the heat input, the filling ratio, the working fluid and the device design.

In particular, TPCTs are often constrained regarding the heat source location: when operation occurs in flooded conditions, the degree of freedom for heat source positioning is rather high, but the associated

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Nomenclature

Roman symbols

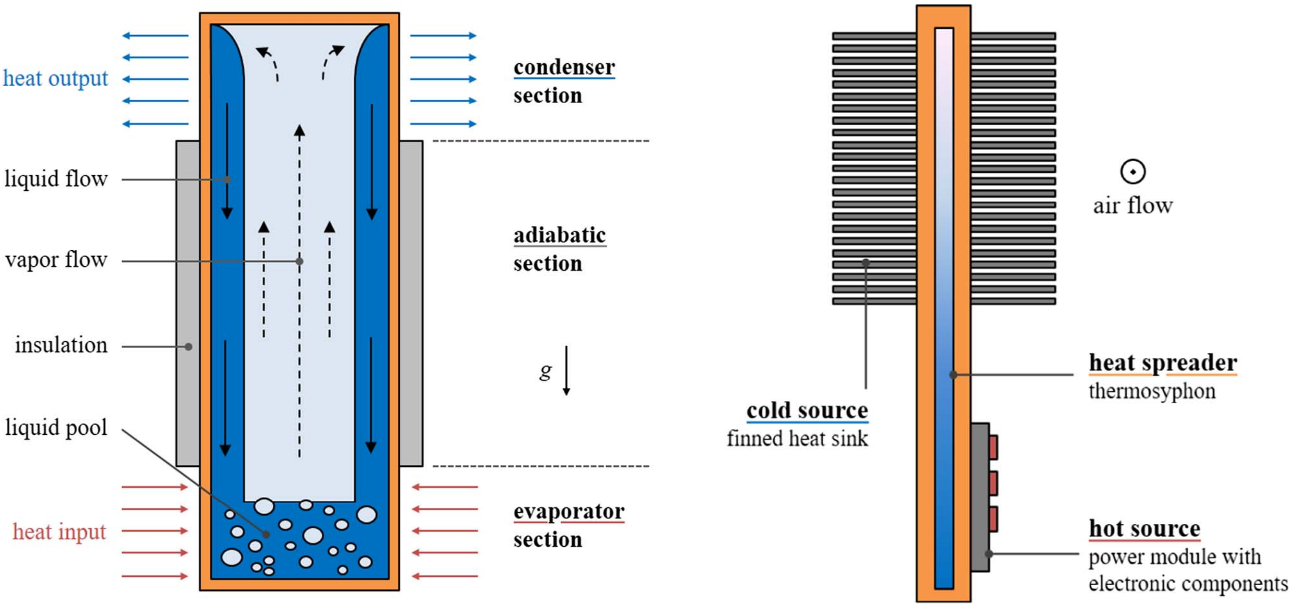
A	surface, [m^2]
Bo	Bond number, [–]
Co	Confinement number, [–]
Cp	specific heat, [kJ/K/kg]
D	diameter, [m]
e	heat spreader inner thickness, [m]
FR	filling ratio, [%]
g	acceleration due to gravity, [m/s^2]
h	heat transfer coefficient, [W/K/m^2]
h_{fg}	latent heat of vaporization, [J/kg]
L	length, [m]
$\dot{m}$	mass flow rate, [kg/s]
P	pressure, [Pa]
Pr	Prandtl number, [–]
Q	heat load, [W]
q	heat flux, [W/m^2]
R	thermal resistance, [K/W]
Re	Reynolds number, [–]
T	temperature, [°C]
x	heat spreader axis coordinate, [m]

Subscripts

atm	atmospheric
b	bubble departure
cap	capillary
cond	condensation
conduction	conduction
cool	cooling
crit	critical
evap	evaporation
exp	experimental
fl	film
i	inner
w	wall
in	inlet
l	liquid
max	maximal
meas	measured
min	minimal
out	outlet
φ	phase change
sat	saturation
theo	theoretical
v	vapor

Greek symbols

Δ	difference
θ	inclination angle, [°]
λ	thermal conductivity, [W/m/K]
μ	dynamic viscosity, [Ns/m^2]
ν	kinematic viscosity, [m/s^2]
ρ	density, [kg/m^3]
σ	surface tension, [N/m]



(*a*) operating principle

(*b*) example of application as heat spreader for electronics cooling

Fig. 1. Classical thermosyphon: operating principle and application.

filling ratios mostly correspond to a degradation of thermal performance compared with lower filling ratios. In non-flooded conditions, available positions for the heat sources are more limited and the evaporator section has to be at the same level than the liquid pool to avoid dry-outs of the liquid film, which often translates into a vertical positioning of the heat source below the condenser section, at the bottom of the device [6]. Most TPCTs require a minimum inclination angle of a few degrees to operate, as gravitational forces are an important driving force for the fluid circulation. The influence of the inclination angle on the thermal performance of classical thermosyphons was studied by various authors [7–10] with different quantitative conclusions depending on the working fluid and heat pipe geometry. Nevertheless,