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Research Paper

Numerical simulation of heat and mass transfer in bidispersed capillary structures: Application to the evaporator of a loop heat pipe

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ABSTRACT

Heat and mass transfer with phase change in an evaporator unit cell is analysed using a mixed pore network model. Two different kind of wick are investigated: a monoporous capillary structure characterised by a monomodal pore size distribution and a bidispersed capillary structure characterised by a bimodal pore size distribution. The evaporator thermal performance, i.e. the conductance, and the overheating of the casing are compared at different heat loads with experimental results and show a good agreement. For a large range of flux, the bidispersed wick has higher thermal performance than the monoporous wick. A bidispersed wick prevents the overheating of the casing which is the most encountered limit in LHP application. The liquid–vapour phase distribution, as well as the vapour saturation and the vapour mass flow rate are investigated to explain these behaviours.

1. Introduction

Capillary pumped loops (CPL) and Loop heat pipes (LHPs) ([1]) are cooling devices used in space, aeronautic or terrestrial applications to meet the thermal control problems of advanced electronics. An LHP (see Fig. 1a) is composed of a condenser, a liquid and a vapour line, a compensation chamber and an evaporator. An LHP can be studied at the scale of the whole system, e.g. [2–4], or at the scale of only one of the components which is generally the evaporator since this is the place of the vaporisation process, e.g. [5,6]. The evaporator consists of a metallic casing, a porous wick, vapour grooves and a liquid-core. The heat flux that needs to be evacuated is transferred by conduction up to the porous wick through the metallic wall of the evaporator. This induces the vaporisation of the fluid and the formation of menisci at the surface and/or within the porous wick. The menisci adjust themselves to balance the total pressure drop in the others components of the loop. The vapour is then evacuated thanks to vapour grooves. A cross section of a cylindrical evaporator is depicted in Fig. 1b, where dashed lines delimit the evaporator unit cell shown in three-dimension in Fig. 1c.

Heat and mass transfer in capillary evaporator have been studied when the vaporisation only occurs at the wick/groove interface (liquid saturated wick) ([8–10]) or within the wick (using the so-called "vapour pocket" assumption, e.g. [11–13]). However, a recent work [7] highlighted that a two-phase zone actually exists under the casing, as already supposed in [14–17], calling into question the relevance of the "vapour pocket" assumption in a three-dimensional capillary evaporator unit cell. As pointed out in [13], the most interesting regime, corresponding to the best evaporator performances, is actually the regime in which there is no vapour pocket and where liquid and vapour coexist within the wick. Identifying the correct operation regime is of course crucial in the prospect of designing better evaporators. Several parameters and/or properties have been investigated numerically and/or experimentally in order to improve the evaporator performances. Amongst other the geometrical dimensions and the position of vapour grooves [10], the choice of the working fluid ([18,19]) or the use of a bilayer wick ([20–22]) were investigated. In this context, the use of a bimodal capillary wick has been considered in the literature and seems to be promising to improve LHP performance.

Bimodal structures are characterised by the existence of two distinct pore size distributions It exists essentially two methods to manufacture them inducing a structural difference ([23]). The first method collects together small pore particles into clusters, leading to a so-called "bidispersed" structure. Large pores are

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Nomenclature

a	step between two pores center (m)
b	lattice spacing of the large network (m)
c_p	specific heat capacity (J/kg/K)
d	diameter (m)
h_{ev}	evaporator conductance (W/m^2/K)
h_g	convective heat transfer coefficient (W/m^2/K)
k	thermal conductivity (W/m/K)
K	permeability (m^2)
l	length (m)
n_i, n_{jw}, n_k	number of pore, i.e. grid point, in the wick in the x, y and z direction
$\mathbf{n}$	unit normal vector
N	number of pore, throat or cluster
P	pressure (Pa)
Q	heat flux (W/m^2)
T	temperature (K)
$\mathbf{u}$	velocity vector (m/s)
V	volume (m^3)

Greek symbols

δ	standard deviation
ε	porosity
ρ	density (kg/m^3)
σ	surface tension (Pa/m)

Superscripts

$*$	effective

Subscripts

c	cluster, casing
cap	capillary
cc	compensation chamber
g	grooves
l	liquid
L	large network
$loop$	loop
max	maximum
p	pore
PN	pore network value
$\mathbb{R}$	experimental value
sat	saturation
sub	subcooled
sup	superheated
S	small network
t	throat
$\mathbb{t}$	theoretical value
T	total
v	vapour
$void$	void
w	wick

located between clusters of small pores (Fig. 2a). The second method consists in sintering a mix of powder and pore formers. The pore formers are then removed through a dissolution or evaporation process. In that case, large pores are located at the places of the pore formers (Fig. 2b), creating a so-called "biporous" structure. Scanning electron microscopy (SEM) images of a bidispersed structure and a biporous one are shown in Fig. 3. The large pores create preferential paths for the vapour while the small pores

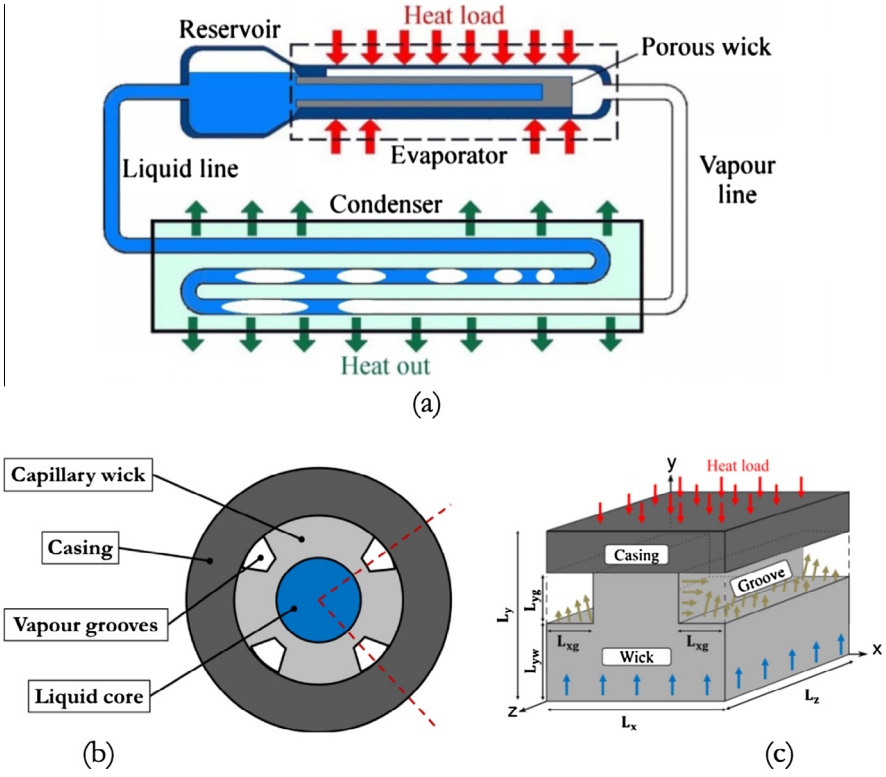

Fig. 1. (a) Schematic of a LHP; (b) cross section of a cylindrical evaporator and (c) evaporator unit cell delimited by the red dashed line in (b). Reprinted from [7] with permission from Elsevier. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)