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Three dimensional liquid and vapour distribution in the wick of capillary evaporators

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ABSTRACT

Heat and mass transfer with liquid–vapour phase change in a representative unit cell of a capillary evaporator is studied using a mixed pore network model. The model combines the computation of temperature and pressure fields in vapour and liquid pores according to mean field approaches with pore scale invasion rules depending on the capillary pressure thresholds associated with each local constriction between two pores. The metallic body through which heat is transferred to the porous wick is also taken into account in the simulations. After comparisons with a visualisation experiment, numerical simulations performed in three dimensional pore networks lead to the identification of three main regimes depending on the applied heat load. Compared with previous works using the so-called vapour pocket assumption, the 3D simulations reveal a regime where the phase distribution within the wick is fundamentally different. This regime is characterised by the coexistence of both the liquid and vapour phases underneath the casing within the wick. This regime is shown to correspond to the best evaporator performance.

1. Introduction

Capillary pumped loops (CPL) and Loop heat pipes (LHPs), e.g. [1,2], are cooling devices developed to meet the increasingly demanding thermal control problems of high-end electronics and radio frequency devices. First developed in relation with aerospace applications, these devices are also studied nowadays for rail-bound transport, automobile transport or aeronautics applications. A sketch of LHP is shown in Fig. 1a. It consists of an evaporator, a compensation chamber (also called reservoir), vapour and liquid transport lines and a condenser.

Two main types of evaporator are encountered in LHP: flat or cylindrical. Fig. 1b shows a schematic of the cross-section of a cylindrical evaporator. Both types of evaporator, i.e. flat or cylindrical, consist of a liquid-passage core, vapour-evacuation grooves, an outer casing and a capillary porous wick. Heat applied to the outer casing leads to the evaporation of the liquid inside the wick or at the wick/vapour groove interface. The produced vapour is collected in the vapour grooves and flows through the vapour transport line towards the condenser. The menisci formed at the wick/grooves interface or inside the wick adjust themselves to establish a capillary suction that balances the total pressure drop in the device. Unwrapping the cylindrical evaporator leads to a structure close to a flat evaporator. In what follows we will concentrate on the unit cell shown in Fig. 2, which is therefore representative of both types of evaporator.

Owing to their technological importance, LHP have been the subject of quite a few investigations. Roughly, one can distinguish two main types of works. The works aiming at studying the whole LHP, e.g. [3–5] to name but a few, and the works focussing on one of the components, the condenser or more often the evaporator because evaporator is generally considered as the key component in this system, e.g. [6,7]. The present work belongs to the second category. We focus on the heat and mass transfer with phase change inside the evaporator. One can then again distinguish two types of works as regards the modelling of heat and mass transfers in the porous wick of evaporator: the works where the wick is assumed to be liquid saturated, e.g. [8–12], and the works where the wick can be partially invaded by the vapour. The latter is the situation of primary interest for the present study. In most of the previous modelling works dealing with the situations where vapour is present inside the wick, e.g. [13–18], only two steady-state

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Nomenclature

a	step between two pores centre, m
c_p	specific heat capacity, J/kg/K
C_{evap}	conductance, W/m^2/K
d	diameter of throats, m diameter of loop heat pipe component, m
D_H	hydraulic diameter, m
g_{ij}	hydraulic conductance of throat, m^3
$\bar{g}$	hydraulic conductance using in mixed model, m^3
h_c	convective heat transfer coefficient, W/m^2/K
h_{lv}	latent heat of vapourization, J/kg
K	permeability, m^2
ℓ	length of throat, m
l	length of loop heat pipe component, m
L_x, L_y, L_z, L_{xv}, L_{yg}, L_{yw}	dimensions of the geometry, m
$\dot{m}$	mass flow rate, kg/s
M	molar mass, g/mol
$\mathbf{n}$	unit normal vector
N	total number of grooves
P	pressure, Pa
q_{ij}	mass flow rate between two pores, kg/s
Q	heat flux, W/m^2
r	radius, m
R	gas constant, J/kg/K
S	surface, m^2
S_{vc}, S_{lc}	fraction of pore occupied by vapour, liquid, under the casing
T	temperature, K
$\mathbf{u}$	velocity vector, m/s

Greek symbols

α	relaxation parameter
ε	porosity
λ	thermal conductivity, W/m/K
λ^*	effective thermal conductivity, W/m/K
μ	dynamic viscosity, Pa s
ν	kinematic viscosity, m^2/s
ξ	depth of the two-phase zone
ρ	density, kg/m^3
σ	surface tension, Pa/m
Σ	pore size distribution
ω	convergence criteria

Dimensionless number

Ca	capillary number
Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number
A	aspect ratio value
γ	proportional factor between Re and fanning factor
G	factor depending of aspect ratio value

Subscripts

b	vapour bubble
c	casing
cap	capillary
cc	compensation chamber
$cond$	condenser
g	groove
int	interface
l	liquid
ll	liquid line
max	maximum
min	minimum
new	new value
$nucl$	nucleation
p	pore
Ref	reference
sat	saturation
sub	subcooled
v	vapour
vl	vapour line
w	wick
0	value for initialisation

regimes were distinguished. For low to moderate heat loads, the wick was assumed to be fully saturated and vapourization took place at the wick/groove interface. Above a certain heat load, bubble nucleation occurred within the wick, leading to the formation of an internal vapourization front as sketched in Fig. 3. All these works were more or less implicitly based on the so-called "vapour pocket" assumption when vapour was present in the wick. As illustrated in Fig. 3, the "vapour pocket" assumption essentially amounts to assuming only two types of region within the wick: a fully dry region in contact with the casing occupied by the vapour and a fully liquid region elsewhere with a sharp interface between the two regions. This is in contrast with the work presented in [19], where it was considered that a two-phase zone, i.e. a zone where liquid and vapour coexists in the same region, formed within the wick. This was for moderate heat fluxes. For higher heat fluxes, a fully dry region could form but a two-phase zone was still present in the wick. However, the porous structure considered by [19] was held vertically, 40 mm in height and formed by large beads (on the order of 1 mm in diameter) and therefore operated in the presence of significant gravity effects. Thus, under conditions presumably

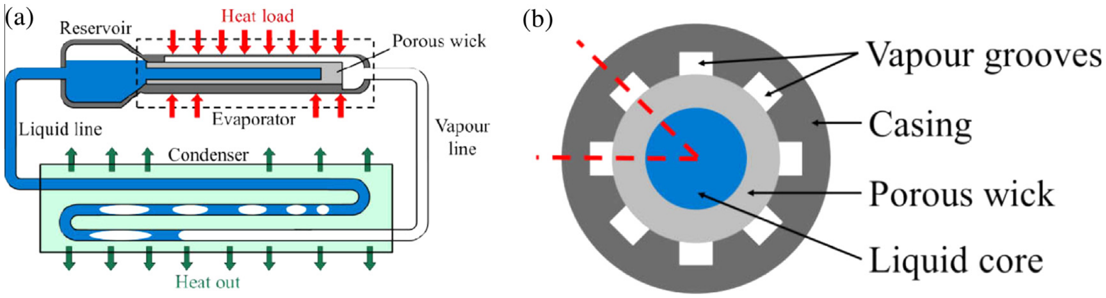

Fig. 1. (a) Schematic of a LHP (b) Schematic of the cross section of a cylindrical evaporator. The dashed lines define the evaporator unit cell.