

Heat and Mass Transfer in Evaporator of Loop Heat Pipe

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Investigation of heat-exchange processes in the evaporator of a loop heat pipe is important for the development of heat transfer devices with low thermal resistances. A two-dimensional mathematical model of the evaporator active zone is presented. Three modes of vapor generation in the wick have been examined, where each differs in the mechanism of the vapor phase formation and in the saturation of the capillary structure: 1) evaporation to the vapor grooves, 2) volumetric evaporation in the two-phase zone, and 3) volumetric evaporation in the two-phase zone separated from the heated wall of the evaporator by dried zones. Conditions identifying changes between modes have been formulated. Structural characteristics of the wick with different pore sizes have been taken into account. Using a numerical–analytical method, results were obtained for three copper loop heat pipes with biporous wicks, where the working fluid was water for one of the loop heat pipes and methanol for the other two. The heat-load dependent temperature drop between the evaporator wall and the vapor in the vapor grooves has been presented. Additionally, a comparative analysis of calculated and experimental results was performed.

Nomenclature

c_p	=	specific heat at constant pressure, J/kg · K
h_{lv}	=	latent heat of vaporization, J/kg
K	=	permeability, m ²
k	=	thermal conductivity, W/m · K
L	=	length, m
n	=	normal vector
P	=	pressure, Pa
Q	=	heat load, W
q_{in}	=	applied heat flux, W · m ⁻²
R	=	thermal resistance, K/W
R, r	=	pore radius, m
T	=	temperature, °C
S	=	area, m
α	=	heat-exchange coefficient, W/m ² · K
ε	=	porosity
μ	=	dynamic viscosity, Pa · s
ρ	=	density, kg/m ³

Subscripts

comp	=	compact
cond	=	condensation
cont	=	contact
dry	=	dry
ext	=	external
gr	=	vapor groove
l	=	liquid
ll	=	liquid line
nucl	=	nucleation
p	=	peak
q	=	active zone (heat input zone)
v	=	vapor
vl	=	vapor line
wall	=	evaporator wall (or case)

$1f$	=	single phase (saturated with liquid)
$2f$	=	two phase

I. Introduction

A LOOP heat pipe (LHP) is a two-phase heat transfer device using capillary pumping of the working fluid. It consists of an evaporator, a compensation chamber, vapor and liquid lines, and a condenser, as shown in Fig. 1, where the LHP principal design is presented. Detailed descriptions of the main working principles of LHPs are presented in [1–3]. The evaporator, the key element of an LHP, primarily determines the operation and performance of the device. The evaporator includes a wall, a wick, vapor grooves, and a liquid core passage. The evaporator is coupled to a compensation chamber, which receives liquid displaced from the condenser during LHP startup and operation. Heat is applied to the outer surface of the evaporator wall where it then is transferred through the wall and wick to the evaporating menisci. The generated vapor is collected in the vapor grooves and travels through the vapor line to the condenser. Liquid then returns to the compensation chamber through the liquid line. To reach the evaporating menisci, liquid flows back through the wick that separates the evaporation zone and the compensation chamber.

Investigations [4–7] have shown that the evaporating menisci creating the capillary pressure can be located both on the groove–wick surface and inside the wick. Mathematical models of heat and mass transfer processes in the evaporation zone consider this situation but at the same time most are based on the assumption of the structural uniformity of a wick, i.e., a wick having pores of the same size [8–14]. However, in actual LHP wicks there are pores of different sizes. In Fig. 2 a typical graph of pore-size distribution for a sintered titanium wick with a porosity of about 60% is presented as an example. Line A is the differential curve of pore-size distribution and B is the corresponding integral curve, where the differential function $\psi(r)$ can be obtained by $\psi(r) = d\Psi^*(r)/dr$. According to Fig. 2, the pore radius of this wick varies from 0.3 to 14 μm .

Figus et al. [15] developed a two-dimensional mathematical pore network model for a wick with a varying pore-size distribution. The pore network simulations indicated that in this case capillary effects could lead to fractal types of vapor–liquid fronts which cannot be predicted by a single pore-size model. A previous investigation [16] suggested a model of heat-exchange processes in an LHP evaporator, where structural characteristics of the wick were also taken into account. Based on the idea regarding different pore-formation modes in porous materials presented in [16] it was suggested using biporous wicks to allow a more advanced vapor removal system. The main

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