Energy 158 (2018) 746–759

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

# Analytical study of impact of the wick's fractal parameters on the heat transfer capacity of a novel micro-channel loop heat pipe

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ARTICLE INFO

*Article history:*
Received 15 February 2018
Received in revised form
14 May 2018
Accepted 12 June 2018
Available online 12 June 2018

*Keywords:*
Micro-channel
Loop heat pipe
Heat transport capacity
Fractal theory
Porous media
Permeability

ABSTRACT

This paper presents an analytical study of the impact of a wick's fractal geometrical parameters on the heat transfer capacity of a novel micro-channel loop heat pipe (MCLHP) which is applicable to solar heating system. By treating the wick of the micro-channel evaporator of the MCLHP as a thin porous layer, i.e. a combination of random/tortuous pores and water-containing skeletons, the impact of the fractal geometrical parameters of the wick on the heat transport capacity of the MCLHP was investigated. Based on the classical heat transfer limits and fractal equations, a dedicated computerised analytical model was developed by using the Newton-Raphson method; this model was then applied to analyze a few macro parameters of the wick (i.e., effective thermal conductivity and permeability) and heat transfer limits of the MCLHP, including capillary, viscous, entrainment, sonic and boiling ones. Comparison among these five limits was made using the minimum value searching approach, leading to the determination of the final heat transfer constraint of the MCLHP, which is identified as the capillary limit. A higher effective porosity and a larger pore diameter lead to an increased wick fractal dimension and thus a higher capillary limit. An increased height difference between the evaporator and the condenser also increases the heat transfer (i.e. capillary) limit of the MCLHP. Decreased effective porosity ($\varepsilon$), pores portion, and increased tortuosity of capillaries help enhance the heat transfer (boiling) limit of the MCLHP. Overall, fractal theory is thought to be an ideal method to address the impact of an irregular porous wick on the heat transfer performance of a MCLHP.

## 1. Introduction

A Loop Heat Pipe (LHP), comprising a heat pipe evaporator (wicked or wickless type), a condenser, a liquid transportation line, a vapour transportation line and a compensation chamber, is a two phase (condensation/evaporation) device that can transport heat throughout a long distance [1,2]. The LHP is usually fitted with some kind of wick, e.g., meshes, sintered powder, or grooves, on the inner surface of the evaporator and condenser that can help distribute liquid streams uniformly across the surface and thus create an enhanced heat transfer performance. In past decades, sintered powder wick has been widely used in the evaporator of loop heat pipes [2], which can be treated as a layer of porous material comprising the metal skeletons and random/tortuous pores. Micro-channel, with an equivalent hydraulic diameter of less than 1 mm, was recently applied to make loop heat pipes, thus forming a Micro-Channel Loop Heat Pipe (MCLHP) [3]. This structure has a relatively smaller cross sectional area for fluid flow that can create a higher vapour flow speed within the MCLHP. A higher speed vapour flow can create a large shear force imposed on the interface of the liquid and vapour phases, thus reducing thickness of the liquid film attained to the heat pipe wall and increasing the effective thermal conductivity of the liquid film. The other benefit of the structure lies in the easy binding approach with the PV module owing to its flat-plate surface.

The characteristic parameters of the wick, including the effective thermal conductivity, pores' maximum diameter and permeability, impose significant impacts on the performance of the MCLHP [4]. Increasing the wick's thermal conductivity may

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https://doi.org/10.1016/j.energy.2018.06.075
0360-5442/

## Nomenclature

| | |
|---|---|
| a | micro-channel port width, size [m] |
| A | total area of the unit cell [$m^2$] |
| $A_p$ | the total pore area for the representative cell [$m^2$] |
| b | micro-channel port height [m] |
| d | euclidean dimension [−] |
| $D_{hp}$ | hydraulic diameter of a single mini-channel tube [m] |
| $D_f$ | fractal dimension of porous media [−] |
| $F_{f,w}$ | the fractal dimension of liquid in porous media[-] |
| $D_{f,g}$ | the fractal dimension of gas/vapour in porous media [−] |
| $D_t$ | fractal dimension for tortuous stream tubes in porous media [−] |
| $D_{v,e}$ | equivalent diameter of the vapour section [m] |
| $D_w$ | the condensed liquid film hydraulic diameter [−] |
| $h_{fg}$ | latent heat of evaporation [J/kg] |
| K | proportional constant for bubble diameter ( 2 or 1.8 [-] |
| $K_e$ | effective thermal conductivity [W/(m·K)] |
| k | thermal conductivity [W/(m·K)] |
| kl | effective thermal conductivity of liquid [W/(m·K)] |
| ks | the effective thermal conductivity of solid [W/(m·K)] |
| $K_p$ | permeability of a porous medium [$m^2$] |
| L | length scale [m] |
| $L_e$ | length of micro-channel evaporator [m] |
| $L_0$ | representative length [m] |
| M | molecular weight of the refrigerant R134a [kg/mol] |
| M(L) | length of a line or area of a surface or the volume of a cube or the mass of an object [−] |
| N | the number of pores [−] |
| $N_{ch}$ | the number of micro-channels of one solar panel [−] |
| Nt | the total number of pores [−] |
| Pc | capillary pressure [Pa] |
| $P_v$ | corresponding saturated vapour pressure [Pa] |
| Q | heat transfer rate [W] |
| $r_b$ | radius of the boiling bubble departure ($2.54 \times 10^{-7}$ m) [W] |
| $R_0$ | universal gas constant [J/(kmol.K)] |
| $R_v$ | vapour constant of R134a [J/kmol K] |
| S | saturation [-] |
| $T_w$ | wall temperature [°C] |

*Subscripts*

| | |
|---|---|
| av | average b bubble |
| BL | Boiling limit c condenser, capillary ch channel |
| CL | capillary limit e effective, evaporator |
| EL | entrainment limit |
| f | fluid, fractal |
| g | gas, vapour |
| hx | heat exchanger |
| hp | heat pipe |
| i | inner |
| lh | liquid header |
| ltl | liquid transportation line |
| l | liquid |
| max | maximum |
| mc | mixed chains of particles/skeletons |
| with | fluid |
| min | minimum |
| n | nontouching particles or skeletons o outer p port, pore s solid (wick skeleton) |
| SL | sonic limit t tortuous, total |
| v | vapour |
| vh | vapour header |
| VL | viscosity Limit |
| vtl | vapour transportation line |
| w | water, wick |

*Greek letters*

| | |
|---|---|
| $\rho$ | density [$kg/m^3$] |
| $\lambda$ | pore diameter or pore size [m] |
| $\varepsilon$ | porosity of porous media [−] |
| $\tau$ | tortuosity of porous media [−] |
| $\mu$ | viscosity of the fluid [Pa.s] |
| $\delta$ | thermal boundary layer thickness [m] |
| $\sigma$ | surface tension [N/m] |
| $\Upsilon$ | vapour-specific heat ratio [−] |
| $\gamma_{a1}$ | the ratio of geometrical length scale for a particle [−] |
| $\gamma_{c1}$ | the ratio of contact length scale for a particle [−] |

increase the radial heat flux, leading to an increased operational temperature and heat transfer capacity of the LHP or MCLHP. Zhang et al. [5] studied the heat transport capacity of a gravitational LHP, indicating that the nature of the wick (screen meshes, sintered powder and open groove) has an impact on its maximum heat transport capacity.

Among the three types of wick structures, screen meshes type delivers the highest heat transport capacity. In terms of the types of constraints, entrainment limit is applied to the groove wick, while capillary limit is applied to screen meshes and sintered powder wick structures. It is also found that the groove wick has a relatively larger pore hydraulic radius and higher effective thermal conductivity compared to the other two wicks, which leads to a higher boiling limit but a relatively lower entrainment limit. Wang and Zhao [6] indicated that the nature of the wick has an impact on their LHP system performance. Compared to sintered powder wick, meshes screen wick was able to achieve a higher heat transport capacity. For all wicks, capillary forces were the governing limit to the LHP heat transfer. Leon et al. and Godet et al. [7,8] found that sintered powder wick has a better control to the porosity and pore size and thus can achieve a higher heat dissipation rate (i.e., $5 \times 10^5$ W/$m^2$) than meshes, which is $10^5$ W/$m^2$. However, when the two types of wicks were applied to the same sized containers, the mesh could achieve a better power handling capacity owing to its larger vapour space and smaller wick thickness [9,10]. Mesh is therefore a favourite wick option compared to sintered powder [11]. By fabricating several wick structures with porosity in the range 65%–80% and measuring a few structural parameters including porosity and pore radius, the effective thermal conductivity and permeability of the wicks were obtained. Zan et al. [11] developed an experimental formula for a sintered nickel powder wick. Further analysis based on the formula indicated that the combination of the optimised wick structural parameters would make it possible to achieve the best operational performance of the LHP. Li et al. [12,13] applied numerous microgrooves into a micro-channel heat pipe in order to enhance the heat transfer capacity of a heat-pipe-based solar collector. Byon and Kim [14] indicated that the boiling limit of a bi-porous wick is 67% higher than that of the mono-porous wick owing to the higher vapour permeability of the bi-porous wick. In fact, the bi-porous wick had separate liquid/vapour flow paths that can increase the wick permeability, thus leading to an increased boiling limit. The optimised geometrical