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An experimental investigation and optimization of screen mesh heat pipes for low-mid temperature applications

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A B S T R A C T

The perspectives of utilization of a screen mesh heat pipe (HP) for low to medium operating temperature applications are studied in this study. A two-dimensional mathematical model for heat and mass transfer of HPs is presented to define its performances under steady state operations. The model couples heat conduction in the wall with both liquid flow in the wick and vapor flow in the core. Experimental analysis is developed to evaluate the influence of operating parameters (the orientation and the cooling temperature) as well as the evaporator section length on the performance of the HP. Furthermore, a modeling approach to optimize the HP performance from a thermal point of view is presented. Using the heat transfer capability and total thermal resistance as the objective function and the structure parameters as the decision variable, the optimization design for the HP is performed using the Non-Dominated Sorting in Genetic Algorithms-II (NSGA-II). The results show that the optimal wick thickness and wick permeability to be a strong function of the heat flux. It is concluded that to have lower thermal resistance at lower heat fluxes for a screen mesh wick HP may have a large effective thermal conductivity, but have a small permeability. While at high heat transfer rate a small effective thermal conductivity, but a large permeability is recommended. The designer must always make trade-offs between these competing factors to obtain an optimal wick design. The investigations are aimed to determine working limits and thermal performance of HPs for low to medium operating temperature applications.

1. Introduction

Energy use has become a crucial concern in the last decades and the improvement of energy efficiency is very important in various sustainable renewable energy technologies. The majority of thermal energy in various energy conversion system applications is at low to medium operating temperature (50–120 °C) [1]. With regard to heat transfer point of view, the magnitude of the temperature difference between the heat source and heat sink is an important factor on the thermal performance. The problems connected with the limitation on the maximum temperature, the temperature difference and the level of temperature uniformity must be solved for the thermal management of various heat exchanger systems. Heat pipes (HPs) as one of the excellent two-phase passive thermal transfer devices, have effective thermal conductivities orders of magnitude higher than those of similarly-dimensioned solid materials [2]. Thus, their integration into heat exchangers has been shown to have strong potential for energy saving. The field of application of HPs in low to medium operating temperature is wide enough [3,4], including, but not limited, heating, ventilation and air conditioning (HVAC) systems [5], automotive cooling systems [6], photovoltaic/thermal systems [7], power plant cooling tower systems [8], solar water heating [9,10] and thermal energy storage systems [11]. The advantage of using HPs in heat exchanger applications includes multiple redundancies (each HP operates independently so unit is not vulnerable to a single HP failure), low fouling, ease of cleaning and maintenance, isothermal operation (no hot or cold spots), low working pressure drop and highly scalable and configurable [12,13].

The design of HPs for a particular application needs of careful consideration. Several modeling approaches have been reported from a simple lumped model [14] to a transient multi-dimensional simulation [15]. However, a steady state thermal performance prediction is of significant value in the design of HPs [16,17]. Among others, Vafai and Wang [18] developed a modeling approach for the heat and mass transfer analyses in a flat HP. They applied Darcy's law to verify the liquid flow in the wick and assumed a parabolic vapor velocity profile to obtain the axial vapor pressure distribution. With the same approach, Vafai et al. [19]

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Nomenclature

c	specific heat (J/kg K)
D	diameter (m)
d_w	wire diameter (m)
F_k	nonempty front
h_{fg}	heat of vaporization (J/kg K)
I	individual
I_e	current (A)
K	permeability
k	thermal conductivity (W/m K)
L	length (m)
$\dot{m}$	mass flow rate (kg/s)
N	mesh number
n_o	number of objectives
n_p	size of population
P	pressure (Pa)
P_c	capillary pressure (Pa)
q	heat flux (W/m^2)
Q	heat transfer rate (W)
R_{tot}	total thermal resistance (K/W)
R	radius (m)
r	radial coordinate (m)
r_c	effective capillary radius (m)
r_n	critical nucleation site radius (m)
S	crimping factor
T	temperature (K)
t	thickness (m)
u	axial velocity (m/s)
V	voltage (V)
v	radial velocity (m/s)
x	axial coordinate (m)

Greek symbols

θ	relative temperature (°C)
ε	porosity
υ	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
μ	dynamic viscosity (Pa s)
σ	surface tension (N/m)
α_c	crowded comparison operator
η	thermal efficiency

Subscripts

a	adiabatic
ave	average
b	boiling
c	condenser
e	evaporator
eff	effective
i	inner
in	inlet
l	liquid
out	outlet
s	solid
tot	total
v	vapor
w	wick

presented a numerical simulation in a disk shaped HPs. Zhu and Vafai [20] extended the work of Vafai et al. [19] considering inertial effects on the liquid flow in the HP wick section. As the most commonly operating limitation to the performance of a HP for low to medium temperature application appears to be capillary limit [2,12,13], researchers investigated this problem. Among others, Lefevre and Lallemand [21] developed a steady state analytical model considering both liquid flow in the wick and vapor flow to analyze thermal behavior of a flat miniature HP as well as prediction of the maximum heat transfer capability. Rice and Faghri [22] developed a numerical model considering the liquid flow in the wick to investigate thermal performance of screen mesh HPs. They show that the capillary dryout limitations can be predicted for a given heating load in their simulations. Aghvami and Faghri [23] presented a steady state model including both liquid and vapor flows to investigate thermal and hydraulic behavior of flat HPs. They investigated capillary pressures for given heat inputs to determine the dryout limitations. Shabgard and Faghri [24] extended the above modeling approach to cylindrical HPs. They coupled two-dimensional heat conduction in the HP's wall with the liquid flow in the wick and the vapor hydrodynamics. Among above presented models Vafai and Wang [18], Vafai et al. [19] and Zhu and Vafai [20] did not considered axial heat conduction in the HP's wall while Shabgard and Faghri [24] found that neglecting the axial heat conduction through the wall resulting in overestimated pressure drops up to 10%.

In reviewing the recent experimental investigations on design variables and operating parameters of HPs, it is apparent that the geometric properties of the wick structure, such as the wick thickness and porosity should always be carefully considered [25–33]. Furthermore, operating parameters such as filling ratio, cooling temperature, input heat flux and orientating could be important factors affecting thermal performance of the HP [34–40] as well as its evaporation to condensation length ratio [41–43]. Brautsch and Kew [25] studied heat transfer process of stainless steel mesh HPs using water as working fluid. They showed that maximum heat flux increases with wick thickness but also thermal resistance increases. Li et al. [26] and Li and Peterson [27] investigated the influence of varying wick thicknesses, porosities and pore sizes on thermal resistance and critical heat flux of a horizontal copper surface sintered with multiple layers of copper mesh. They illustrated that the evaporation/boiling is strongly dependent on the wick thickness, however, it is weakly dependent on the porosity. Kempers et al. [28] investigated the effect of the wick thickness on the heat transfer performance of screen mesh wick HPs using water as the working fluid. They observed that there is a small increase in the thermal resistance when increasing the wick thickness; however, the maximum heat transfer also increases. Wang and Peterson [29] investigated a sintered copper screen mesh flat HP to examine its maximum heat transport capacity. They concluded that increasing the structural thickness increased the thermal resistance, but it enhanced heat transfer capacity. Wong and Kao [30] investigated screen mesh HPs using ether as working fluid at different mesh wicks, fluid charges and heat loads. They found a partial dryout at small filling ratio and boiling in the larger water/wick thickness. Weibel et al. [31] analyzed the dependence of thermal resistance on the thickness of sintered powder wicks surfaces. They showed a trade-off between the increased area for heat transfer and increased thermal resistance. Brahim et al. [32] investigated screen mesh HPs and showed that the mesh number is an important factor which affects the overall thermal performance of the system. Tsai and Lee [33] investigated the effects of structural parameters on the evaporation heat transfer in sintered wick HPs. They suggested thinner structural thickness to enhance evaporation heat transfer. Among operating parameters affection on thermal performance of HPs, the tilt angle have a considerable