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Research Paper

The influence of thermal contact resistance on the relative performance of heat pipe-fin array systems

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HIGHLIGHTS

- Impact of contact resistances on finned-heat pipes (HPs) is investigated.
- Two configurations: (i) HP-heat sink and (ii) HP-fins are considered.
- Influence of contact resistance on heat transfer within the HP is shown.
- Tradeoff between (i) low overall system resistance and (ii) range of operation is quantified.

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ABSTRACT

Externally-finned heat pipes (HPs) using individual fins (a HP-fin configuration) or a finned heat sink (HP-heat sink) are subject to thermal contact resistances at the HP-fin or HP-heat sink interfaces. A detailed HP model is used to quantify the influence of the contact resistances on the heat transfer and fluid flow within the HP, as well as on the overall heat transfer rate. For similar area-averaged contact resistance values, the HP-heat sink typically provides a lower overall thermal resistance than the HP-fin configuration. Under off-design operating conditions, however, the HP-heat sink option can underperform the HP-fin geometry. A thermal resistance model is also developed and its predictions compare qualitatively to those of the HP model. It is shown that the overall resistance of the HP-fin configuration is proportional to the number of fins in the array that are subject to a contact resistance. Using the detailed model it is also demonstrated that the order in which the fins (fins without versus fins with contact resistances) are placed within the array has little effect on the overall thermal resistance of the HP system.

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1. Introduction

Heat pipes (HPs) are devices that transfer heat more effectively than high thermal conductivity media of the same physical dimensions [1,2]. Heat transfer within HPs is characterized by various thermal resistances, including the small thermal-resistance processes of evaporation (within the HP evaporator section) and condensation (in the HP condenser section) at the vapor–liquid interfaces of an internal working fluid. Applications of HPs have been reviewed [3–15], and in many practical situations the limiting system-level thermal resistances are associated with the flow of single-phase fluids *external* to the HP's condenser or evaporator sections. The larger external thermal resistance will typically be on the condenser end of the HP if, for example, air is used as the coolant and a flowing liquid heats the HP evaporator section. External arrays of fins, foils, and porous metallic foams have been added to HPs to reduce the overall system thermal resistances [16–29].

Two- and 3D models of HPs that account for the complexity of transient, conjugate heat transfer phenomena, including phase change of the HP working fluid, have been developed [27,28,30–35]. Recently, Stark et al. [36] presented a detailed, experimentally-verified model capable of predicting the performance of a HP system involving fins that are attached to the condenser (cold) section of the HP. The 3D, transient mixed convection of air through the fin array was predicted by both direct simulation and use of a shear stress turbulence model, and the predictions of external convection were coupled to those of a 2D model that accounted for the pertinent heat transfer phenomena within the HP. It was shown that 3D effects within the HP did not significantly influence the performance of a HP-fin array system similar to that of interest in this study, justifying use of the 2D HP model.

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Nomenclature

c_p	specific heat (J/kg K)
g	gravitational acceleration (m/s^2)
h	convection coefficient (W/m^2 K)
h_{fg}	latent heat (J/kg)
k	thermal conductivity (W/m K)
L	length (m)
m	fin constant (1/m)
m''	local mass flux (kg/s m^2)
N	number of fins
p_{sat}	vapor pressure (Pa)
Q	heat rate (W)
R	thermal resistance (K/W)
R''	thermal resistance per unit area (m^2 K/W)
r, z	coordinate directions (m)
S	fin pitch (m)
T	temperature (K)
t	thickness (m)
U	heat pipe centerline vapor velocity (m/s)
V	air velocity (m/s)
Greek symbols	
θ	reduced temperature (°C)
μ	dynamic viscosity (Pa s)
ρ	density (kg/m^3)
Superscripts	
--	average
$\sim$	no contact resistance
Subscripts	
a	adiabatic, axial
b	heat sink base
c	condenser, contact
e	evaporator
eff	effective
f	fin
fc	corrected fin radius
hp	heat pipe
r	radial, ratio
t	thermal
v	vapor
$v–wi$	vapor–wick interface
w	wall
wi	wick
$w–wi$	wall–wick interface
∞	ambient

In practice, thermal contact resistances will exist at the interface between the exterior surface of a HP and the roots of individually-mounted, external fins (or the base of a finned heat sink). The magnitudes of these resistances depend on the manner in which the HP and fins (or the finned heat sink) are bonded. A wide range of thermal contact resistance values have been reported for finned-tube heat exchangers [37–41], a geometrical configuration similar to the finned-HP of interest here.

The specific objective of this study is to quantify the effect of thermal contact resistances on the performance of a vertical HP system using two approaches: (i) a detailed 2D numerical HP model that accounts for the effects of fin conduction and external convection (the fins are populated along the HP condenser section) and (ii) a thermal resistance network analysis. As will be shown and as expected, the presence of contact resistances decreases the performance of either the HP-fin or HP-heat sink configurations. However, it will also be demonstrated that the preferred system configuration (HP-fin versus HP-heat sink) is influenced by the presence of thermal contact resistances under certain operating conditions. This study represents, to the authors' knowledge, the first in depth investigation of how contact resistances modify heat transfer phenomena within the HP of such systems, and how they impact the range of conditions over which a HP-fin array system may successfully operate.

2. Numerical models

Two numerical models, a detailed HP model and a thermal resistance model, will be used to investigate the influence of thermal contact resistances on the performance of an externally-finned HP. Again, the fins are either directly attached to the HP (HP-fin) or incorporated in a heat sink whose base is in contact with the HP (HP-heat sink).

2.1. HP model

Fig. 1 shows a vertical HP-heat sink assembly that includes N annular fins incorporated into a heat sink of base thickness t_b. A second configuration (HP-fin, not shown) involves annular fins that are attached directly to the exterior surface of the HP at $r = r_{hp}$ (i.e., $t_b = 0$). In either configuration, the length of the HP, $L_{hp} = L_e + L_a + L_c$, includes an evaporator section (of length L_e), an adiabatic section (of length L_a) and a condenser section (of length L_c). Radially, the HP includes a vapor region ($0 \leqslant z \leqslant L_{hp}$; $0 \leqslant r \leqslant r_v$), a porous wick

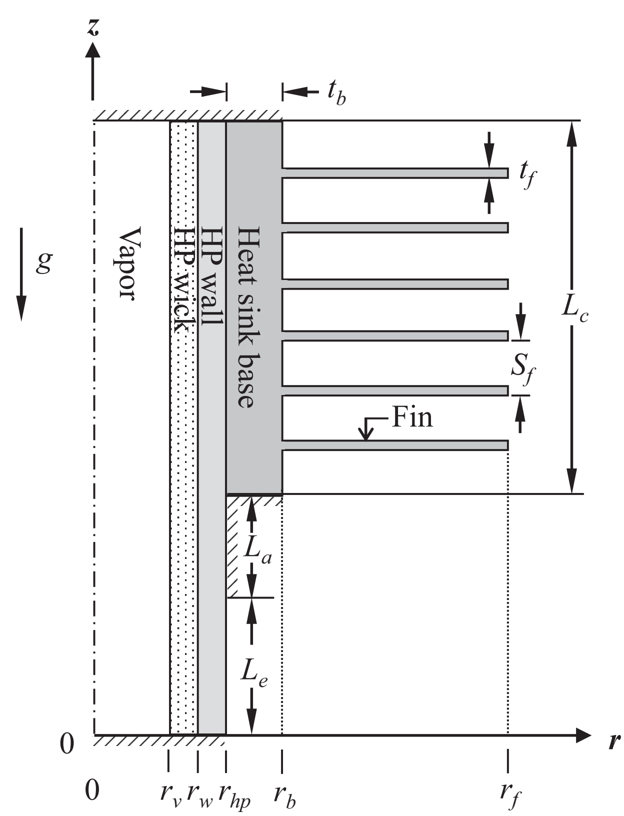

Fig. 1. Computational domain and fin array (HP-heat sink configuration).