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Thermal numerical model of a high temperature heat pipe heat exchanger under radiation

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HIGHLIGHTS

- Thermal modeling of the HPHEX for the high-temperature.
- Radiation heat transfer analysis in the high-temperature HPHEX.
- Prediction of the temperature distribution by adopting nodal approach.
- Design and analysis of the HPHEX for the high-temperature.

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ABSTRACT

The heat transfer of an air-to-air heat pipe heat exchanger (HPHEX) with counter flow and a high-temperature range was modeled. The HPHEX was constructed from sodium-stainless steel (STS) heat pipes (HPs) using a staggered configuration. The thermal numerical model was developed by the nodal approach, and the junction temperature and thermal resistance of the HP and heat transfer fluid of each row were defined. Surface-to-surface radiant heat transfer was applied to each row of the liquid metal HPHEX. The cold-side inlet air temperature was determined by iteration to converge to the minimum operating temperature of the sodium HP. The cold-side inlet velocity and position of the common wall were considered as the main variables in evaluating the performance of the liquid metal HPHEX, and their effects on the temperature distribution, effectiveness, heat transfer rate of each row were investigated. The proposed row-by-row heat transfer model is useful for understanding the temperature distribution of each row and can be used to predict the cold-side inlet temperature of a liquid metal HPHEX with counter flow. The recovery heat and effectiveness of the heat exchanger were calculated for various configurations and operating conditions. The simulation results agreed with experimental data to within 5% error for normal operation of the heat pipes, and within 11% error when the minimum temperature was lower than could allow normal operation of the sodium heat pipes.

1. Introduction

Heat pipes (HPs) are two-phase heat transfer devices with highly effective heat transfer capabilities. Heat exchangers (HEXs) with HPs or thermosyphons (TSs) have superior heat transfer capabilities compared to conventional HEXs. Furthermore, they are useful for generating a high heat flux in a small space and are widely used in industry because of their structural stability and economic advantages [1–3]. The operating principle of HPs in which vaporization and condensation are repeated in the evaporator and condenser is described in detail in Refs. [4,5]. The working fluid inside the evaporator vaporizes as it absorbs thermal energy. The vapor is then transported to a condenser by the vapor pressure and then liquefied by a cooling medium in the condenser. The liquid is returned to the evaporator by the capillary pressure produced by a capillary structure. A HP can also be used over various temperature ranges depending on the material of the container and the operating temperature of the working fluid.

Theoretical and experimental studies have been conducted to investigate medium- and low-temperature HPHEXs [1–3,5–7]. These previous works addressed the working characteristics, thermal performance, and practical application of HPHEXs, as well as theories for their practical design. The equation of the optimum area ratio between the hot-and cold-side in terms of the total thermal resistance was presented in Ref. [5] and the optimum

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Nomenclature

A	area (m^2)
c	specific heat (kJ/kg °C)
D	fin density (fins/m)
d	diameter (m)
F	view factor
f	friction factor
G	mass velocity (kg/s m^2), $G[= \dot{m}/\sigma A_{fr}]$
h	heat transfer coefficient (W/m^2 °C)
H	height (m)
HP	heat pipe
$HPHEX$	heat pipe heat exchanger
J	radiosity (W/m^2)
j	index for row number or Colburn factor
k	thermal conductivity (W/m °C)
L	HPHEX length (m)
$\dot{m}$	mass flow rate (kg/s)
N	number of heat pipes in a row
NTU	number of transfer units
p	pipe or fin pitch
P	pressure (Pa)
pr	Prandtl number
Q	heat transfer rate (W)
R	thermal resistance (°C/W)
Re	Reynolds number
r	radial position (m) or radius (m)
St	Stanton number
S	fin spacing (m)
T	temperature (°C)
U	overall heat transfer coefficient (W/m^2 °C)
u	velocity (m/s)
v	specific volume (m^3/kg)
X	tube bank pitch (m)
X_d	tube bank diagonal pitch, $\left[(X_T/2)^2 + X_L^2\right]^{1/2}$

Greek symbols

δ	fin thickness (m)
σ	ratio of free flow area to frontal area, A_{min}/A_{fr} or Stefan–Boltzmann constant (W/m^2 K^4)
ε	effectiveness or emissivity
η	fin efficiency or overall extended surface efficiency
μ	fluid dynamic viscosity (m^2/s)
φ	porosity of capillary wick structure
ρ	density (kg/m^3)

Subscripts

a	ambient
c	cold-side
cap	screen capillary structure
c	cold-side
eff	effective
equ	equivalent
f	fluid
fr	frontal
fin	fin
$fin{\to}in$	from fin to inlet
$fin{\to}out$	from fin to outlet
$fin{\to}p$	from fin to pipe
$f\text{-}fin$	between fluid and fins
h	hydraulic or hot-side
in	inlet
j	row index
$j \to j+1$	from j^{th} row to $(j+1)^{th}$ row
$j \to j-1$	from j^{th} row to $(j-1)^{th}$ row
$j \to j+2$	from j^{th} row to $(j+1)^{th}$ row
$j \to j-2$	from j^{th} row to $(j-2)^{th}$ row
$j+1 \to j$	from $(j+1)^{th}$ row to j^{th} row
$j-1 \to j$	from $(j-1)^{th}$ row to j^{th} row
$j+2 \to j$	from $(j+2)^{th}$ row to j^{th} row
$j-2 \to j$	from $(j-2)^{th}$ row to j^{th} row
L	length
$mean$	mean value
min	minimum value
o	outer or overall
out	outlet
p	pipe or pressure
$p \to fin$	from pipe to fin
$p \to in$	from pipe to inlet
$p \to out$	from pipe to outlet
rad	radiation
re	recovery
T	total
w	wall or width
wi	wick inner
wf	working fluid inside HP

effectiveness from the viewpoint of the operating limit of the HPs was considered in Ref. [6]. Soylemez [7] also presented an economic design methodology that considered the optimum effectiveness and critical effectiveness.

Liquid metals such as sodium, lithium, potassium, and cesium have been used for high-temperature applications of over 500 °C, which require the container materials to be chemically inert [8] and resistant to high-temperature corrosion [9–11] by the working fluid. Whereas a number of analytical and experimental studies have been conducted on medium- and low-temperature HPHEXs, relatively few studies have been devoted to high-temperature HPHEXs [12,13].

Yoo et al. [12] presented experimental results on the performance of an HPHEX that consisted of 90 sodium-stainless steel (STS) HPs in ten rows. A maximum recovery heat rate of 115 kW was achieved by applying various hot- and cold-side inlet conditions. The experimental results suggested that the cold-side inlet air temperature should be above 450 °C for normal operation of the HPs in all the rows and the achievement of satisfactory HPHEX performance. Zhuang et al. [13] experimentally investigated the performance of an HPHEX that used sodium as the working fluid, with hot- and cold-side inlet temperatures of 1000 °C and 20 °C, respectively, and an inlet pressure of 0.19 MPa on both sides. Previous studies have mainly developed theories on HPHEX performance based on the NTU-ε relation [1–3,5,6]. Although the NTU-ε method is useful for predicting the temperature at the hot- and cold-side outlets, it is of limited usefulness in determining the wall temperature of the HPs and the temperature distribution of the heat transfer fluid in each row. Furthermore, there is currently no analytical model applicable to high-temperature liquid metal HPHEXs. Such a model should reflect the effect of radiation, which could be ignored in medium- and low-temperature ranges.

In this study, a thermal analysis model was developed by the nodal approach and used to predict the thermal performance of a high-temperature HPHEX. The numerical thermal model was useful for determining not only the temperature distribution of the fluid in each row but also the temperatures at various points of the HP. This was because the analytical outlet results for one row were considered the inlet conditions for the next row. In particular, surface-to-surface radiant heat transfer was applied to each row for