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An efficient optimization and comparative analysis of ammonia and methanol heat pipe for satellite application

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ABSTRACT

In this work, a satellite heat pipe operated with the ammonia and methanol are investigated for the multi-objective optimization. Optimization results are used for the comparative analysis of both the heat pipe. Optimization problem of the heat pipe is formed considering minimization of the thermal resistance and total mass of heat pipe and solved using the heat transfer search algorithm. An application example of satellite heat pipe is presented, and results are obtained in the form of Pareto-optimal points. Seven geometric parameters which include the length of evaporator and condenser section, tube wall thickness, vapor core diameter, mesh number of wick, thickness of wick, and diameter of wick wire are investigated in the optimization study. Further, the effect of condenser temperature, heat load, and length of the adiabatic section on ammonia and methanol heat pipe is explored and discussed. Furthermore, the effect of the design variables and its sensitivity to performance parameters of the heat pipe are also presented. Comparative results revel that, for any given value of the total mass of heat pipe, 82.17–57.16% lower thermal resistance is observed with the ammonia heat pipe as compared to methanol heat pipe. Finally, uncertainty propagation analysis of the obtained Pareto solutions are carried out with the different uncertainty levels and observed that the results have relatively good robustness performance for uncertainty less than 5%.

1. Introduction

Heat pipes are efficient heat exchange device which can transmit high heat with a relatively small temperature gradient. The working of heat pipes combines the principles of phase change and thermal conductivity [1]. The other noticeable advantages of heat pipes are; it can transmit heat over a considerable distance without any external power requirement, simple design and manufacturing, low maintenance cost and high reliability, light weight, and it can operate over wide range of temperature. Therefore, the heat pipes are used for cooling purpose in many applications like satellite, spacecraft, computer system, solar thermal system, etc. [2].

A heat pipe is a hollow sealed container with wick structure and working fluid. From the construction viewpoint, heat pipe comprises three sections; evaporator section, adiabatic section, and condenser section (as shown in Fig. 1). Working fluid of the heat pipe vaporized at evaporator section by extracting heat from the heat source. After that, the vapor moves towards condenser section via adiabatic section. This movement of vapor from evaporator section to condenser section takes place through the core of heat pipe. At condenser section, working fluid converts into the liquid state by rejecting heat to the surrounding. Then, the working fluid again moves towards evaporator section through the periphery of heat pipe due to capillary action provided by wick structure [3].

Earlier, researchers had carried out various analytical and experimental works related to the effect of working fluid, wick structure, operating parameters, etc. on performance of a heat pipe. Recently, few works were also reported related to the optimization of a heat pipe. Kim et al. [4] developed a mathematical model for the miniature heat pipe. Based on the developed model, authors performed numerical optimization to enhance its thermal performance. Vlassov et al. [5] performed the geometric optimization of a heat pipe used for space application for minimization of the mass of heat pipe. Sousa et al. [6] used generalized external optimization to optimize the mass of a heat pipe used for space application. The authors investigate different working fluid like methanol, ammonia, and ethanol in their optimization study. Zhang et al. [7] carry out the optimization of a heat pipe for minimization of total thermal resistance. The authors considered structural parameters of the heat pipe as decision variables and used the genetic algorithm as an optimization tool. Sousa et al. [8] perform the optimization of a heat pipe for different heat loads, and heat sink temperatures. The authors investigated different working fluid and used generalized external optimization as an optimization tool in their study. Jokar et al. [9] presented simulation and optimization of pulsating heat pipe to identify its

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Nomenclature

d	wick wire diameter (m)
d_i	heat pipe internal diameter (m)
d_o	heat pipe outer diameter (m)
d_v	vapor core diameter (m)
F_l	liquid frictional coefficient (N/W m)
F_v	vapor frictional coefficient (N/W m)
K	permeability (m^2)
k_{eq}	effective thermal conductivity of wick (W/K m)
k_w	thermal conductivity of the wick material (W/K m)
k_l	thermal conductivity of liquid (W/K m)
k_t	thermal conductivity of the heat pipe wall (W/K m)
L_a	adiabatic section length (m)
L_c	condenser section length (m)
L_e	evaporator section length (m)
L_{eff}	effective length of heat pipe (m)
L_{total}	total length of heat pipe (m)
M_v	Mach number at vapor core (–)
m_{cont}	mass of the container (Kg)
m_{total}	total mass of the heat pipe (kg)
m_{vapor}	mass of the vapor inside the heat pipe (Kg)
m_{wd}	mass of the dry wick (Kg)
m_{wl}	mass of the liquid in the wick (Kg)
N	mesh number of wick (1/m)
P_a	ambient pressure (N/m^2)
P_c	capillary pressure (N/m^2)
Q	heat load (W)
Q_b	boiling limit (W)
Q_c	capillary limit (W)
Q_e	entrainment limit (W)
Q_v	viscous limit (W)
R	thermal resistance of the heat pipe (K/W)
R_{ct}	wall thermal resistance corresponding to condenser (K/W)
R_{cw}	thermal resistance of heat pipe wick corresponding to condenser (K/W)
R_{et}	wall thermal resistance corresponding to evaporator (K/W)
R_{ew}	thermal resistance of heat pipe wick corresponding to evaporator (K/W)
R_v	gas constant for vapor (J/kg mol K)
Re_v	Reynolds number at vapor core (–)
r_c	capillary radius (m)
r_n	nucleation radius (m)
r_h	hydraulic radius (m)
r_v	radius of vapor core (m)
T_{si}	outside surface temperature of the condenser section (K)
T_{so}	outside surface temperature of the evaporator section (K)
T_{si}	saturated vapor temperature (K)
t_t	heat pipe tube thickness (m)
t_w	heat pipe wick material thickness (m)
u_{ts}	ultimate tensile strength of the heat pipe wall material (N/m^2)

Greek letters

ρ	density (kg/m^3)
μ	viscosity ($N\ s/m^2$)
ε	porosity (–)
λ	latent heat of vaporization (J/kg)
γv	ratio of specific heat(–)
σ	surface tension (N/m)

Subscripts

l	liquid
v	vapor
t	heat pipe material
w	wick material

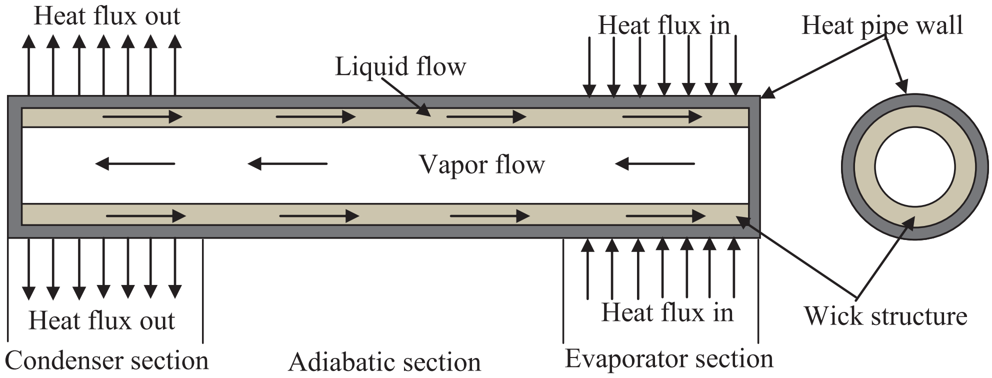

Fig. 1. Heat pipe geometry.

optimized operating point by simultaneous adaption of artificial neural network and genetic algorithm.

Song et al. [10] presented thermodynamic analysis and optimization of a heat pipe to provide theoretical guidance for the structural design of heat pipe used in space power system. Esarte et al. [11] investigate the influence of heat pipe length, wick thickness and condensing temperature on the optimized performance of a loop heat pipe. Kiseev et al. [12] carried out the optimization of geometric parameters of the capillary structure. The authors perform the optimization through extensive experimentation on different capillary structure material and working fluid. Jeong et al. [13] perform the optimization of a satellite heat pipe with thermal conductance and total mass of the heat pipe as an objective function. The authors used the genetic algorithm as a optimization tool in their investigation. Kiseev et al. [14] investigate the influence of the capillary structure characteristics on the performance of a heat pipe. The authors developed the theoretical formulation of heat pipe and compared analytical results with experimental. Rao and More [15] adapted teaching learning-based optimization algorithm for the optimization of thermal resistance and total mass of the heat pipe. Liang and Hung [16] carried out the experimental investigation to obtain an optimum ratio of the evaporator section length to the condenser section length of the U-shape heat pipe for minimum thermal resistance.

Roper [17] performs the multi-objective optimization of a sandwich