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The influence of non-condensable gas on an integral planar heat pipe radiators for space applications

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ABSTRACT

A unique heat rejection system for space applications is proposed herein by integrating a variable conductance planar heat pipe with a radiator panel. The working temperature of the planar heat pipe charged with a small amount of non-condensable gas (NCG) can be maintained at a desired level when it is subjected to a sudden heat load or an environmental temperature variation. This advantage makes the variable conductance planar heat pipe (VCPHP) technology appealing to space heat rejection system designers. In the present work, a comprehensive study of the effect of a non-condensable gas on the planar heat pipe performance is conducted. A simple 2D mathematical model was derived from the ideal gas law and flat front assumption. Through this model, the effects of factors such as the NCG inventory, the reservoir size and the sink temperature on the behavior of non-condensable gas as well as on the performance of the planar heat pipe radiator can be analyzed mathematically. To validate this model, a heat rejection experiment was performed. In the experiment, different amounts of nitrogen were carefully measured and injected into the prototype brass planar heat pipe. Temperature profiles were measured and compared with the results calculated from the Steady-State Heat Pipe Operation Model combined with the NCG expansion model. The results indicate that the NCG expansion model is able to predict the location of the vapor-NCG interface as well as the working temperature accurately. In addition, the self-adjustment mechanism of the integral VCPHP is identified to support the applicability of the flat shape Vapor-NCG interface assumption when a non-uniform heat input is applied.

1. Introduction

For two-phase heat transfer devices such as heat pipes, a non-condensable gas (NCG) has usually been regarded as a defect, because it greatly reduces the thermal performance. Nevertheless, heat pipes charged with a small amount of non-condensable gas, referred to as "variable conductance heat pipes" (VCHPs), are capable of adapting themselves to accommodate various heating and cooling conditions. This advantage makes the VCHP technology a promising solution for next-generation space heat rejection systems. According to information from the Altair lunar lander [1], due to the relative position and direction towards the sun, the environmental temperature on the moon surface changes nearly 200 K within a few hours. Under such a large variation of the environmental temperature, the coolant inside the traditional radiator panel might eventually freeze and endanger the entire space mission. To avoid this problem, it is required to develop a reliable heat rejection system which is able to maintain a nearly constant radiator surface temperature under a high system turndown ratio, which is defined as:

$$T_R \equiv \frac{Q_{max}}{Q_{min}} \tag{1}$$

To meet this requirement, the variable conductance technique was introduced by Anderson et al. [2]. They combined a series of titanium/water heat pipes, using a highly conductive graphite foam to build a variable conductance heat pipe radiator. By introducing a carefully measured quantity of non-condensable gas into the heat pipes, the VCHPs can operate normally, with a turn-down ratio of 5:1 or larger. VCHPs also have the advantage of a short recovery time after being frozen, since the gas-loading keeps the evaporator temperature above the freezing point while a section of the condenser region is frozen. In their design, between the circular heat pipes and the radiator panel, heat transfer still relies on pure conduction, which makes the temperature distribution non-uniform, and reduces the efficiency of the heat rejection rate. In lieu of a series of isolated heat pipes, Lee et al. [3] proposed an integral variable conductance planar heat pipe (VCPHP) combining the

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Nomenclature

A	area (m^2)
D	height (m)
E_R	expansion ratio (defined in Eq. (8.1))
$\vec{f}_b$	body force per unit volume (N/m^3)
$\vec{f}_s$	surface tension force per unit volume (N/m^3)
h_{fg}	latent heat of vaporization (J/kg)
j	fluid properties
k	thermal conductivity (W/m·K)
k_x	thermal conductivity in x-direction (W/m·K)
L	length (m)
m	mass (kg)
$\overline{m}_g$	normalized mass of NCG (defined in Eq. (8.3))
P	pressure (N/m^2)
Q	heat load (W)
q''	heat flux through L-V interface (W/m^2)
R	specific gas constant (kJ/kg·K)
T	temperature (K)
T_R	turn-down ratio (defined in Eq. (1))
U_∞	wind speed (m/s)
U	velocity (m/s)
V	volume (m^3)
$\overline{V}_r$	non-dimensional reservoir volume defined in Eq. (8.1)
(x, y)	coordinates defined in Fig. 3
W	width (m)

Greek letters

α	volume fraction
ε	emissivity (assumed to be 1.0)
ρ	density (kg/m^3)
σ_r	Stefan-Boltzmann constant ($W/m^2 \cdot K^4$)
τ	temperature factor (defined in Eq. (6))

Subscripts and superscripts

a	active region
amb	ambient
c	condenser
e	evaporator
g	non-condensable gas
i	inactive region
in	input
max	maximum
min	minimum
out	output
r	reservoir
s	solid wall
surf	surface
0	reference value, initial value

radiator panel and the planar shape heat pipe as a whole unit, which was expected to eliminate the thermal resistance between junctions of separated pieces and was to have a more uniform temperature distribution across the entire radiator (see Fig. 1). VCPHP is a planar heat pipe that acquires the excess thermal energy from the thermal control system (TCS) and rejects it through its condenser at its outer radiating surface. It contains an inert gas that varies the active radiator zone depending on the heating and cooling conditions [3]. From a feasibility study based on a mathematical model, the maximum turn-down ratio of 10.6 can be achieved by their design [4].

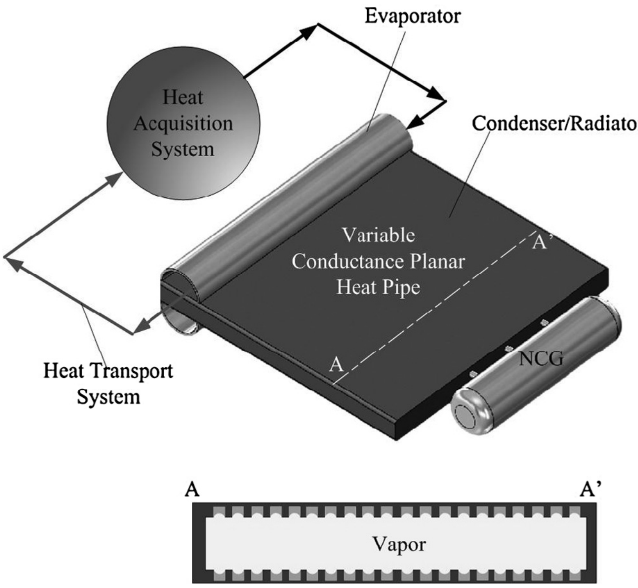

Fig. 1. Conceptual design of integral variable conductance planar heat pipe by Lee et al. [4].

Analyses of gas-loaded heat pipes have been carried out for about 40 years. The classic flat-front analytical model proposed by Marcus and Fleischman [5] can successfully describe the behavior of a non-condensable gas in a circular heat pipe. In their study, the axial heat conduction was of much greater importance than the other parameters to determine the location of the vapor-gas front. Rohani and Tien [6] developed a two-dimensional, steady-state gas loaded heat pipe model. They found that the vapor condensation is hindered due to the accumulation of non-condensable gas at the liquid-vapor interface. The axial non-condensable gas diffusion term causing the accumulation of NCG at the interface was then considered in Hijikata's model [7]. Harley and Faghri [8] presented a two-dimensional transient gas-loaded heat pipe model and successfully simulated the high-temperature heat pipe designed and studied by Ponnappan [9]. Leriche et al. [10] applied variable conductance heat pipes in the combustion engine thermal management system. In their research, they developed a nodal model to study the "thermal switch" behavior of VCHP during the vehicle cold start process. The effect of non-condensable gas on the operation of loop heat pipes for the space application was studied experimentally by He et al. [11,12]. The results revealed that adding more NCG into the system will increase the operating temperature of the evaporator as well as the heat load range. For planar heat pipe with NCG, Ababneh et al. [13,14] applied the thermal resistance model to predict the thermal performance of the thermal ground plane (TGP) with small amount of NCG. Their prediction suggested that the TGP's thermal conductivity is inversely proportional to the mole fraction of NCGs, and the evaporator temperature sharply increases with NCG. Chen and Chou [15] experimentally studied the cooling performance of a (150 mm × 50 mm × 2.5 mm) flat plate heat pipe (FPHP) with different filling ratios. In the experiment, they tested an imperfect case in which the FPHP is not fully evacuated. The results indicated that the thermal resistance of FPHP with a small amount of air increased by almost ten times compared with when the heat pipe is completely evacuated first. Recently, Huang et al. [16] reviewed