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Effects of cooling temperature on heat pipe evaporator performance using an ideal fluid mixture in microgravity

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ABSTRACT

The effect of cooling temperature on heat pipe performance has generally received little consideration. In this paper, we studied the performance of a Constrained Vapor Bubble (CVB) heat pipe using a liquid mixture of 94 vol%-pentane and 6 vol%-isohexane at different cooling temperatures in the microgravity environment of the International Space Station (ISS). Using a one-dimensional (1-D) heat transfer model developed in our laboratory, the heat transfer coefficient of the evaporator section was calculated and shown to decrease with increasing cooler temperature. Interestingly, the decreasing trend was not the same across the cooler settings studied in the paper. This trend corresponded with the change in the temperature profile along the cuvette. When the cooling temperature went from 0 to 20 °C, the temperature of the cuvette decreased monotonically from the heater end to the cooler end and the heat transfer coefficient decreased slowly from 456 to 401 ($W\,m^{-2}\,K^{-1}$) (at a rate of 2.75 $W\,m^{-2}\,K^{-2}$). However, when the cooling temperature increased from 25 to 35 °C, a minimum point formed in the temperature profile, and the heat transfer coefficient dramatically decreased from 355 to 236 ($W\,m^{-2}\,K^{-1}$) (at a rate of 11.9 $W\,m^{-2}\,K^{-2}$). A similar change in decreasing trend was observed in the pressure gradient and liquid velocity profile. The reduced heat pipe performance at high cooling temperatures was consistent with the reduced evaporation which was indicated by the decreasing internal heat transfer and the increasing liquid film thickness along the cuvette as seen in the surveillance images. The result obtained is important for future heat pipe design because we now have a better understanding of the working temperature ranges of these devices.

1. Introduction

Together with the rapid growth of space research is the huge demand for heat transfer systems that are light, can reliably operate without any pumping requirement, and can transport heat over long distances under widely varying external conditions. Heat pipes are one of a small number of systems that satisfy all of those requirements. Heat pipes operate without any moving parts. The fluid flow in a heat pipe is not controlled by a mechanical mechanism, but instead by interfacial free energy gradients. This makes heat pipes light and reliable heat transfer systems that are extensively used not only in spacecraft but also in numerous applications such as computer systems, solar thermal water heating applications, permafrost cooling, or nuclear power conversion [1–4].

Due to the importance of heat pipes, a large amount of work has been done in this topic [1–10]. Different aspects of heat pipes have been studied. An extensive amount of work has been focused on the effect the working fluid has on heat pipe performance ranging from water, organic solvents to nano-fluids [1,11–14]. The structure and material of the wick inside the heat pipe have also been studied carefully [15–21]. Beside heat pipe construction and working fluid, the working conditions of the heat pipe such as liquid level, chamber pressure or heat load are also equally important. Those parameters, especially the heat load, have been well studied [8,22–27]. Due to the effect of the heat load on the heat pipe, this parameter has been thoroughly studied by different research groups, including our group [8,23–27]. The results showed signifi-

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Nomenclature

Roman symbols

A_c	cross sectional area of the wall of the cuvette (m^2)
A_l	cross sectional area of the liquid (m^2)
h_{fg}	latent heat of evaporation (J/mol)
h_{in}	effective internal heat transfer coefficient (W/m^2 K)
k	thermal conductivity of the cuvette material (W/m K)
K	interface curvature (1/m)
P	measured pressure at each cooling setting (Pa)
P_l	pressure of the liquid along the cuvette (Pa)
P_v	vapor pressure (Pa)
P_i and P_o	inside and outside perimeters of the cuvette (m)
Q_{cond}	conduction heat transfer rate (W)
$Q_{out,rad}$	thermal radiation heat transfer rate (W)
Q_{in}	internal heat transfer rate (W)
q'_{cond}	conduction heat flow per unit length (W/m)
$q'_{out,rad}$	outside radiation heat flow per unit length (W/m)
q'_{in}	internal heat transfer flow per unit length (W/m)
q'_e	evaporation/condensation heat flow per unit length (W/m)
r	projected liquid film thickness along the heat pipe (m)
T	temperature (K)
T_v	temperature of the vapor (K)
T_∞	temperature of the external environment (K)
U_l	liquid velocity (m/s)
x	distance (m)
x_p	pentane molar concentration (mol/mol)

Greek symbols

ε	emissivity of the cuvette material (dimensionless)
ρ_l	liquid density (mol/m^3)
σ	Stefan–Boltzmann constant (W/m^2 K^4)
σ_l	surface tension of the liquid mixture (N/m)
σ_1 and σ_2	surface tensions of pentane and isohexane at different temperatures (N/m)

cant change in interfacial forces and heat transfer mechanism with increasing heat input. The performance of heat pipes with multiple evaporators and various heat loads has also been studied [28]. However, not much work on the effect of the cooling end temperature on the heat pipe performance has been done [21], especially at low cooler temperatures. Recently, a study on the effect of cooling parameters in systems similar to the heat pipe has revealed the importance of the cooling condition. A study on cryogenic thermosyphons showed that the cooling condition of the condenser has significant impact on the heat transfer performance of the heat pipe [29]. The authors showed that they can raise the heat transfer limit by immersing the condenser completely in liquid nitrogen instead of using a contact thermal resistance between the condenser and the liquid nitrogen reservoir. They also found that the cooling condition affected the heat transfer mechanism. A study on a loop heat pipe both experimentally and computationally also showed the importance of the cooling sink temperature [30–32]. Those results have motivated us to look into the effect of the cooling temperature on our heat pipe system.

Marangoni flow and heat transfer limits are well-known in the heat pipe field [25,33–35]. Recently, several research groups have added a second component to the working fluid to control the Marangoni flow and therefore improve the efficiency of the heat pipe [36–38]. Di Francescantonio et al. were able to increase the dryout limit of their heat pipe from 15 W to 39 W by adding 0.1 wt% heptanol to the working fluid of water [37]. In another study, Armijo and Carey increased the critical heat flux at the heater surface by 52% and 45% by using solutions of 0.2 M and 0.05 M 2-propanol in water respectively instead of pure water. They also found that the evaporator section performed better in the lower concentration case. The evaporator heat transfer coefficient in the 0.05 M case is 11% higher than in the 0.2 M case. In both papers, the water/alcohol system was chosen due to its special property of increasing surface tension with temperature for a certain composition range, and therefore, created the Marangoni flow that drove the liquid toward the heater end. Motivated by those results, we have used an ideal mixture of 94 vol%-pentane and 6 vol%-isohexane as the working fluid and found that the heat transfer coefficient of the heat pipe has improved almost twice that of the case where pure pentane was used as the working fluid; and the Marangoni stress has decreased about five times [39]. These data have led us to enlarge our study on the heat pipe using the pentane/isohexane mixture.

Working without any mechanical mechanism, the driving force for fluid flow in a heat pipe is the interfacial free energy gradients. This is probably the most attractive feature of the heat pipe, but also makes it challenging to study. Due to the gravitational field, the system of interfacial forces inside the heat pipe running on Earth is extremely complicated because of the asymmetric nature of the liquid-vapor interface and the corresponding pressure field. Therefore, it is desirable to run the heat pipe experiment in an environment where the effect of gravity is eliminated. In collaboration with the National Aeronautics and Space Administration (NASA), we had the Constrained Vapor Bubble (CVB) heat pipe experiments run on the International Space Station (ISS). The transparent walls of the CVB heat pipe allowed us to look into the liquid-vapor interface inside. We have observed data and phenomena that are quite different from that obtained in Earth gravity [25–27]. This led us to expand our study of the CVB heat pipe in microgravity to different working conditions.

Combining all three factors mentioned above, for the first time, we studied the effect of the cooling temperature on the performance of the CVB heat pipe using an ideal fluid mixture of 94 vol %-pentane and 6 vol%-isohexane in microgravity.

2. Experimental apparatus

The details of the CVB experimental apparatus have been described extensively in our previous publications [23–27]. In this paper, we will only give a short description of the main components. The main part of the CVB heat pipe is a transparent quartz cuvette with sharp corners (Fig. 1(a)). An ideal mixture of 94 vol %-pentane and 6 vol%-isohexane was used as the working fluid. The internal and external cross section of the cuvette were 3 × 3 mm and 5.5 × 5.5 mm respectively. A cold finger was used to keep the temperature of the cooler end constant during each experimental run. The heater end was supplied with a constant heat input through an electrical resistance heater. The cooler end temperature and the heat input were electronically controlled and could be effectively set at different values. Type-E thermocouples, made from insulated, 36 gauge wire, were used to measure