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The effect of an ideal fluid mixture on the evaporator performance of a heat pipe in microgravity

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ABSTRACT

Previous studies on wickless heat pipes showed that a temperature induced “Marangoni flow” prevents liquid from recirculating to the heater end, and therefore reduces the effectiveness of the heat pipe. Recently, several research groups used a water and alcohol mixture, with a low concentration of alcohol, resulting in better performance of the heat pipe. The alcohol/water combinations were peculiar in that for a certain composition range, the surface tension increases with increasing temperature thereby driving liquid toward the hotter end. It was believed that changing the direction of the Marangoni stress or reducing its magnitude by differential evaporation of an ideal binary mixture would also improve the performance of the heat pipe. For the first time, an ideal fluid mixture of 94 vol%-pentane and 6 vol%-isohexane was used as the working fluid in the Constrained Vapor Bubble (CVB) heat pipe experiment on the International Space Station (ISS). Using a simple heat transfer model developed in our laboratory, an internal heat transfer coefficient in the evaporator section was determined and shown to be almost twice that of the case where pure pentane was used under the same conditions. The Marangoni stress in the mixture was five times lower. Interestingly, reducing the Marangoni stress led to less liquid accumulation near the heater end and surveillance images of the device, taken at the steady state, showed that the bubble gets much closer to the heater end in the mixture case instead of being isolated from the heater by a thick liquid pool as in the pure pentane case. The proximity of the bubble to the heater wall led to more evaporation at the heater end in the mixture case, and therefore a higher heat transfer coefficient. The pressure profile calculated from the Young–Laplace equation supports the observations made from the surveillance images.

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1. Introduction

A heat pipe transfers heat via conduction along its walls and the phase transition of its working fluid. The fluid flow in a heat pipe is controlled by interfacial free energy gradients instead of a mechanical mechanism. This results in a simple, light, and reliable heat transfer system that is of great interest for the thermal control of critical spacecraft components.

The history of the heat pipe is dated back to the nineteenth century, when the Perkins tube was developed and introduced by the Perkins family [1]. The system was a closed tube boiler wherein water was circulated in single phase between a heating end (a furnace) and a cooler end (a steam drum), which provided an indirect heating system. In 1936, Jacob Perkins patented a two phase Perkins tube that is the forerunner to the modern day heat pipe. In 1944, Gaugler of the General Motors Corporation patented the first heat pipe that is a closed system partially filled with a volatile liquid [2]. In this first design, heat is absorbed at one end by evaporation of the working fluid and then dissipated at the other end by condensation. Heat pipe research began in earnest in 1964 when Grover at Los Alamos National Laboratory independently reinvented the heat pipe [3,4]. His team demonstrated that heat pipes are high performance heat transmission devices, and proposed several applications. In 1965, Cotter published the preliminary theoretical results and design tools that began world-wide research on heat pipes [5].

Currently, heat pipes are used in a large range of applications, including spacecraft and computer cooling systems. A significant

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amount of computational and experimental work has been conducted and a number of review articles have been published on this topic [6–13]. Different types of wicked and wickless heat pipes have been designed and studied [14–20]. The application of heat pipes is continuing to expand, and work is going on in this field to overcome limitations. How best to control the liquid motion inside the heat pipe, the effects of fluid mixtures, and visualizing the real liquid–vapor interface inside the heat pipe are of particular importance.

Although a large amount of work has been invested in the heat pipe field, the potential of interfacial forces, driven by temperature and concentration gradients, to affect the performance of heat pipes has not been fully explored. There is little work done on the transport processes occurring in a fluid mixture either computationally or experimentally [21–26]. Recently, the idea of using a fluid mixture in a heat pipe has caught the attention of several groups [27–29]. Their work focused on a water and alcohol system. The data show that adding the right amount of alcohol to the working fluid can improve the performance of a heat pipe. Di Francescantonio et al. found that a 0.1 wt% heptanol/water solution increased the dry-out limit of their heat pipe from 15 W to 39 W [28]. Armijo and Carey showed that 0.2 M and 0.05 M solutions of 2-propanol in water increased the critical heat flux at the heater surface by 52% and 45% respectively relative to pure water. They also found that reducing the 2-propanol concentration from 0.2 M to 0.05 M improved the evaporator heat transfer coefficient by 11% [29]. The alcohol/water combinations were peculiar in that for a certain composition range, the surface tension increased with increasing temperature thereby driving liquid toward the hotter end. In both papers, the lower concentration solution offered better performance. The results showed that Marangoni flow in a heat pipe can be controlled and that the efficiency of a heat pipe can be increased by adding a small amount of a second component to the working fluid.

In addition to the heat transfer characteristics and the composition of the working fluid, the shape of the liquid–vapor interface is also of great importance to the internal hydrodynamics of a heat pipe. Due to the Earth's gravitational field, the shape of the liquid–vapor interface is asymmetric, and so is the corresponding pressure field. This makes the interfacial phenomena inside a heat pipe difficult to control, use, and analyze. Much work has been done to simulate and predict the interfacial forces inside the heat pipe. Of significance is the work on the interfacial forces of the flow in the interior corner of a container or the wedge-flow models that were studied by researchers such as Concus et al., Homsy et al., Weislogel et al., Savino et al., Stephan et al., Ha and Peterson, Wu and Peterson [9,10,20,30–36]. In the absence of gravity, the effect of interfacial forces on the transport processes is easier to study and can be more accurately evaluated. Although there is a significant amount of work done on heat pipes on Earth, very little work has been done in microgravity environments. In collaboration with the National Aeronautics and Space Administration (NASA), we recently studied the Constrained Vapor Bubble (CVB), a wickless heat pipe with transparent walls, that allows us to image the inside of the heat pipe, in microgravity.

Our successful results on the CVB heat pipe using pure pentane in microgravity [37–41] together with data from previous research on fluid mixtures under normal gravitational conditions mentioned above [25–29] led us to extend the CVB experiment on the International Space Station (ISS) to a two-component system consisting of 94 vol%-pentane and 6 vol%-isohexane. This mixture forms an ideal liquid containing a low concentration of lower-vapor-pressure and higher-interfacial-tension, isohexane. With isohexane added, the composition of the liquid will change with position in the heat pipe. The normal change in interfacial tension due to the temperature gradient will be opposed by an opposite change in interfacial tension due to the change in mixture composition. The goal was to decrease the temperature gradient induced "Marangoni flow" observed in experiments performed using pure pentane and thereby improve the performance of the heat pipe.

The 6 vol% concentration of isohexane was chosen based on the ground based work conducted using a mixture of pentane and octane. It was shown that adding a small amount of octane to the working fluid of pentane improved the heat transfer performance [25]. We wanted a minority second component so that we did not change the refractive index of the liquid significantly, and therefore, did not affect the liquid film thickness measurement. The 6 vol% concentration of isohexane was a good compromise given the auto-ignition temperature restrictions on the type of fluid we could use and the difference in vapor pressure and surface tension of the two liquids we could achieve.

2. Experimental apparatus

The CVB experimental apparatus was operated in the U.S. Destiny Module of the ISS and consisted of a transparent quartz cuvette with sharp corners that was partially filled with a working fluid—pentane (CVB1) or an ideal mixture of 94 vol%-pentane and 6 vol%-isohexane (CVB2) (Fig. 1a). The cuvette was 3 × 3 mm in internal, and 5.5 × 5.5 mm in external cross section. The heat pipe was kept in a liquid cooled container that allowed for full field of view with a surveillance camera. A microscope was used to measure detailed film thicknesses. An electrical resistance heater that provided a constant heat input was attached to the heater end. The cooler end was kept at constant temperature by a cold finger attached to thermoelectric coolers. Temperature was measured by thermocouples installed at 1.5 mm intervals along the first 35 mm of one wall of the cuvette, in the heater section, and in the cooler section. Prior to launch of the experiment, the thermocouples were calibrated. The measurement errors were ±0.5 °C. Pressure was measured with a pressure transducer whose accuracy was ±350 Pa. A full description of our experiments is presented in previous publications [37–41].

3. Results and discussion

For both the CVB1 and CVB2 runs in this paper, the cooler was set at 10 °C. The heater was set at 0.2 and 0.4 ± 0.01 W for CVB1 and 0.25 ± 0.01 W for CVB2. For easy comparison, we extrapolated the data for 0.25 W in CVB1 from the data at 0.2 and 0.4 W. Fig. 1(b) shows the temperature profiles along the heat pipe.

To understand the difference in heat transfer between the pure liquid and the mixture, we used a one-dimensional, analytical model, which is a combination of two models presented in our previous publications [39–41]. The model will be described briefly as follows.

Due to the microgravity environment of the space station, we assume zero natural convection at the external surface. We need only consider heat conduction within the walls of the heat pipe (Q_{con}), thermal radiation from the walls to the surroundings ($Q_{\mathrm{out,rad}}$), and internal heat transfer (Q_{in}) between the walls, the liquid, and the vapor. The diagram of the model system is shown in Fig. 1(c). An energy balance about the control volume of the cuvette shown in Fig. 1(c) is:

$$(Q_{\mathrm{con},x} + Q_{\mathrm{in}}) - (Q_{\mathrm{con},x+\Delta x} + Q_{\mathrm{out,rad}}) = 0 \tag{1}$$

From Fourier's law and the Stefan–Boltzmann law, we have:

$$-kA_c\left(\left.\frac{dT}{dx}\right|_x - \left.\frac{dT}{dx}\right|_{x+\Delta x}\right) + Q_{\mathrm{in}} - \sigma\varepsilon P_o \Delta x\left(T^4 - T_\infty^4\right) = 0 \tag{2}$$

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