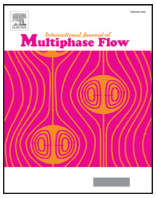
International Journal of Multiphase Flow 82 (2016) 65–73

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

journal homepage: www.elsevier.com/locate/ijmultiphaseflow



Arresting the phenomenon of heater flooding in a wickless heat pipe in microgravity

Akshay Kundan[a], Thao T.T. Nguyen[a], Joel L. Plawsky[a,*], Peter C. Wayner Jr.[a], David F. Chao[b], Ronald J. Sicker[b]

[a] The Howard P. Isermann Department of Chemical and Biological Engineering, Rensselaer Polytechnic Institute, Troy, NY 12180 United States
[b] NASA Glenn Research Center, Cleveland, OH 44135 United States

ARTICLE INFO

Article history:
Received 9 October 2015
Accepted 6 February 2016
Available online 11 March 2016

Keywords :
Marangoni flow
Capillary pressure gradient
Heat pipe
Performance limitation
Dry-out, flooding

ABSTRACT

The Constrained Vapor Bubble (CVB) is a transparent, wickless heat pipe experiment carried out in the US Labs of the International Space Station (ISS). Experiments were carried out using the 40 mm CVB, 3 mm × 3 mm in cross-section, pentane as the working fluid, with the power inputs of up to 3 W. Due to the low Bond number (Bo) in microgravity and materials of construction, the CVB system was ideally suited to determine the contribution of the Marangoni forces toward the limiting heat pipe performance, and the transparent quartz shows exactly how that limitation occurs.

Previous literature models and experimental temperature and pressure measurements suggested that at high enough temperature gradients, the working fluid should be subjected to enough Marangoni force to force it away from the heater and ultimately, dry out the hot end. The CVB experiment shows that high temperature gradients lead to a totally opposite behavior, i.e., 'flooding' of the heated end. Flooding of the heater end is attributed to a competition between Marangoni-induced flow due to high temperature gradients at the heater end and capillary return flow from the cooler. This creates a thick liquid layer in the corner of the cuvette at the heater end. At the point of flow balance, a thick layer of liquid is observed on the flat surface of the quartz cuvette. This is defined as the central drop. The region from the top of the heater end to the central drop is referred to as the interfacial flow region. The interfacial flow region develops at a power input of around 0.7 W, and increases in length to the power input of 2 W. At 2 W, the strength of the Marangoni forces saturate. As a result, the forces in the flooded interfacial region are not able to push the liquid further into the capillary region and a further penetration of liquid down the axis of the heat pipe is arrested. As the power input is increased to nearly 3 W, an increase in the vapor space is observed near the heater end at 3 W. This behavior suggests that the flooding might just be an intermediate stage in reaching the dry-out limitation.

The flat quartz surface at the hot end is covered by a wavy thin liquid film due to the interfacial forces. The hot end region closest to the heater is a superheated vapor region that leads to the condensation. This additional observation is discussed in Appendix.

Introduction

Heat pipes are passive heat transfer devices that can transfer heat at high rates over large distances with extremely small temperature drops, without a requirement of external pumping power. They are commonly used for high heat flux applications because of an increased effective conductivity of the material. The basic working of a heat pipe is dependent on the capillary pumping of the fluid from the cold end to the hot end using a wick or a wickless design. Liquid is evaporated at the heated end; the vapor then travels back to the cold end where it condenses and is then recirculated back to the hot end by the capillary pumping.

The concept of a micro-heat pipe was first published by Cotter (1984). Since then, many papers and books have been published regarding the working of a heat pipe. The equations, the operation and limitations associated with heat pipes are well developed (Peterson, 1994; Faghri, 1995). Peterson (1992) and Faghri (2012) have written excellent reviews about the advances in the numerical modelling, the analysis and the experimental simulation of different types of heat pipes. Khrustalev and Faghri (1994) de-

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* Corresponding author.
E-mail addresses: akshaykundan@gmail.com (A. Kundan), nguyen.thaoche@gmail.com (T.T.T. Nguyen), plawsky@rpi.edu (J.L. Plawsky), wayner@rpi.edu (P.C. Wayner Jr.), David.F.Chao@grc.nasa.gov (D.F. Chao), Ronald.J.Sicker@nasa.gov (R.J. Sicker).

http://dx.doi.org/10.1016/j.ijmultiphaseflow.2016.02.001
0301-9322/

veloped a detailed mathematical model describing the distribution of a liquid in a micro-heat pipe and its thermal characteristics. Swanson and Peterson (1995) formulated a thermodynamic model of the vapor–liquid interface to provide a fundamental insight into the critical mechanism for a proper micro-heat operation. Babin et al. (1990) and Longtin et al. (1994) have also developed steady state models to predict the operating parameters of a micro-heat pipe. Bowman et al. (1999, 2000), and Bowman and Maynes (2001) developed a simple model for comparing the efficiency and the thermal performance of a heat pipe with a solid fin using a lumped inside heat transfer coefficient. They provided a simple method to evaluate the feasibility of a heat pipe in any application without indulging in more expensive and time consuming design methods.

The Marangoni flow is a surface tension driven flow caused either by a temperature or a concentration gradient. The Marangoni flow was first identified in the ‘tears of wine’ phenomena by Thompson (1855). However, the name of the effect is due to the Italian physicist, Marangoni (1865) of Pavia and Florence (1840–1925), who studied the ‘tears of wine’ phenomena for his doctoral dissertation and published his results in 1865. Scriven and Sternling (1960) published the first review of the Marangoni effects in 1960. The Marangoni convection plays a major role in the heat and mass transport in the crystal growth melts (Schwabe and Scharmann, 1979), rates of mass transfer in process engineering problems leading to the surface renewal phenomena (Sawistowski, 1973), the hydrodynamic stability of the bi-component droplet evaporation (Aharon and Shaw, 1996), the stability of the pulmonary alveolar structure of lungs (Clements et al., 1961), the spreading of liquid mixtures on a solid surface (Pesach and Marmur, 1987), the hydrodynamic instability that causes the interfacial turbulence observed between the two unequilibriated fluids (Sternling and Scriven, 1959) and in the case of a diffusion accompanied by a chemical reaction (Ruckenstein and Berbente, 1964). The Marangoni flow can induce a wetting fluid on a flat surface to climb against the action of the gravity (Carles and Cazabat, 1993; Fanton et al., 1996). The climbing thin wetting film can induce the fingering instability and the tear drop formation (Cazabat et al., 1990; Golovin et al., 2001; Ajaev et al., 2012). Other Marangoni-driven behaviors associated with the boiling within an evaporating meniscus (Liu et al., 2012; Dhavaleswarapu et al., 2007) and an enhanced boiling heat transfer (Maroo and Chung, 2013) have also been studied.

A heat pipe has various operating limits to the maximum heat transfer rate it can achieve. These limits, which include the boiling limit, the wicking limit, the entrainment limit and the sonic limit, result from a breakdown or a rate limit in the circulation of the working fluid. Ma and Peterson (1996) carried out experiments to measure the capillary heat transport limit in small triangular grooves, similar to those used in micro-heat pipes. Suman and Hoda (2005) presented a detailed model for a V-shaped micro-heat pipe and used that to determine the capillary limit and the dry-out length of the device. He also carried out various sensitivity studies that give us a better understanding of variations in the thermophysical properties and the design parameters of a micro-heat pipe. Researchers have developed various analytical and semi-analytical models to predict the capillary limit and heat transfer characteristics of a heated triangular groove (Xu and Carey, 1990; Stephan and Busse, 1992; Migliaccio et al., 2011; Holm and Goplen, 1979; Catton and Stroes, 2002). Pratt and Kihm (2003) studied the interactions of a binary fluid mixture and concluded that added concentrations of decane in pentane delays the onset of the meniscus instability without a degradation in the heat transfer. Karchevsky et al. (2015) studied the heat and mass transfer process near the dynamic three phase liquid–gas–solid contact line of an evaporating sessile droplet.

Mathematical models have been developed studying the effect of a significant Marangoni flow in a heat pipe (Yang and Homsy, 2006; Markos et al., 2006; Savino and Paterna, 2006). The models suggest that if a significant Marangoni flow is generated, it will drive the liquid away from the hot end, creating a region of a total dry-out and a reduction in the heat pipe performance. These models led to the experimental work using self-rewetting fluids to assist the fluid movement to the heated end of the device (Savino et al., 2007; di Francescantonio et al., 2008; Armijo and Carey, 2011). These models were based on the signature associated with the temperature measurements indicating the presence of the dry-out region. Ha and Peterson (1994) decoupled the evaporation from the condensation and directly observed the dry-out length by measuring the length of the evaporator region. Anand et al. (2004) and Suman et al. (2002) predicted the dry-out length by solving the nonlinear governing equations numerically to predict the onset, the location and the propagation of the dry-out point and confirmed it experimentally through the dry-out signature associated with the temperature profile. All these models are based on the signature associated with the temperature profile, and the actual liquid-vapor distribution inside a complete working heat pipe is still missing. Numerical solutions are developed that predicts that a high Marangoni stress can create a virtual dry region in V-shaped grooves (Yang and Homsy, 2006; Markos et al., 2006; Savino and Paterna, 2006; Ha and Peterson, 1994; Suman et al., 2002) and micro-heat pipes (Anand et al., 2004). The existence of the dry-out phenomena associated with these models is yet to be confirmed with the internal pictures of a working heat pipe.

In this paper, we study the performance limitation at the hot end of a ‘wickless’ heat pipe in a microgravity environment. In CVB experiments, a competition between the capillary pumping of fluid and the Marangoni stresses caused a flooding limitation instead of dry-out (Yang and Homsy, 2006; Markos et al., 2006; Savino and Paterna, 2006). At high power inputs, the flooding limitation reaches its peak, a further penetration down the axis of a heat pipe is arrested and, this phenomena is defined in this paper as ‘arresting phenomena’. The arresting phenomenon is verified by a simple, one dimensional, thermal fluid model that gives us an insight on the temperature signature associated with the flooding limitation and the characteristics of the interfacial flow. This model can be recast to obtain an internal heat transfer coefficient for the heat pipe and so help to quantify the flooding limitation and the arresting behavior associated with it. In the Appendix, a model to calculate the chemical potential per unit volume is used to describe the interfacial effects observed near the heater end. The model suggests the presence of a superheated vapor in the region near the heater end leading to the condensation, and confirms the results from the thermal and fluid models in the paper.

Experimental set-up and measurements

The experiments discussed herein were carried out in the Fluids Integrated Rack (FIR) on the International Space Station. The system consists of a fused silica quartz cuvette closed at one end. The inner dimensions of the cuvette are 3 mm × 3 mm with a wall thickness of 1.25 mm. The cuvette is partially filled with pentane as a working fluid. The thermocouples are located till 45.5 mm, but the vapor bubble is approximately 40 mm long. This CVB setup is referred to as 40 mm CVB runs/experiments in this paper. The heater is attached to the closed end, insulated on all sides to ensure a maximum flow of heat into the cuvette. A cold finger is attached to the other end of the cuvette and maintains the liquid pool at a low temperature. The pentane is pumped from the cold end of the device towards the heated end by the capillary flow along the four sharp corners of the cuvette. The basic working of the CVB is shown in Fig. 1, and the experimental setup is explained