Experimental Thermal and Fluid Science 66 (2015) 13–27

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

Visualization of the boiling phenomenon inside a heat pipe using neutron radiography

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ARTICLE INFO

Article history:
Received 13 August 2014
Received in revised form 28 February 2015
Accepted 28 February 2015
Available online 17 March 2015

Keywords:
Heat pipe
Visualization
Neutron radiography

ABSTRACT

Heat pipes are effective heat exchangers that have a wide range of applications because of their ability to passively transfer large amounts of heat. Research into heat pipe technology has dramatically increased over the last decade and, more recently, has incorporated the use of visualization to help researchers gain a better understanding of the boiling phenomenon and heat transfer occurring inside a heat pipe. Neutron radiography is one method of visualization suitable for use in heat pipe investigations due to unique attenuation characteristics of neutrons attaching to various materials. In this study, an aluminum-based heat pipe was tested using working fluid filling ratios from a 10% to 90% capacity. Visualization using neutron radiography was conducted at a neutron radiography facility, RN1, under the supervision of the Centre of Science and Technology of Advanced Materials (PSTBM), National Nuclear Energy Agency of Indonesia (BATAN). Using temperature and pressure sensors, this study revealed that the optimum value of working fluid filling ratios directly correlates to the pressure inside a heat pipe and the size of vapor space available. The neutron radiography facility maintains high neutron flux at 10^6–10^7 n/cm^2 s; high quality images were captured utilizing this radiography visualization technology. The captured images demonstrate that the boiling phenomenon inside a pressure-reduced heat pipe varies when compared with the boiling phenomenon at atmospheric pressure. The visualization result also shows the importance of wick structure in pumping return condensate from the condenser to the evaporator.

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1. Introduction

Heat pipes are passive heat exchangers operating on the two-phase principle. The passive description refers to lack of additional energy needed during operation; two-phase indicates that the heat pipe uses the phase change phenomenon of working fluids as the main mode of heat transfer [1,2]. A heat pipe may have circular or rectangular cross sections and generally contains a vacuum container with a wick structure and a working fluid. When heat is applied to the evaporator, the working fluid evaporates and rushes to fill the evacuated space. As the vapor enters, it contacts the wall of the lower temperature heat pipe. The vapor then condenses and releases latent heat. This condensate naturally flows back to the evaporator, either by gravity or capillarity action induced by the wick structure. The high amount of latent heat needed during the phase change process enables the heat pipe to have higher effective thermal conductivity [3,4].

Heat pipes used for various cooling systems have been extensively tested for many applications such as central processing units (CPUs) hard disks, light emitting diodes (LEDs) lamps, avionics and various medical devices including those used in cryosurgery and vaccine transport mechanisms [5–11]. Heat pipe components for each application were investigated for optimum performance. Wick structures were made of biomaterials, bi-porous structures, sintered powder, grooved assemblies and metal foam [12–16]. Working fluids such as nanofluids, methanol, acetone, propylene glycol and refrigerant have also being tested [17–20].

Another parameter affecting heat pipe performance is the working fluid filling ratio. This ratio is the volumetric measure of fluid injected into the heat pipe compared with the volume of evacuated space. Naphon et al. [21] tested vapor chambers on CPU cooling systems with various filling ratios and found that the optimum ratio of fluid to volume is 20%. Any ratio lower than 20% leads to the dry-out phenomenon; higher ratios, however, cause the liquid

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http://dx.doi.org/10.1016/j.expthermflusci.2015.02.026
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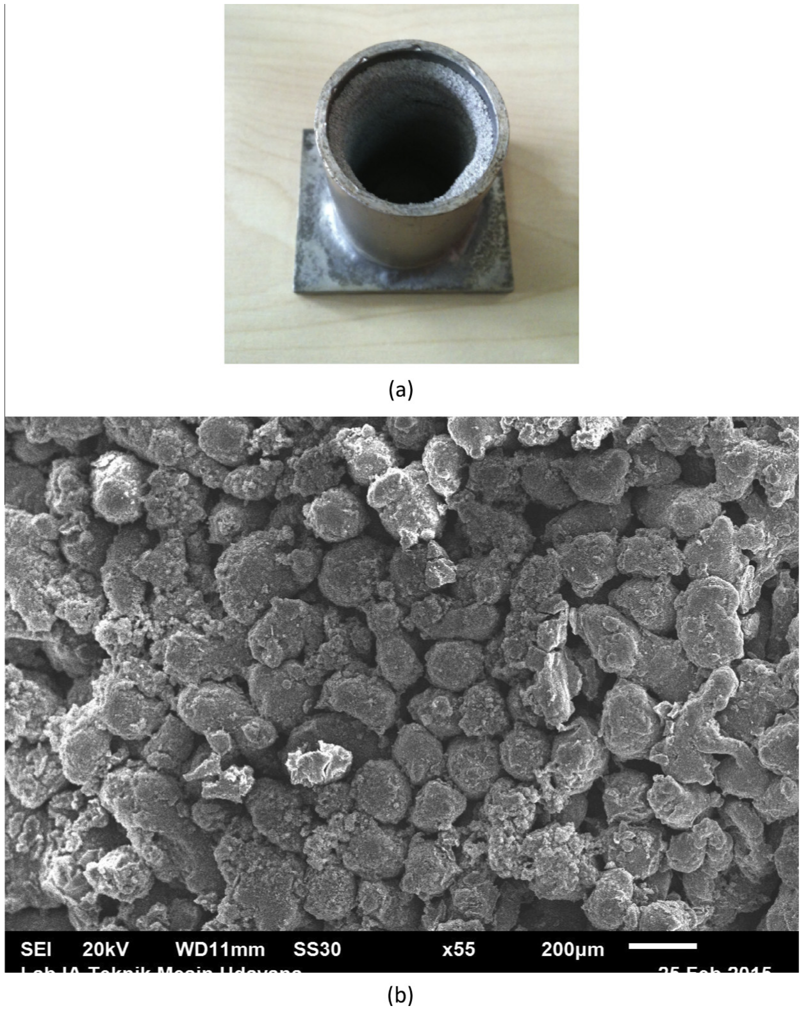

Fig. 1. (a) Picture of the sintered aluminum powder wick structure and (b) SEM image of the wick.

layer to hamper heat transfer at the heat input region. Sukchana and Jaiboonma [22] investigated the effect of the filling ratio compared with thermal efficiency of a 10 cm, R-134a charged heat pipe. The investigation also showed the optimum value of filling ratio relates to the saturation pressure increment and temperature inside the heat pipe. Lips et al. [23] studied the effect of the filling ratio of a flat heat pipe and found that this ratio affects the thermal resistance of a heat pipe. Small filling ratios lead to dry-out at the evaporator while large filling ratios lead to flooding at the condenser. Hussein et al. [24] investigated wickless heat pipes utilizing various filling ratios and found that a higher filling ratio provided higher thermal capacity resulting in lower temperature and lower pressure at the same heat flux. Ong and Alahi [25] tested a R-134a filled heat pipe employing filling ratios in the range of 35–80% while discovering that the optimum-filling ratio was 80%. Lin et al. [26] studied heat pipes with silver-nanofluids at filling ratios of 20%, 40%, 60% and 80%. The study revealed the optimum-filling ratio for successful heat transfer was 60%. Finally, Naphon et al. [27,28] tested heat pipes with both Titanium and R11 nanofluids across various filling ratios. This study established the optimum value of this ratio was 66% and 50%, respectively.

The heat transfer process ensuing inside a heat pipe with boiling working fluids reduced the pressure and fluid circulation through the capillary structure. This complex process triggered the evaporation-boiling phenomenon inside the heat pipe to appear differently than more commonly assumed processes. The visualization technique clearly proved these differences and provided important outcomes toward the characterization of heat pipe operation. The visualization results also show the importance of wick structure to heat pipe operation [29–31].

Most visualization techniques used during heat pipe operations employ transparent media such as glass windows [32–35]. Radiography is one method of visualization that uses transmission imaging and is a technique that utilizes the penetration of radiative energy to non-destructively study the internal portions of opaque objects. Finally, neutron radiography uses neutron beam techniques to penetrate heavy materials while beam are absorbed by lighter materials. This technique is suitable for use in visualization of the two-phase flow of hydrogen-based fluids inside metal enclosures [36,37].

Mishima et al. [38] visualized and measured two-phase flow using neutron radiography, providing a result that could be used not only as a qualitative measurement but also as a quantitative measure. The need of high-speed video (HSV) technology with capture speeds up to 1000 frame per second was also highlighted in this study. With an HSV camera, Mishima et al. were able to observe the characteristics of the two-phase flow and the vapor fraction. Uchimura et al. [39] stated that the inability of the glass-transparent pipe to hold high pressure, and temperature became the main disadvantage of the glass-based visualization method. They further used real time neutron radiography (RTNR) to visualize the two-phase flow of liquid metal and to calculate

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