International Journal of Heat and Mass Transfer 83 (2015) 586–590

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Technical Note

Experimental investigation of the influence of surfactant on the heat transfer performance of pulsating heat pipe

X.H. Wang, H.C. Zheng, M.Q. Si, X.H. Han *, G.M. Chen

Institute of Refrigeration and Cryogenics, State Key Laboratory of Clean Energy Utilization, Zhejiang University, Hangzhou 310027, China

ARTICLE INFO

Article history:
Received 5 June 2014
Received in revised form 26 November 2014
Accepted 2 December 2014
Available online 8 January 2015

Keywords:
Pulsating heat pipe
Surfactant
Thermal resistance
Heat transfer

ABSTRACT

An experimental study was conducted to investigate the heat transfer performance of a pulsating heat pipe (PHP) charged with deionized water and surfactant solution. The inner diameter of the PHP was 2 mm. The surfactant was sodium stearate, and the concentrations of sodium stearate solutions were 10, 20 and 40 ppm. The experimental results indicated that the heat transfer performance of the PHP was greatly influenced by the surfactant solution, and the influence was dependent on the charge ratio and the concentrations of the solutions. The PHP with 10 ppm sodium stearate solution showed better performance than the PHP with deionized water within the whole test range (0–160 W). Nevertheless, the enhancement effect of the heat transfer was apparent only when the heat flux was very high for the 40 ppm sodium stearate solution. Compared with the PHP with deionized water, the thermal resistance and the temperature difference between the evaporation section and condensation section could be decreased by 0.13 K/W and 20.8 K when the charge ratio, the heating power and the concentration of the solution was 58%, 160 W and 40 ppm, respectively.

1. Introduction

Recently, the heat dissipation from the electronic chips increases sharply but with the reducing of the physical size. As a result, the thermal management has become and will continue to be one of the most important issues in this area [1]. As a newly heat transfer device, pulsating heat pipe (PHP) was proposed by Akachi [2] in 1990 and was considered as one of the most effective methods to meet the challenge of higher heat flux due to its distinct advantages, such as high heat transfer coefficient, very low cost and high flexibility [3–5]. The PHP is made of a long capillary tube and bent into many turns. The maximum allowable inner diameter of the PHP is determined by the formula: $D_{\max} = 2\sqrt{\sigma/(\rho_l - \rho_g)g}$ [6–8] (where the σ, ρ_l and ρ_g represent the surface tension, the liquid density and the vapor density of the working fluid corresponding to the operational temperature, respectively). Due to that the inner diameter of the PHP is very small, the influence of the surface tension of the working fluid is greater than the gravity and thus the liquid slugs and vapor plugs can be formed in the PHP. The operational mechanism of the PHP is quite different from the traditional heat pipes, and no wick structures are needed to help the backflow of the working fluid. In a PHP, the heat is dissipated from the evaporation section to the condensation section mainly by the oscillation motions of the liquid slugs and vapor plugs.

The researches have indicated that the heat transfer performance of the PHP is greatly influenced by some thermodynamic and transport properties of the working fluid, such as the thermal conductivity, surface tension, latent heat and sensible heat [9,10]. However, few researches reported the explicit guidance for improving the heat transfer performance of the PHP through ameliorating the thermodynamic and transport properties of the working fluid. As so far, most researchers used the nanofluids as the working fluid to improve the heat transfer performance of PHP due to their apparently increasing effect on the thermal conductivity of the base fluid. Ma et al. [11] investigated the heat transfer performance of PHP with the 1.0 vol% diamond nanofluids. The experimental results showed that the PHP with the nanofluid could decrease the temperature difference between the evaporation section and the condensation section by 16.6 K when the heating power was 80 W. Lin et al. [12] conducted an experimental investigation to study the effect of silver nanofluid on the heat transfer performance of PHP. It was found that the PHP with silver nanofluid of 100 ppm showed the best performance when the charge ratio was 60%. According to Jamshidi et al. [13], the heat transfer performance of PHP was enhanced by 30% when the working fluid

* Corresponding author. Tel./fax: +86 571 87953944.
E-mail address: hanxh66@zju.edu.cn (X.H. Han).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.12.010

was nanofluid. Furthermore, the PHP with the nanofluid also had a shorter response time. Riehl and Santos [14] conducted an experimental study for an open PHP with copper nanofluid. It was found that the using of the nanofluid not only enhanced the heat transfer performance of the PHP, but also increased the oscillation amplitude of the working fluid. Qu et al. [15] found that for the PHP with Al_2O_3 nanofluid, the optimal concentration was 0.9 wt%, at which concentration the thermal resistance of the PHP and the temperature difference could achieved 0.057 K/W and 5.6 K. He also [15] pointed out that the settlement of the nanofluid was mainly found in the evaporation section, which greatly enhanced the heat transfer process.

In addition to the thermal conductivity of the working fluid, researchers [16–18] have also pointed out that the surface tension had a great influence on the heat transfer performance of PHP, considering the heat transfer process occurring in a small scale. When the inner diameter of the PHP was given, the influence of the surface tension mainly reflected in the capillary resistance of the working fluid. The analysis model of the capillary resistance in the PHP was shown in Fig. 1. Where θ_1 and θ_2 represented the contact angles between the tube wall and the working fluid. By assuming that all the vapor–liquid interfaces were perfect spherical and the surface tension almost kept as a constant. According to Young–Laplace equation, the capillary resistance caused by the surface tension was:

$$p_1 - p_2 = 4\sigma(\cos\theta_1 - \cos\theta_2)/d \quad (1)$$

For the interface of water–copper, the maximum advancing contact angle and minimum receding contact angle are 84° and 33° [19], and the surface tension of the water is 72 mN/m at 298.15 K. Thus the capillary resistance of a single liquid slug was calculated to be 3.24×10^{-4} N. Although this value was very small, the capillary resistance could be very large considering the great numbers of the liquid slugs in the pipe. From Eq. (1) it could be found that the capillary resistance in the PHP could be decreased by reducing the surface tension of the working fluid, and thus improved the heat transfer performance of the PHP. Furthermore, with the decreasing of the working fluid's surface tension, the working fluid could wet the tube wall better, which also enhanced the heat transfer though increasing the area of the thin film.

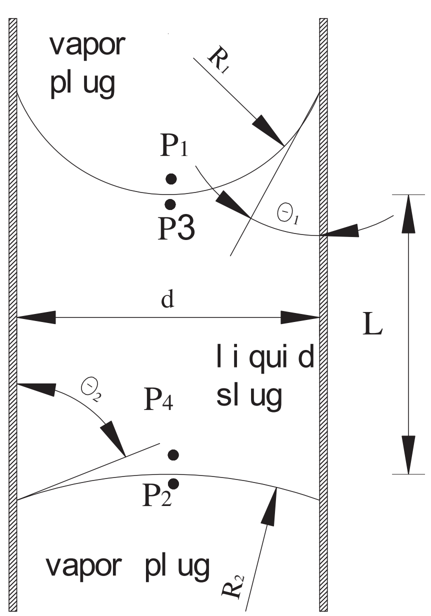

Fig. 1. The analysis model of the capillary resistance in the PHP.

However, few experimental researches were conducted to investigate the effect of the working fluid's surface tension on the PHP.

The surfactants are a kind of special material, and a small amount of the surfactant can greatly reduce the surface tension of the base fluid [20,21]. In this paper, the heat transfer performances of PHP with deionized water and different concentration surfactant solutions were experimentally investigated. Meanwhile, the influence of surfactant solution on the heat transfer performance of PHP was also discussed and analyzed based on the experimental data.

2. Experiment

2.1. Samples

In this experiment, deionized water was selected as the base fluid. Sodium stearate, as a kind of anionic surfactant, was chosen as the surfactant, because it was easily obtained and with very low cost. The purity of sodium stearate was greater than 99.9%. Four different concentrations (0, 10, 20, 40 ppm) of the sodium stearate solution were prepared and tested. From the experimental data of Ref. [22], when the concentrations of the sodium stearate solution were 10, 20 and 40 ppm, the surface tension of the working fluid was greatly reduced. To ensure the high accuracy of the weight, the mass of the sodium stearate powder was weighted by a high precision electronic balance whose weighing capacities and accuracy were 110 g and 0.001 g, respectively. The mass of the deionized water was weighted by another high precision electronic balance, whose weighing capacities and accuracy were 10000 g and 1 g. All of the sodium stearate solutions were stirred by the magnetic stirrer for about 2 h, and then the solutions were placed in the environment with the room temperature of 293.15 K. For the solutions of 10, 20 and 40 ppm concentration, no apparent agglomerations or precipitations in the solutions were observed four days later.

2.2. Experimental setup

The experimental setup in this work was shown in Fig. 2. It mainly consisted of four modules: the PHP module, the heating module, the cooling module and the data acquisition module. The tube was bent into ten "U" shape turns to form a closed PHP. The total length and the inner diameter of the copper tube were 5.73 m and 2.0 mm, respectively. The length of the evaporation section, adiabatic section and condensation section were 90 mm, 80 mm and 60 mm, respectively. In the evaporation section, the nickel-chrome wire with a diameter of 0.3 mm was wrapped outside of the tube to simulate the heating of electronics and the heating power could be changed by a transformer. A three-phase wattmeter with a measurement range of 250 W and an accuracy of 0.5% FS was used to record the heating power of the evaporation section. Nine thermocouples were used to measure the temperatures, and the locations were shown in Fig. 2. The accuracies of these thermocouples were calibrated to be ±0.1 K. The temperature of the cooling water was set at 19 ± 0.5 K. All the experimental data were recorded by the Agilent 34970A (6½ digits) which was connected with a PC. The evaporation section and the adiabatic section of the PHP were both insulated by polyurethane foam material. Before the experiment, the impurity inside of the tube was blowed away by high-pressure nitrogen (1.5 MPa) for about 1 h to ensure the cleanliness of the PHP channel.

In this experimental study, the heat transfer performances of the PHP with (0, 10, 20 and 40 ppm) sodium stearate solutions were studied when the heating power was within the range of (40–160 W), and the charge ratios were (39%, 47%, 58%).