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Experimental study on effect of inclination angles to ammonia pulsating heat pipe

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Abstract In this paper, a novel study on performance of closed loop pulsating heat pipe (CLPHP) using ammonia as working fluid is experimented. The tested CLPHP, consisting of six turns, is fully made of quartz glass tubes with 6 mm outer diameter and 2 mm inner diameter. The filling ratio is 50%. The visualization investigation is conducted to observe the oscillation and circulation flow in the CLPHP. In order to investigate the effects of inclination angles to thermal performance in the ammonia CLPHP, four case tests are studied. The trends of temperature fluctuation and thermal resistance as the input power increases at different inclination angles are highlighted. The results show that it is very easy to start up and circulate for the ammonia CLPHP at an inclining angle. The thermal resistance is low to 0.02 K/W, presenting that heat fluxes can be transferred from heating section to cooling section very quickly. It is found that the thermal resistance decreases as the inclination angle increases. At the horizontal operation, the ammonia CLPHP can be easy to start up at low input power, but hard to circulate. In this case, once the input power is high, the capillary tube in heating section will be burnt out, leading to worse thermal performance with high thermal resistance.

1. Introduction

The closed loop pulsating heat pipe (CLPHP), is considered as one of the promising technologies for a high heat transfer device on small space. It has been widely utilized in electronics and computer components due to its potential heat transport capability, simple structure, compact sizes and low cost of manufacturing.[1–4] Although simple in its construction, CLPHP seems very complicated when we try to understand its operation for phase change and interactions between the vapor plugs and liquid slugs. The CLPHP has been studied in experiment by many researches,[5–10] focusing on either visual observation of flow patterns in CLPHP or various operation parameters related to thermo-hydrodynamics of CLPHP.

Gi et al.[11] performed the flow visualization of an R142b CLPHP with an 8 mm camera to record the flow, but little information of detailed description of flow pattern was observed. Tong et al.[12] firstly visualized the flow patterns of a glass CLPHP filled 60% with methanol. It was found that

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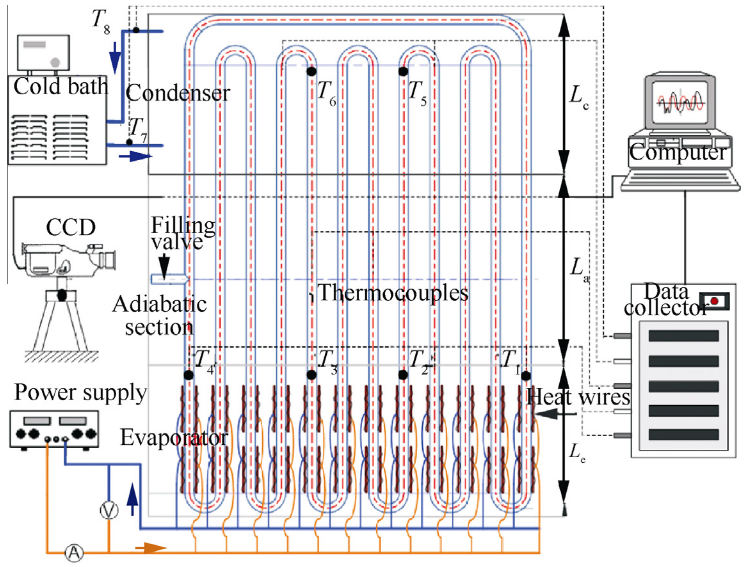

Fig. 1 Schematic of full visualization setup.

large amplitude oscillations from evaporator to the condenser during the startup period; however, in steady operating state, the working fluid circulated, coupled with complex processes such as nucleation boiling and coalescence of bubbles. The direction of circulation was consistent once circulation was attained, but it could be different for the same experimental run. Qu and Ma[13] also conducted an experimental investigation on a glass CLPHP with water, and two kinds of vapor bubbles, i.e., small round (Globe) bubbles and long column (Taylor) bubbles, were formed and circulated in the whole CLPHP. It can be concluded that the startup of CLPHP and steady circulation were primarily due to the boiling heat transfer associating with the temperature difference and pressure difference between heating section and cooling section. Charoensawan et al.[14] studied the parameter effect on thermal performance of the copper CLPHP, including the variation of internal diameter, number of turns, working fluid and inclination angle. The working fluids employed were water, ethanol and R-123. The results indicated a strong influence of gravity on the performance that the highest heat flux of CLPHP in horizontal mode decreased obviously compared to vertical mode if the turns were less than a certain number. Besides, thermo-physical properties of working fluids affected the performance strongly. Khandekar et al.[15] indicated that the operating mechanism of CLPHP was not well understood and the present state of the art could not predict required design parameters for a given task. And he summarized the choice of working fluids which had high value of $(\mathrm{d}p/\mathrm{d}T)_{\mathrm{sat}}$, low dynamic viscosity, low latent heat and low surface tension.

It is found that the working fluids of CLPHP employed as mentioned earlier usually are usually water, ethanol, methanol, acetone, R-134a,[16] etc. But for ammonia, there is rarely used, especially in the whole glass CLPHP. Nevertheless, ammonia has much more advantages than these working fluids. It has much higher value of $(\mathrm{d}p/\mathrm{d}T)_{\mathrm{sat}}$, much lower superheat required,[17] little lower dynamic viscosity and surface tension than those fluids, and much lower latent heat than water. So we infer that ammonia could be regarded as one kind of excellent fluid for CLPHP.

In our recent work, a novel study on full visualization and startup performance of glass CLPHP using ammonia as working fluid was experimented.[18] It was found that the ammonia CLPHP was quite easier to startup than other working fluids, even under the conditions that the temperature of evaporator is only 4 K higher than condenser. This paper will observe the thermal performance of the ammonia CLPHP at different inclination angles. Firstly, the experimental setup and procedures are introduced. Then, the temperature fluctuations of evaporator and condenser are presented, and operation characteristics at different inclination angles are detailed. Lastly, the thermal resistance is analyzed, on behalf of the performance of ammonia CLPHP.

2. Experiment introduction

2.1. Experimental setup

The schematic of the tested CLPHP constituting six meandering turns is shown in Fig. 1. The prototype is fully made of quartz glass capillary tubes with the total length of 320 mm from the top to the bottom. The inner and outer diameters of the glass tube are 2 mm and 6 mm, respectively. The evaporator section of the CLPHP is heated by the 0.2 mm electrical wires of 4.86 Ω/m resistance. The heat wires are wrapped at intervals of 1.5 mm on the outer wall surface of the CLPHP. The input heat power can be adjusted by step of 40 W. The total length of heating section shown as L_e in Fig. 1 is 100 mm. In order to prevent heat radiation losses from heat wire, there will cover some insulation materials in the evaporator. The condenser part of the CLPHP is cooled by cooling water in cooler box which is circulated by a cold bath appliance. The inlet temperature of cooling water is maintained at 28 °C with ± 2 °C accuracy. The length of cooling section named as L_c is 100 mm. The length of adiabatic section named as L_a is 120 mm. The motions of vapor bubbles and liquid slugs are photographed and recorded by a high speed CCD (Charge Coupled Device) camera. There are eight thermocouples (T_1 to T_8) located as shown in Fig. 1 to