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Research paper

# Effects of filling ratio and condenser temperature on the thermal performance of a neon cryogenic oscillating heat pipe

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ABSTRACT

A cryogenic oscillating heat pipe (OHP) made of a bended copper capillary tube is manufactured. The lengths of the condenser section, adiabatic section and evaporator section are 100, 280 and 100 mm, respectively. Neon is used as the working fluid. Effects of liquid filling ratio and condenser temperature on the thermal performance of the OHP are studied. A correlation based on the available experimental data sets is proposed to predict the thermal performance of the neon cryogenic OHP with different filling ratios and condenser temperature. Compared with the experimental data, the average standard deviation of the correlation is about 15.0%, and approximately 92.4% of deviations are within ± 30%.

## 1. Introduction

Operation of cryogenic systems requires efficient thermal management. The high purity metal bar like copper bar usually serves as the heat link between the cooled target (such as superconducting magnets and infrared detectors) and cold source (such as cryocoolers and the liquid cryogens). But for long heat transport distance, the heat pipe can be a better option because of its excellent heat transfer performance [1]. Among many types of heat pipes, the oscillating heat pipe (OHP) is a novel two-phase flow device, which is formed by bending a metallic capillary tube into many turns [2,3]. Comparing with other conventional heat pipes, the employment of flexible capillary tube makes the OHP more convenient as the thermal link in the cooling system. The thermal performance of the OHP using the cryogenic working fluids such as hydrogen, neon, helium and nitrogen has already been studied [4–13]. The results show that the thermal conductivity of the cryogenic OHP is several orders of magnitude greater than that of high purity copper.

The operational temperature range of the cryogenic OHP is ultimately determined by the triple point and the critical point of the working fluid. When the cooled target operates between 30 and 40 K, the only option of the working fluid is neon. Natsume et al. [7,8] investigated a neon cryogenic OHP with the filling ratios from 16 to 95%, and they found the effective thermal conductivity reached 1000–8000 W/m K at 26–34 K. Liang et al. [10] also designed a neon cryogenic OHP and studied the thermal performance at different filling ratios. The effective thermal conductivity of 6100–22,180 W/m K was obtained at the filling ratio of 24.5%. The material of these OHPs is stainless-steel. However, the copper can be better material since its thermal conductivity is much higher than that of stainless-steel at cryogenic temperature. In addition to the filling ratio, the condenser temperature which is determined to the cold source has a significant influence on the thermal performance of cryogenic OHP, but few of researches focused on it. In this paper, a cryogenic OHP made of a copper capillary tube is fabricated and neon is used as the working fluid. Effects of the filling ratio and condenser temperature on the thermal performance are studied. Then, with available experimental data sets, a correlation based on dimensionless groups is established to predict the thermal performance of the OHP.

## 2. Experimental apparatus and procedures

### 2.1. Experimental apparatus

Fig. 1(a) and (b) show the configuration of the cryogenic OHP and the schematic of the experimental system, respectively.

The OHP is made of a bended copper capillary tube with an inner diameter of 1.0 mm and an outer diameter of 2.0 mm. The lengths of the condenser section, adiabatic section and evaporator section are 100, 280 and 100 mm, respectively. The evaporator section is connected with the condenser section through 10 parallel tubes. There are two other tubes in the adiabatic section, connected end to end to form a

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**Nomenclature**

| | |
|---|---|
| ASD | average standard deviation |
| $Bo$ | Bond number |
| $c_p$ | specific heat of the liquid ($J\,kg^{-1}\,K^{-1}$) |
| $D_i$ | inner diameter (m) |
| $g$ | gravitational acceleration ($kg\,m^{-3}$) |
| $h_{lv}$ | latent heat of vaporization ($J\,kg^{-1}$) |
| $Ja^*$ | modified Jacob number |
| $k$ | thermal conductivity of the OHP ($W\,m^{-1}\,K^{-1}$) |
| $Ka$ | Karman number |
| $Ku$ | Kutateladze number |
| $L_{eff}$ | distance of the two centers of the evaporator and the condenser (m) |
| $M$ | times of charge procedure |
| $n$ | number of parallel tubes |
| $N$ | number of experimental data sets |
| $P_0$ | pressure of buffer tank before charging with gas (Pa) |
| $P_a$ | pressure of buffer tank after charging with gas (Pa) |
| $Pr$ | Prandtl number of liquid |
| $q$ | input heat flux ($W\,m^{-2}$) |
| $Q$ | heat input (W) |
| $R$ | the gas constant ($J\,kg^{-1}\,K^{-1}$) |
| $S$ | the summation out cross sectional area of the capillary tube ($m^2$) |
| $T$ | temperature (K) |
| $V$ | volume ($m^3$) |

*Greek symbols*

| | |
|---|---|
| $\mu$ | the dynamic viscosity of the liquid phase (Pa s) |
| ρ | density ($kg\,m^{-3}$) |
| $\sigma$ | surface tension ($Nm^{-1}$) |
| $\varphi$ | the volumetric liquid filling ratio (%) |

*Subscripts*

| | |
|---|---|
| BT | buffer tank |
| $c$ | condenser |
| $CT$ | charge tube |
| $e$ | evaporator |
| exp | experimental |
| $l$ | liquid |
| $OHP$ | oscillating heat pipe |
| pre | predicted |
| $v$ | vapor |

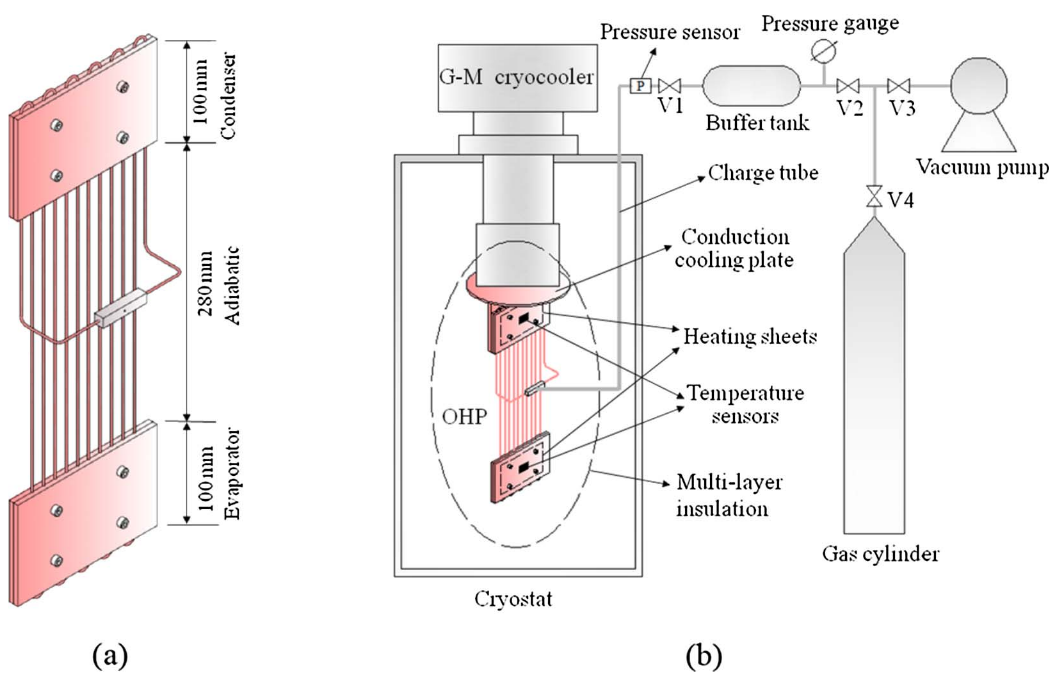


**Fig. 1.** (a) The configuration of the cryogenic OHP and (b) schematic illustration of the experimental apparatus.

close loop. The condenser section is soldered in the grooves of the two copper blocks connecting the cold head of a single stage G-M cryocooler (RDK500B, Sumitomo Heavy Industries., Ltd.) through a conduction cooling plate. A heating sheet is attached on the conduction cooling plate to control the condenser temperature. The evaporator section is also soldered in the grooves of the two copper blocks with the same size, and a heating sheet is attached on the copper blocks to apply the heat load for the experiment. Two silicon diode sensors (DT-670 -SD, Lake Shore Cryogenics) are attached on the outer surfaces of the copper blocks to measure the temperature of the condenser and evaporator, respectively. The OHP assembly is wrapped with multi-layer insulation, and placed in a cryostat. A long stainless steel pipe connects the OHP with the working fluid charging system outside the cryostat and a pressure sensor is installed in the tube to monitor the pressure of the OHP.

### 2.2. *Experimental procedures*

Before the experiments, with the valve V1 open, V2 open, V3 open and V4 closed, the atmosphere in the OHP, charge tube, and the buffer tank is evacuated by a mechanical vacuum pump. After that, with all the valves closed, the OHP is cooled down with the G-M cryocooler, and the temperature of the condenser section is controlled with the heating sheet. When the condenser section is cooled down to the preset temperature, the charge procedure starts. First, with the valve V1 closed, V2 open, V3 closed, V4 open, the neon gas as the working fluid is filled into the buffer tank from the gas cylinder and the pressure $P_{0i}$ of the buffer tank is measured by the pressure gauge. Then, with the valve V2