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Investigation on the temperature dependence of filling ratio in cryogenic pulsating heat pipes

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ABSTRACT

The pulsating heat pipe (PHP) is an efficient two-phase heat transfer device. Its heat transfer performance and internal working fluid flow patterns are affected by a variety of parameters. The filling ratio (FR) is one of the most important parameters, and it is usually regarded as a temperature-independent constant during the operation of the PHP. In this study, the fact that the FR is temperature dependent is pointed out, recognizing that the specific volumes of the liquid working fluid and vapor working fluid change with temperature. FR lines on a *T-v* diagram are used to analyze the trend of the FR with temperature. Also the influence of the variation of the FR on the heat transfer performance is discussed with the experimental data obtained from a hydrogen-filled PHP and a helium-filled PHP. For a cryogenic PHP, the optimal FR is close to the critical FR, and different initial FRs cause the PHP to either reach a dry-out limit or reach a liquid convection limit. Moreover, the temperature dependence of the FR for room temperature fluids can be ignored.

1. Introduction

The pulsating heat pipe (PHP) is a structurally simple heat transfer device. It is made of a smooth tube, whose inner diameter is small enough so that the surface tension forces of the working fluid dominate over gravitational forces, and is bent in a serpentine shape to form either a closed loop PHP (CLPHP) or an open loop PHP (OLPHP). Depending on whether the check valve is used, the PHP can be divided into valve and valveless type. The structure of a valveless CLPHP is shown in Fig. 1. Similar to other types of heat pipes, the PHP is composed of the evaporator section, the adiabatic section and the condenser section, and needs to be filled with a certain amount of liquid working fluid before operation. A distinctive feature of the PHP is that it does not need any wick structure inside the tube. Above a certain heat flux, the internal working fluid will produce reciprocating oscillatory motion, resulting in an efficient heat transfer between the evaporator section and the condenser section. Because of its simple structure, flexible arrangement and high performance, the PHP is finding use in battery thermal management systems [1,2], power electronic systems [3,4], heat recovery [5,6], and HTS magnets [7].

There are many physical parameters affecting the heat transfer performance and flow patterns of the PHP, and the filling ratio (FR) is one of the most important parameters. Most of the heat is transferred by the liquid's sensible heat [8] and the driven force of the oscillation comes mainly from the formation and collapse of vapor bubbles. Low FR corresponds to less sensible heat hindering the thermal performance, and high FR corresponds to less latent heat which is the energy required to form vapor bubbles and to drive the fluid. Therefore an optimal FR should exist at which the PHP has a minimum thermal resistance (or maximum effective thermal conductivity) [9].

Many researchers have studied the effect of the FR in room temperature [10,11] and low temperature [12–15] versions. Liu et al. [16] studied the heat transfer performance and flow characteristics of an ethanol-filled PHP with the FR ranging from 10% to 100%. They pointed out that when the FR was between about 20% and 50% the thermal resistance was clearly lower than that when it was 100% full. On the contrary, the heat transfer limit increased with the increase of the FR. Meanwhile, visualization experiments showed that with the increase of the FR, it became easier to remain the flow as slug flow and more difficult to transform into annular

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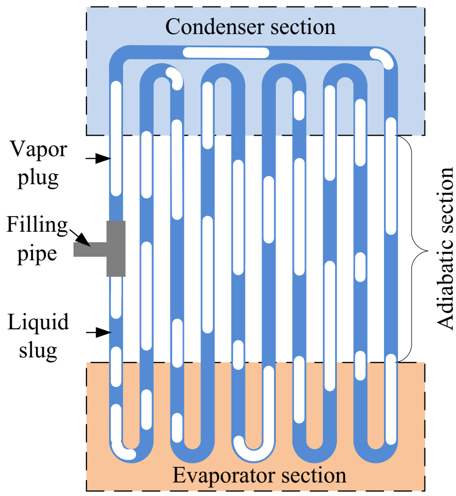

Fig. 1. Schamatic structure of a valveless CLPHP.

flow. Wang et al. [17] investigated the heat transfer performance of acetone-filled and ethanol-filled CLPHPs with FRs of 35%, 53% and 70%. In the stable operation range, the better thermal performance occurred at a lower FR in the acetone-filled PHP while the better thermal performance occurred at a higher FR in the ethanol-filled PHP. Gamit et al. [18] reported the heat transfer performance of a water-filled PHP with FRs of 40%, 50%, and 60%. For the same heat input values, the system performed better with a lower FR and it took a longer time to reach steady state as the FR increased. Wang and Jia [19] proposed a non-dimensional correlation considering FR to predict the thermal resistance of PHP, the calculated results agreed well with the experimental results with the average relative error within 25% when the FR was 85.17%. Fonseca et al. [20] investigated a horizontally oriented helium PHP with FRs in the range of 12–26%, and reported that the effective thermal conductivity was optimum at a FR = 25.35%. Our group [21] described the thermal performance of a hydrogen-filled PHP with FRs of 35%, 51%, and 70% at different levels of heat input. The thermal performance of the PHP when the FR = 35% was better than that with the other two FRs, while the largest heat transfer limit occurred when the FR = 70%. Liang et al. [22] studied the neon PHP, they reported that in the case of FR = 43.1% and 51.5%, the effective thermal conductivity increased as the heat load increased, but in the case of FR = 15.3%, 22.1%, 28.9% and 35.9%, the effective thermal conductivity firstly increased and then decreased with increasing heat load. Xu et al. [13] found that the helium-filled PHP possessed the optimal FR which could make the maximum effective thermal conductivity. Furthermore, the optimal FR changed with the heat load. In addition, many researchers report that an optimal FR exists in a given PHP [10,23,24]. However, the results obtained by different researchers are not the same. One of the reasons for this disagreement may be that the researchers usually regard the FR as a constant, and ignore the fact that the FR changes with temperature. In this study, The temperature dependence of the FR is explained based on the mathematical definition of the FR and *T-v* diagram, and its effect on the heat transfer performance is analyzed with experimental data in cryogenic field.

2. Methods

The FR of the PHP is defined as the ratio of the liquid working fluid volume to the total PHP volume:

$$\mathrm{FR} = \frac{V_l}{V_\mathrm{t}} \times 100\% \tag{1}$$

After completing the filling process, the total mass of the working fluid is the sum of the mass of the liquid and the vapor working fluid:

$$m_\mathrm{t} = m_l + m_\mathrm{v} \tag{2}$$

The total volume of the working fluid is the sum of the volume of the liquid and the vapor:

$$V_\mathrm{t} = V_l + V_\mathrm{v} \tag{3}$$

The mass and volume of each part are linked by their respective specific volumes.

$$m_\mathrm{t} = \frac{V_\mathrm{t}}{\upsilon_\mathrm{t}} \tag{4}$$

$$m_l = \frac{V_l}{\upsilon_l} \tag{5}$$

$$m_\mathrm{v} = \frac{V_\mathrm{v}}{\upsilon_\mathrm{v}} \tag{6}$$

Substituting Eqs. (1) and (3)–(6) into Eq. (2), we obtain

$$\frac{1}{\upsilon_\mathrm{t}} = \mathrm{FR}\left(\frac{1}{\upsilon_l} - \frac{1}{\upsilon_\mathrm{v}}\right) + \frac{1}{\upsilon_\mathrm{v}} \tag{7}$$

The meaning of each symbol and subscript is shown in Table 1.

After completing the filling process, the total volume of the PHP (V_t,) and the total mass of the working fluid (m_t) are known and remain unchanged. The total specific volume (υ_t) can be calculated by Eq. (4). Assuming that the liquid and vapor are in saturated states, the corresponding specific volumes υ_l and υ_v can be obtained from the filling temperature, and the FR can subsequently be calculated by Eq. (7). During the operation of the PHP, υ_l and υ_v change with temperature. Consequently, the FR will also change with temperature. To establish the standard for analysis, we define the initial filling ratio (FR_0) as the FR realized when the filling process is finished and the heat load is 0 W.

3. Analysis

Nitrogen is used as an example cryogenic working fluid with different values of FR_0 determined at 77 K, and the corresponding FRs at various other temperatures are calculated. The temperature dependence of the FR is shown in Fig. 2. Curve ‘a’ represents the nitrogen-filled PHP with FR_0 = 20%@77 K. As the operating temperature gradually increases from 77 K, the FR decreases gradually until the FR = 0% at about 123 K, where the PHP is completely dried out. Curve ‘b’ represents the nitrogen-filled PHP with FR_0 = 70% @77 K. As the operating temperature increases from 77 K to 116 K, the FR gradually increases until the FR = 100% at about 116 K, when the PHP is filled with saturated liquid nitrogen. It can be seen

Table 1
Nomenclature.

Symbol	Physical meaning (unit)	Subscript	Meaning
A	Cross-sectional area (m^2)	amb	Ambient
FR	Filling ratio (–)	BT	Buffer tank
k	Thermal conductivity (W/m K)	crit	Critical
L	Effective length (m)	eff	Effective
m	Mass (kg)	f	Final
P	Pressure (Pa)	FP	Filling pipe
Q	Heat load (W)	l	Liquid
V	Volume (m^3)	t	Total
v	Specific volume (m^3/kg)	tri	Triple point
T	Temperature (K)	v	Vapor
ΔT	Temperature difference (K)	0	Initial