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Operational limit of closed loop pulsating heat pipes

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Abstract

This paper presents an experimental study on the operational limitation of closed loop pulsating heat pipes (CLPHPs), which consist of a total of 40 copper tubes with 1 mm and 2 mm inner diameter, respectively. R123 was employed as the working fluid with filling ratios of 30%, 50% and 70%, respectively. Three operational orientations were investigated, viz. vertical bottom heated, horizontal heated and vertical top heated orientations. The effects of inner diameter, operational orientation, filling ratio and heat input flux on thermal performance and performance limitation were investigated. The results show that for the CLPHP with 2 mm ID tubes the best performance existed in the vertical orientation with heating at the bottom, while for the CLPHP with 1 mm ID tubes, orientation played almost no role. A filling ratio of 50% was optimum for both CLPHPs to obtain best performances in all orientations. The CLPHPs were operated till a performance limit characterized by serious evaporator overheating (dry-out) occurred. Rather high heat loads could be accommodated. Dry-out heat fluxes in the vertical bottom heat mode were about 1242 W/cm^2 (1 mm ID) and 430 W/cm^2 (2 mm ID) for axial heat transport, and about 32 W/cm^2 (1 mm ID) and 24 W/cm^2 (2 mm ID) for radial heat input, always with respect to the inner tube diameter.

Keywords: Closed loop pulsating heat pipes; Performance limit; Dry-out

1. Introduction

Pulsating heat pipes (PHPs) or oscillating heat pipes (OHPs) are relatively young members in the family of heat pipes. They have been introduced by Akachi in the 1990s [1,2] and can be divided into 3 groups: (a) closed loop PHP without check valve (CLPHP), also called open end PHP (OEPHP); (b) CLPHP with check valves; (c) open loop PHP (OLPHP), also called closed end PHP (CEPHP), see Fig. 1.

It is well known that there are various limitations of the performance of heat pipes [3,4], e.g. capillary limit, boiling limit, entrainment limit, sonic limit, viscous limit. With regard to cooling electronic devices, the capillary and boiling limits are in general the most important ones. In both cases the limit will manifest itself by an unacceptable overheating of the evaporator due to lack of cooling working fluid (dry-out, burn-out). While quite some research has been performed on the operational behavior and physical phenomena in PHPs, including various experimental studies [5–12] and attempts of mathematical modeling [13–18], rather limited knowledge exists on the ultimate performance or performance limits of PHPs [19–22]. Owing to their wickless structure, PHPs will not be subjected to the capillary limit, though the boiling limit might occur. Miyazaki and Akachi [19] experimentally studied a CLPHP with check valves, which comprised of a total of 28 copper tubes with 2 mm ID. The working fluid was R134a and the filling ratio was approximately 50%. The set-up could operate in all heat modes. They confirmed the existence of dry-out due to insufficient amplitude of oscillatory flow and demonstrated that the installation of check valves is an effective countermeasure to this problem. Maezawa et al. [20] tested an OLPHP, which comprised of a total of 40 copper tubes with 1 mm ID. The working fluid was R142b and the filling

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Nomenclature

A	area (m^2)
d	diameter (m)
FR	filling ratio (V_{liq}/V_{tot})
g	gravitational acceleration (9.81 m/s^2)
l	length (m)
n	number of tubes
P	electrical power (W)
Q	heat load (W)
q	heat flux (W/m^2)
R	thermal resistance (°C/W); radius (m)
T	temperature (°C)
t	time (s)

Greek symbols

Ψ	efficiency of thermal insulation
ρ	density (kg/m^3)
σ	surface tension (N/m)

Subscripts

ax	axial
c	condenser
crit	critical
e	evaporator
i	inner
liq	liquid
loss	heat loss
max	maximum
m	mean
min	minimum
o	outer
rad	radial
sys	system
tot	total
vap	vapour

Abbreviations

CEPHP	closed end pulsating heat pipe
CLPHP	closed loop pulsating heat pipe
ID	inner diameter
OD	outer diameter
OEPHP	open end pulsating heat pipe
OHP	oscillating heat pipe
OLPHP	open loop pulsating heat pipe
PHP	pulsating heat pipe

ratio was varied among 30%, 50% and 70%. Their set-up could operate both in the bottom and horizontal heat modes, but could not operate in the top heat mode. They found that the OLPHP with 50% filling ratio showed a better thermal performance and a higher performance limit, while the OLPHP with 30% and 70% filling ratios experienced a dry-out at lower thermal performances. Katpradit et al. [21] performed a visual study on two OLPHPs, which consisted of 10 Pyrex glass tubes with inner diameters of 1 mm and 2 mm, respectively. R123 was used as the working fluid with a filling ratio of 50%. Their set-up could only operate in the bottom heat mode. Various flow patterns and their transitions were observed, such as slug flow, churn flow and annular flow. They concluded that the major cause of dry-out was flooding at the entrance of the evaporator section. In the OLPHP with the smaller

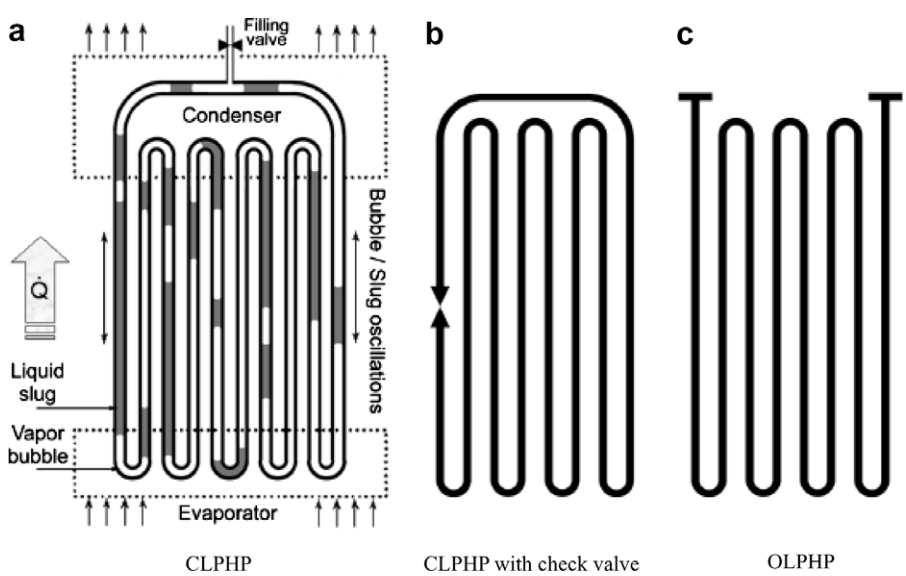


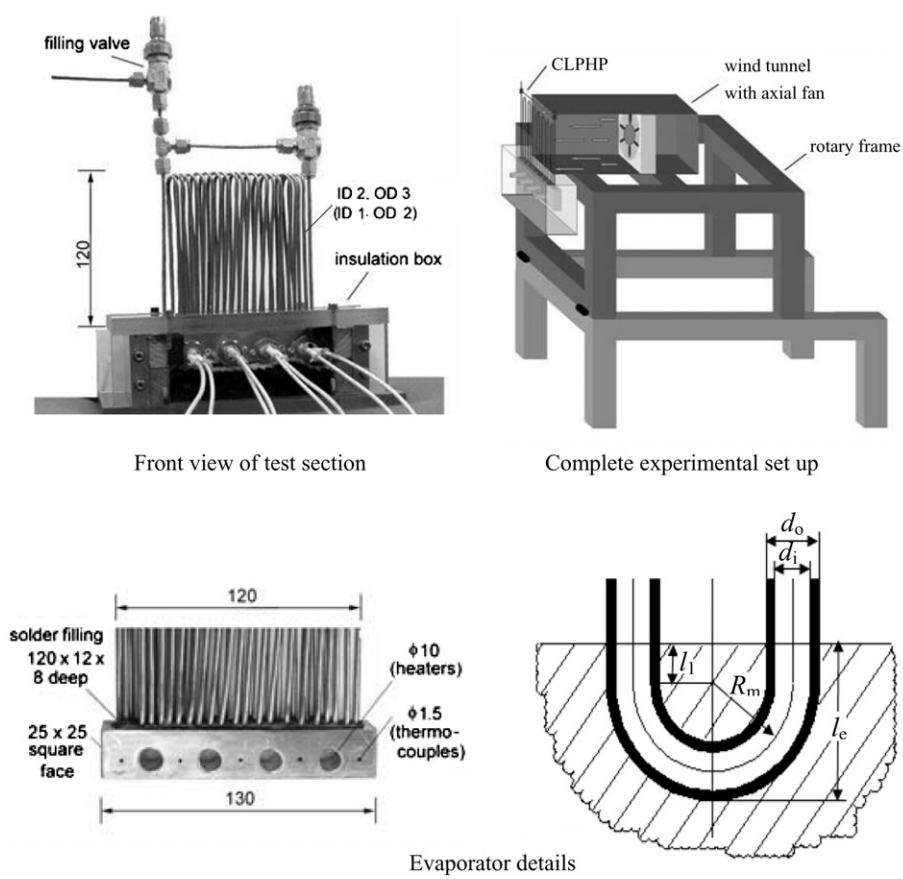
Fig. 1. Schematic of PHPs: (a) CLPHP; (b) CLPHP with check valve; (c) OLPHP.

inner diameter, flooding occurs in annular flow resulting in a lower performance limit, while in the OLPHP with the bigger ID, the flow pattern changed from annular flow to churn flow, causing a higher performance limit. In a recent paper [22], Katpradit et al. presented two correlations based on experimental data of OLPHPs having 5, 10 and 15 turns of copper tubes with 2.03, 1.06 and 0.66 mm ID, respectively. The working fluids were R123, ethanol and water with a filling ratio of 50%.

As above mentioned, there are only few studies considering performance limits of PHPs. This is especially true for CLPHPs without check valve, which have been confirmed to be more advantageous than OLPHPs and CLPHPs with check valves [2,10,23–25]. Therefore the present paper is mainly focused on the performance limit of CLPHPs without check valve.

2. Experimental set-up and procedure

The experimental set-up comprises the test specimen with instrumentation which is fixed on a rotary frame (see Fig. 2) plus equipment for heating and cooling of the specimen and a PC data acquisition system. The CLPHP was formed from 40 copper tubes with an inner diameter of 2 mm and 1 mm, respectively. In the temperature range from 40 °C to 160 °C these diameters are greater ($d_i = 2$ mm) and smaller ($d_i = 1$ mm), respectively, than the so-called critical diameter ($d_{crit} \leqslant 2\sqrt{\sigma/g(\rho_{liq} - \rho_{vap})}$), which reduces from about 2 mm at 40 °C to about 1 mm at 160 °C for R123 filled PHPs, as shown in Fig. 3. The U-turns at one end are embedded into an evaporator block. The remaining part of the CLPHP is cooled by forced air



	n	l_e (mm)	l_1 (mm)	d_i (mm)	d_o (mm)	R_m (mm)	A_{ax} (mm^2)	A_{rad} (mm^2)
CLPHP 1	40	8	2	1	2	5	31.4	1238.3
CLPHP 2	40	8	2	2	3	4.5	125.6	2279.2

$$A_{ax} = n\frac{\pi \cdot d_i^2}{4}; A_{rad} = n \cdot \pi \cdot d_i\left(l_1 + \frac{1}{2}\pi \cdot R_m\right)$$

Fig. 2. Schematic of experimental set-up and photo of test section (dimensions in mm).

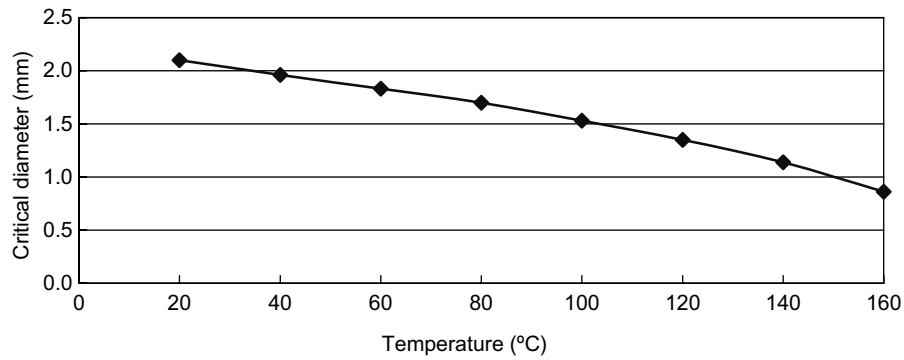


Fig. 3. Variation of critical diameter with temperature for R123 filled PHPs.

cooling (standard axial fan, AC 230 V, capacity 190 m^3/h, arranged in a wind tunnel of size $120 \times 120 \times 38$ mm^3). Average air velocity was 5 m/s with ambient air temperature 27 °C ± 1.5 °C. The evaporator block, which was made of copper, has the size $130 \times 25 \times 25$ mm^3. To accommodate the U-turns of the CLPHP, a preformed cavity with the size $120 \times 12 \times 8$ mm^3 was machined into the copper block. After vertically locating the CLPHP U-turns into this cavity, a tin based solder alloy was poured in and allowed to solidify. Four holes were laterally drilled into this copper block to accommodate four cylindrical cartridge AC heaters (∅10.0×25 mm) by mechanical fit. Additionally, five holes were also laterally drilled halfway through to locate the thermocouples (K-Type, 0.5/1.5 mm ID/OD by Thermacoax®, accuracy ±0.5 °C after calibration) to measure the average temperature of the evaporator block. The evaporator block was then secured into a Makrolon® box to provide thermal insulation. The entire set-up was mounted on a rotary frame so that experiments could be performed in all orientations. R123 was employed as the working fluid, and its filling ratio varied among 30%, 50% and 70%.

During the experiments the heat input was stepwise increased, and then evaporator temperatures were recorded after the system had reached a new steady state. The procedure was repeated until the evaporator temperatures started to increase rapidly. This means dry-out occurred in the evaporator, and the performance limit of the CLPHP was reached. An example of average evaporator temperature varying with time is given in Fig. 4 for a CLPHP with 2 mm ID tubes in the three heat modes, respectively. The filling ratio is 50%.

There are some important data to evaluate the thermal performance of PHPs, such as heat load, heat flux, average evaporator temperature and thermal resistance.

The heat load is the thermal input to the CLPHP, and is determined as

$$Q = P - Q_{\text{loss}} \tag{1}$$

where P is the electrical power (measured by a digital multi-meter with an accuracy of ±1.5%), while Q_{loss} is the heat loss. During the experiments, the evaporator block was well insulated to reduce the heat loss from the evaporator to the ambient air. Q can be approximately calculated as

$$Q \approx \Psi P \tag{2}$$

where Ψ can be taken as 0.96 for all heat loads.

There are two heat fluxes, namely radial and axial heat fluxes, which are determined as

$$q_{\text{rad}} = Q/A_{\text{rad}} \tag{3}$$

$$q_{\text{ax}} = Q/A_{\text{ax}} \tag{4}$$

where A_{rad} and A_{ax} are radial and axial heat transfer areas with respect to the inner tube diameter. Their calculations are shown in detail in Fig. 2.

The thermal resistance for the overall system is defined as

$$R_{\text{sys}} = \Delta T_{\text{e-air}}/Q \tag{5}$$

$$\text{with } \Delta T_{\text{e-air}} = T_{\text{e}} - T_{\text{air}} \tag{6}$$

where T_{air} is the air temperature in the laboratory, which is kept at 27 °C ± 1.5 °C, while T_{e} is the average temperature of the evaporator block, calculated as

$$T_{\text{e}} = \frac{1}{5}\sum_{j=1}^{5} T_{\text{e},j} \tag{7}$$

3. Results and discussion

3.1. Effects of heat mode and inner diameter on performance limit

Fig. 5 shows the thermal performance of the CLPHP with 1 mm ID for the three heat modes. The filling ratio was 50%. From Fig. 5a, we find that all average evaporator temperatures increase about linearly with increasing heat input, then they increase rapidly near 380 W due to the occurrence of dry-out. This is true for all three heat modes. Also we find that the influence of gravity is a practically negligible; the maximum heat loads are 390 W for +90°, 380 W for 0° and 380 W for −90°, respectively (see also Table 1). From Fig. 5b, we find that all thermal resistances decrease with increasing heat load, till a minimum is reached

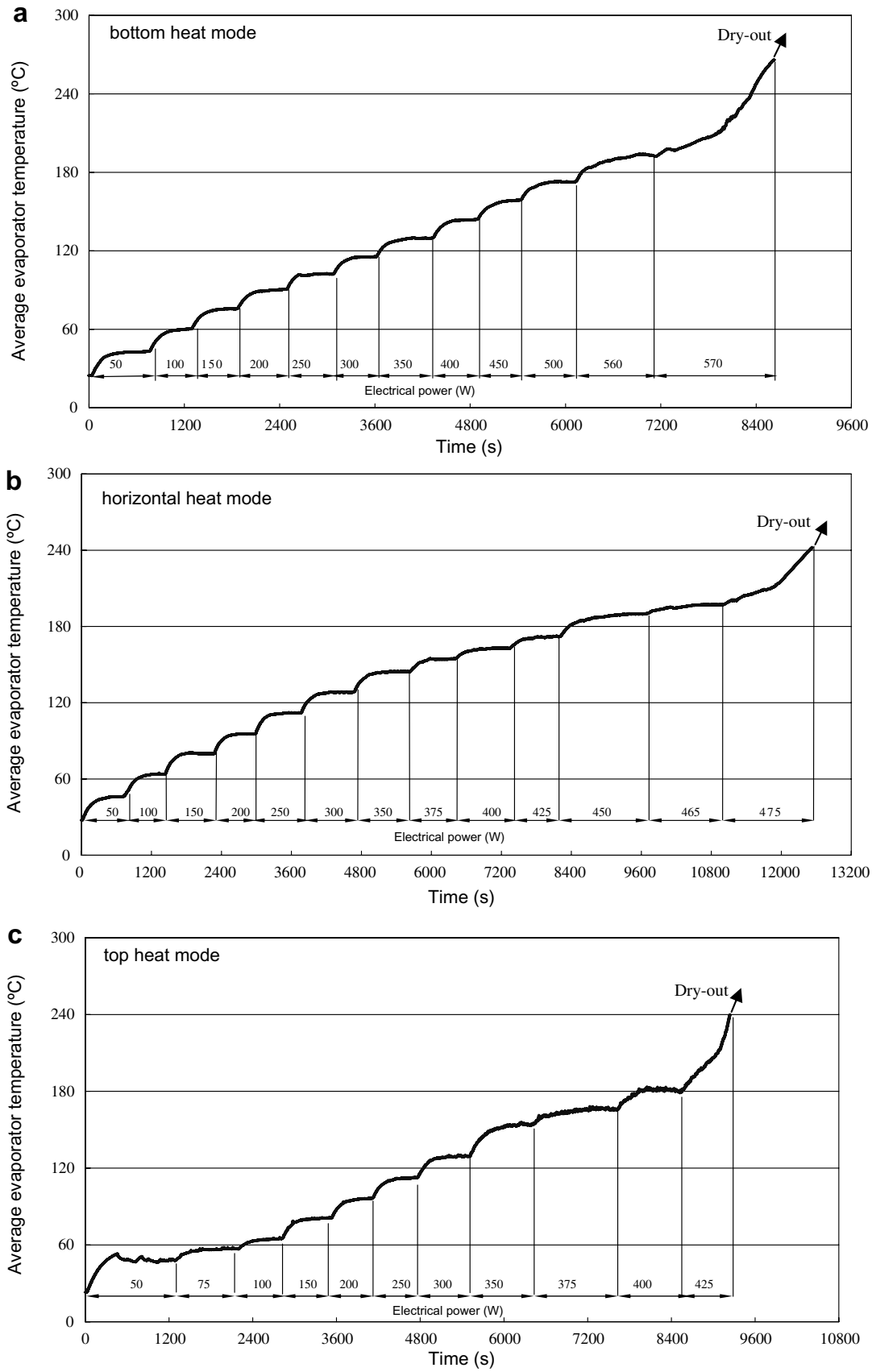


Fig. 4. Variation of average evaporator temperature with time for CLPHP 2 (2 mm ID, FR = 50%): (a) bottom heat mode; (b) horizontal heat mode; (c) top heat mode.

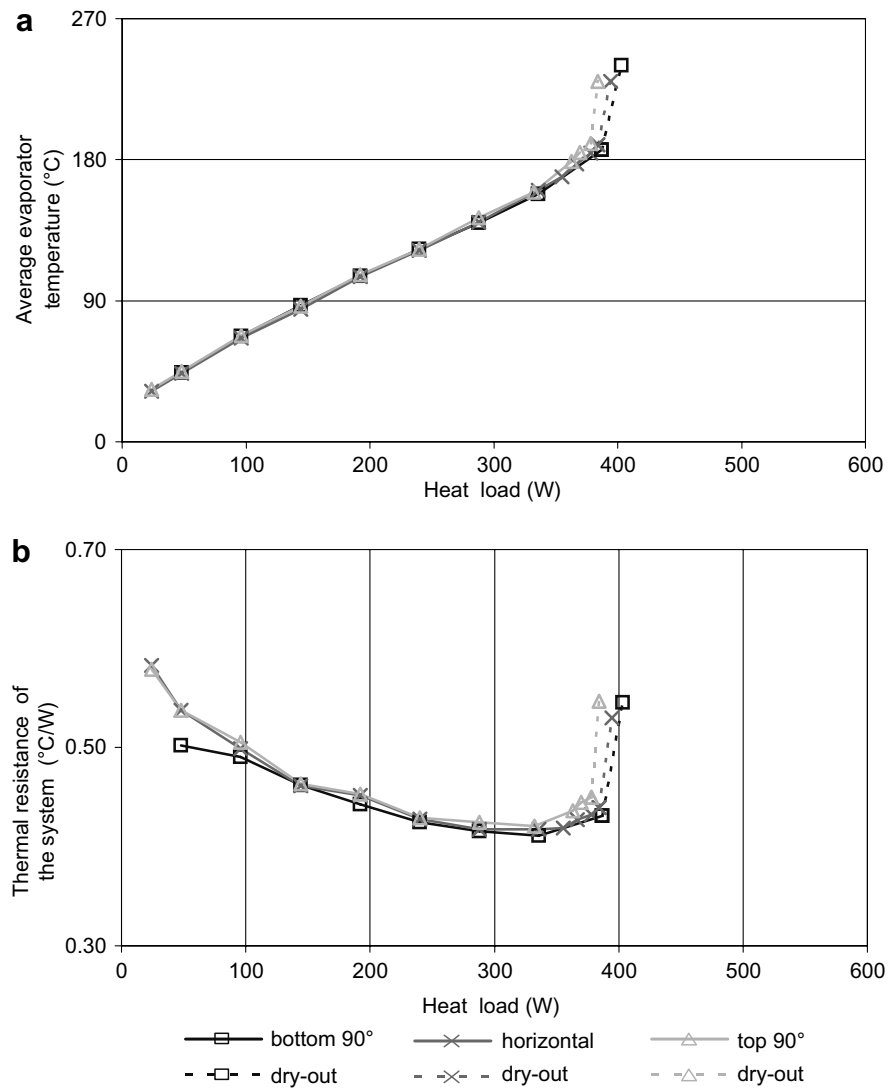


Fig. 5. Thermal performance of CLPHP 1 for three heat modes (ID/OD = 1 mm/2 mm; FR = 50%).

Table 1
Maximum heat loads and heat fluxes at dry-out limit for both CLPHPs (three heat modes; FR = 50%)

	ID = 1 mm			ID = 2 mm		
Heat mode	+90°	0°	−90°	+90°	0°	−90°
Q_{max} (W)	390	380	380	540	450	380
$q_{ax,max}$ (W/cm^2)	1242	1210	1210	430	358	303
$q_{rad,max}$ (W/cm^2)	31.5	30.7	30.7	23.7	19.7	16.7

Table 2
Minimum thermal resistance (°C/W) for both CLPHPs (three heat modes; FR = 50%)

Heat mode	ID = 1 mm	ID = 2 mm
+90°	0.42 (Q = 250–360 W)	0.32 (Q = 300–530 W)
0°	0.42 (Q = 250–360 W)	0.36 (Q = 250–400 W)
−90°	0.43 (Q = 250–350 W)	0.38 (Q = 200–300 W)

(≈0.42 °C/W) at about 330 W. Then the thermal resistances increase again, especially sharply at 380 W (dry-out). Thermal performance data (Q_{max}, $q_{ax,max}$, $q_{rad,max}$ and $R_{sys,min}$) are summarized in Tables 1 and 2 for both CLPHPs for a filling ratio of 50% and all three heat modes.

Fig. 6 shows the thermal performance of the CLPHP with 2 mm ID for the three heat modes. The filling ratio was 50%. A similar tendency as in Fig. 5 can be observed. However, considerable performance differences are found for the different heat modes, which means that the thermal performance is clearly influenced by gravity. Performance limits are about 540 W for +90°, 450 W for 0° and 380 W for −90°, respectively (see also Table 1). From Figs. 5 and 6, we find that the effect of operational orientation (i.e. gravity) becomes relatively small or even insignificant with decreasing inner tube diameter. This is because surface tension dominates the fluid flow in the smaller tube.

Considering the occurrence of dry-out, a tentative explanation is: under normal operation, slug flow is the prevail-

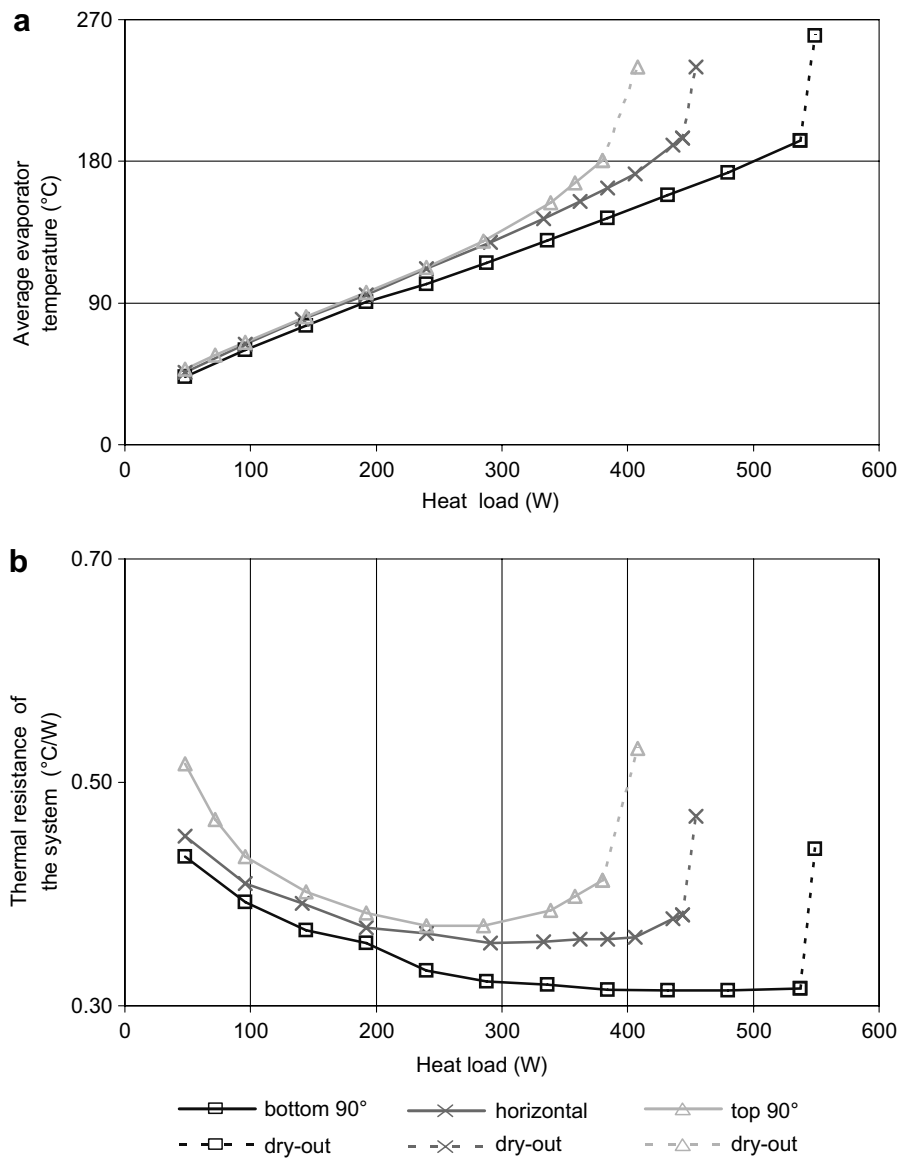


Fig. 6. Thermal performance of CLPHP 2 for three heat modes (ID/OD = 2 mm/3 mm; FR = 50%).

ing flow pattern in the CLPHP, and bubble pumping action is most efficient. Therefore the working fluid oscillations efficiently transport heat from the evaporator to the condenser. As the heat flux increases, both the evaporator temperature and, more importantly, the fluid temperature increase gradually, causing a decrease of surface tension and latent heat. Thus more vapor has to be generated, resulting in a faster vapor flow. Gradually the flow regime changes from slug flow to churn or annular flow, resulting in a liquid film in the evaporator, which gets thinner and thinner; at last dry spots and ultimately a stable dry-out occur.

3.2. Effect of filling ratio on performance limit

Fig. 7 depicts the thermal performance of the CLPHP with 1 mm ID tubes for the horizontal heat mode with the filling ratios 30%, 50% and 70%, respectively. For FR = 50% the CLPHP shows the maximum performance limit and the lowest thermal resistance. This is true for all three heat modes. In the case of FR = 30%, dry-out occurs at a very low heat input (about 120 W), with a low evaporator temperature of only about 90 °C. A reasonable explanation is that for FR = 30% the total liquid inventory in the CLPHP is too small, resulting in insufficient liquid slugs, thereby flow pattern transition occurs already at lower heat loads.

Fig. 8 shows the thermal performance of the CLPHP with 2 mm ID tubes for the horizontal heat mode with the filling ratios 30%, 50% and 70%, respectively. Similar trends are found as in Fig. 7. However, two differences are evident. The first one is that when dry-out occurs in the case of FR = 30%, the CLPHP with 2 mm ID tubes reaches a maximum heat load of about 380 W with the

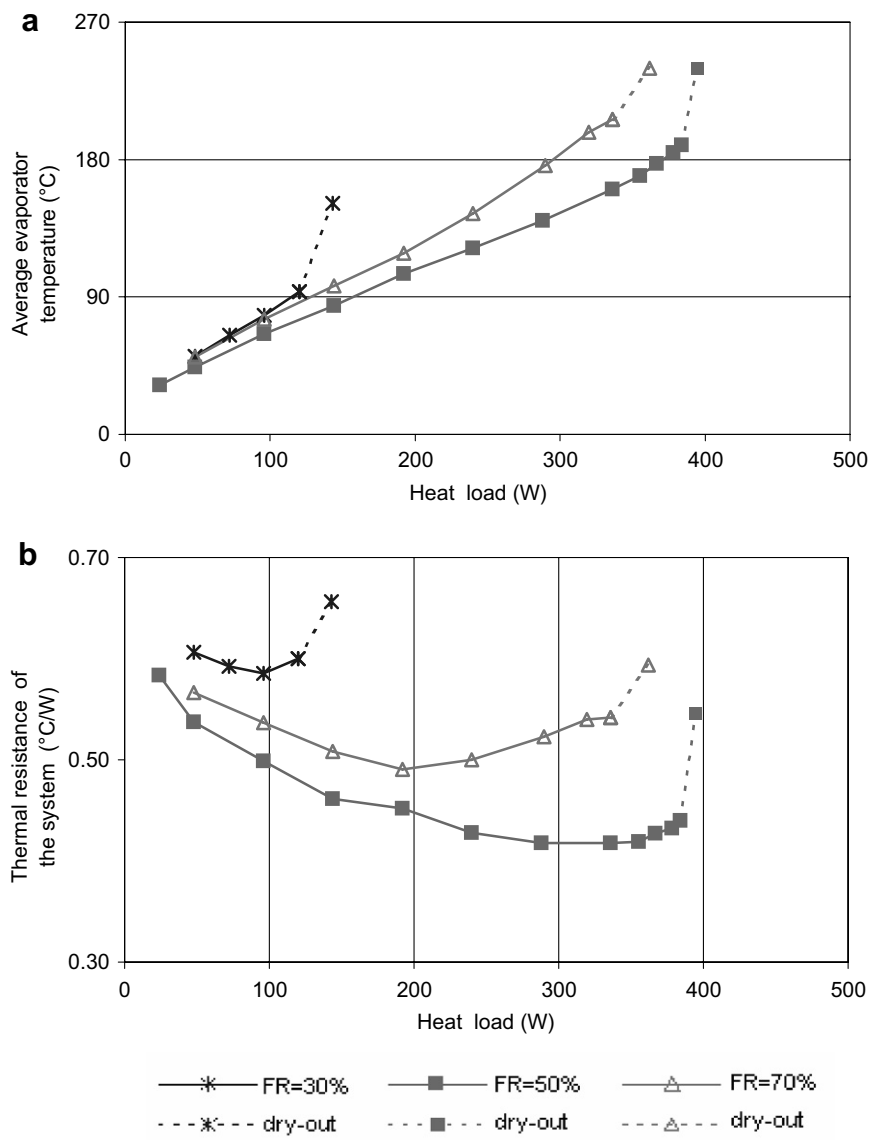


Fig. 7. Thermal performance of CLPHP 1 for three filling ratios (ID/OD = 1 mm/2 mm; horizontal heat mode).

evaporator temperature of about 165 °C. These data are significantly higher than those of the CLPHP with 1 mm ID tubes for the same filling ratio. A reasonable explanation is that the total liquid inventory in the CLPHP with 2 mm ID tubes is considerably higher (about 4 times) than that in the CLPHP with 1 mm ID tubes. The second difference is that performance differences due to the different filling ratios are much smaller in the CLPHP with 2 mm ID tubes than in the CLPHP with 1 mm ID tubes.

In Tables 3 and 4, thermal performance data (Q_{max}, $q_{ax,max}$, $q_{rad,max}$ and $R_{sys,min}$) are summarized for both CLPHPs in the horizontal heat mode with the filling ratios 30%, 50% and 70%, respectively. Figs. 9 and 10 depict the maximum heat loads at dry-out limit and the minimum thermal resistances of the CLPHPs versus the filling ratio, respectively. Again it is clearly shown that FR = 50% is optimum for both CLPHPs.

4. Summary and conclusions

An experimental study was performed on two closed loop pulsating heat pipes (CLPHPs) to investigate the effects of inner diameter, filling ratio, operational orientation and heat load on thermal performance and occurrence of performance limitation in the form of evaporator dry-out. The major results are:

- Both CLPHPs with 1 mm or 2 mm inner diameter operated successfully in all three heat modes and showed excellent performances. The CLPHP with 2 mm ID tubes had a lower thermal resistance (by about 10%). Concerning the specific performance data, the CLPHP with 1 mm ID tubes achieved much higher dry-out heat fluxes, which are about 1242 W/cm^2 and 32 W/cm^2 for axial and radial heat fluxes, respectively, while the

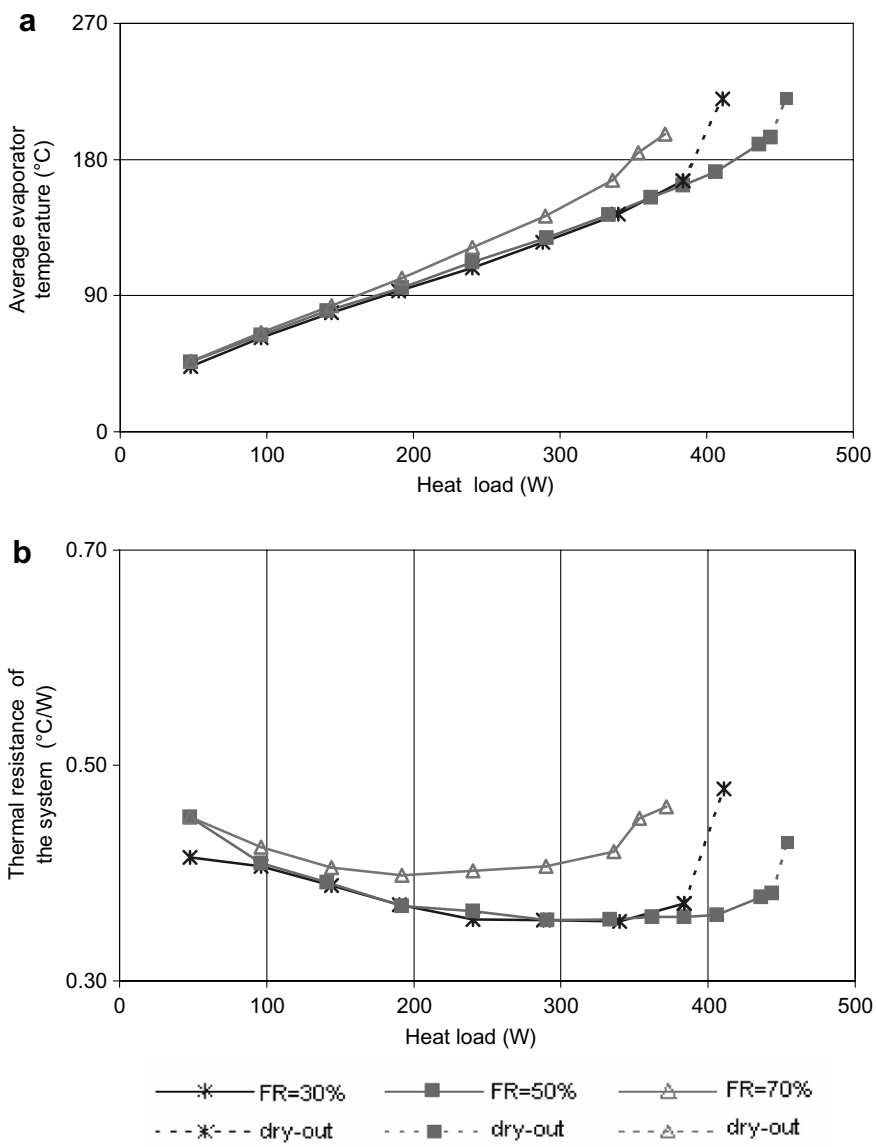


Fig. 8. Thermal performance of CLPHP 2 for three filling ratios (ID/OD = 2 mm/3 mm; horizontal heat mode).

Table 3
Maximum heat loads and heat fluxes at dry-out limit for both CLPHPs (horizontal heat mode; FR = 30%, 50%, 70%)

	ID = 1 mm			ID = 2 mm		
Filling ratio (%)	30	50	70	30	50	70
Q_{max} (W)	120	380	330	380	450	370
$q_{ax,max}$ (W/cm^2)	382	1210	1051	303	358	295
$q_{rad,max}$ (W/cm^2)	9.7	30.7	26.6	16.7	19.7	16.2

Table 4
Minimum thermal resistance (°C/W) for both CLPHPs (horizontal heat mode; FR = 30%, 50%, 70%)

Filling ratio (%)	ID = 1 mm	ID = 2 mm
30	0.59 (Q = 75–110 W)	0.36 (Q = 230–350 W)
50	0.42 (Q = 250–360 W)	0.36 (Q = 250–400 W)
70	0.50 (Q = 150–250 W)	0.41 (Q = 120–300 W)

CLPHP with 2 mm ID tubes achieved about 430 W/cm^2 and 24 W/cm^2 for axial and radial heat fluxes, respectively.

- In general, the CLPHPs obtain the best thermal performance and maximum performance limitation when they operate in the vertical bottom heat mode with 50% filling ratio. As the inner diameter decreases, performance differences due to the different heat modes (i.e. the effect of gravity) become relatively small and even insignificant, as can be seen for the CLPHP with 1 mm ID tubes.

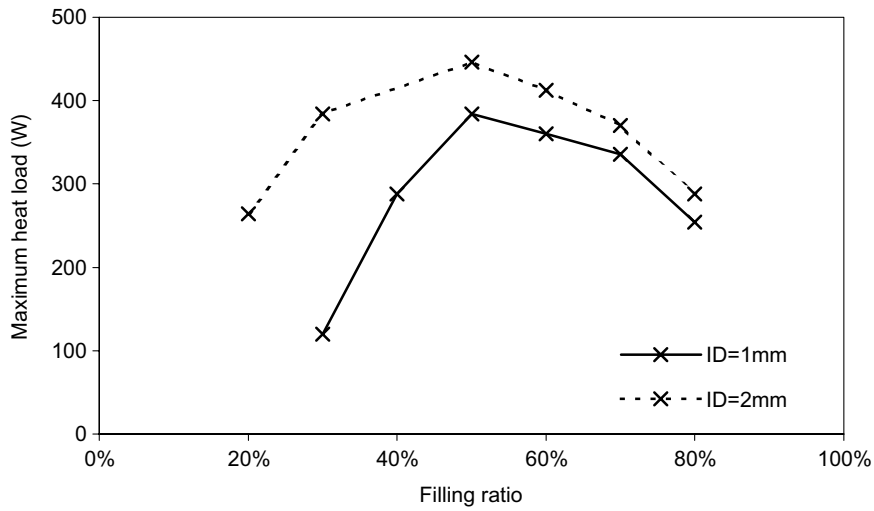


Fig. 9. Maximum heat load at dry-out limit versus filling ratio (horizontal heat mode).

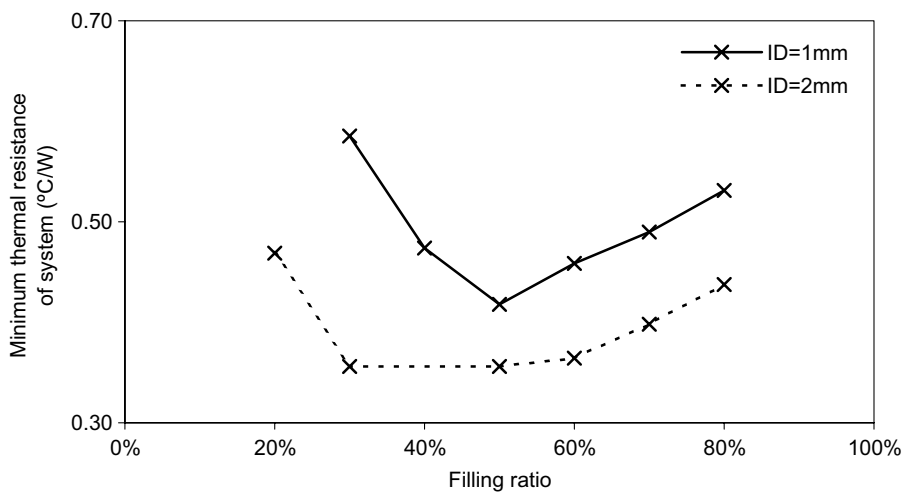


Fig. 10. Minimum thermal resistance of system versus filling ratio (horizontal heat mode, air cooling with 5 m/s).

Acknowledgements

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