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RESEARCH ARTICLE

Experimental Study of a Closed Loop Pulsating Heat Pipe Aiming at Assessing the Optimized Operational Conditions

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Abstract
In recent times pulsating heat pipes turn into a pleasing field of study for researchers as useful devices to enhance and intensify heat transfer. Experimental data under various operating conditions for a better theoretical understanding are needed. This paper presents an experimental study on a closed loop pulsating heat pipe made of copper with 14 U-turns. The experiments were carried out for different working fluids (acetone, distilled water, ethanol and methanol) and their mixing, heat input, filling ratio and evacuation levels to optimize operational conditions. Thermal resistance at steady state specified for performance evaluation and showed better results for acetone. The mentioned working fluids in filling ratio of 60 % have better operation and acetone has the best. As well as experiments in different evacuation levels showed, more evacuation lead to more performance.

Keywords
Pulsating heat pipe, heat exchanger, filling ratio, Vacuum, Dry-out

1 Introduction

Heat pipes are occasionally referred to as thermal superconductors because of their remarkably high effective thermal conductivity that is considerably higher than every metal [1]. In the 1990s Akachi introduced alternative special category of heat pipes, named pulsating or oscillating heat pipes (PHPs) [2]. Fabrication of the compound wick structure of conventional heat pipes is the most cost-intensive factor and PHPs are cheaper than wicked heat pipes. Whilst up to date, there is no complete theoretical understanding about operational characteristics of PHPs many applications such as electronics thermal management [3] as shown in Fig. 1, solar energy and thermal desalination [4], intensified unit operations, especially in reactors [1], or generally as high performance heat transfer devices obtained. Another possible application of such PHP structures could be in the terrestrial and space applications [3].

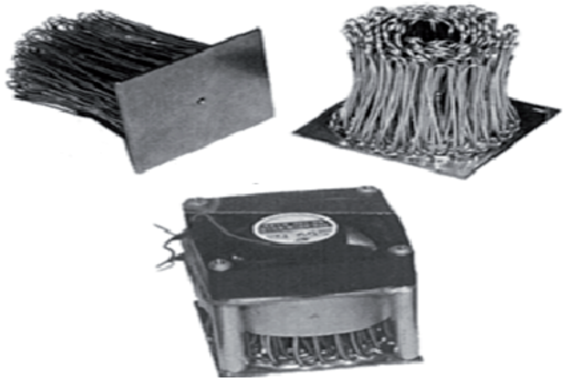

Fig. 1 Application of CLPHP in electronic devices with blower

The limitation of conventional models in microelectronics caused more attention to PHPs. The main structure of a typical pulsating heat pipe consists of bending capillary tubes having no internal wick structure. It can be designed in at least three ways [5]: (a) closed loop pulsating heat pipe (CLPHP) system, (b) closed loop with check valve and (c) open loop system, as shown in Fig. 2. Heat pipes have several limitations of the performance, for example, boiling limit, capillary limit, entrainment limit, viscous limit and sonic limit. Concerning cooling

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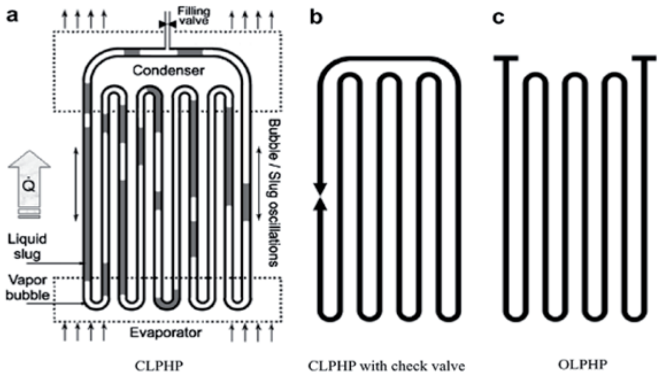
electronic devices, the capillary and boiling limits are generally the most important ones. In both cases the limit will display itself by overheating of the evaporator in consequence of the shortage of cooling working fluid (dry-out point) [6]. However, different mathematical modeling and experimental investigations have been performed on the operational behavior of PHPs, but restricted knowledge exists on the performance limits of PHPs. Due to wickless structure, PHPs will not be exposed to the capillary limit, but the boiling limit could occur.



CLPHP

CLPHP with check valve

OLPHP

Fig. 2 Schematic of PHPs: (a) CLPHP, (b) CLPHP with check valve, (c) OLPHP [adopted from 6]

Honghai Yang et al. [6] investigated operational limit of a closed loop pulsating heat pipe, R123 was employed as the working fluid with filling ratios of 30 %, 50 % and 70 %. 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 and filling ratio of 50 %. In reference [6] some of previous old works on PHPs have been reviewed and new researches that specifically investigate limitation of a CLPHP have not found. For more information you can see [6]. According to the literature review, there are only few studies considering performance limits of PHPs especially for CLPHPs without check valve, which have been confirmed to be more advantageous than OLPHPs and CLPHPs with check valves [6]. Therefore the present paper is mainly focused on the performance limit of a CLPHP without check valve. The copper U-turns as Fig. 3 receives heat at one end and is cooled at the other by a fan. The producing and crashing bubbles perform as driving force for transporting the entrapped liquid slugs in PHP. This lead to heat transfer as a combination of the sensible and the latent heat transfer through liquid slugs and vapor bubbles, respectively [6]. Our experiments assess the effect of filling ratio, evacuation level, working fluid and mixing of them. Distilled water (DW), ethanol, methanol and acetone were employed as the working fluids, and filling ratios are 20 %, 40 %, 50 %, 60 % and 80 %. Evaluation of performance of working fluids mixing were done by mixing of each working fluid with DW at the optimized filling ratio that was 60 % and then experiments in different pressures continued for acetone to find out optimized condition.

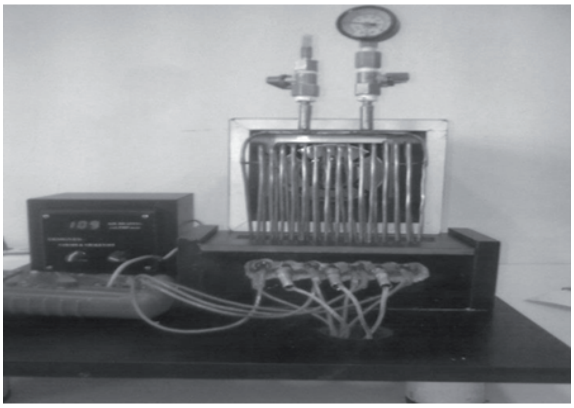


Fig. 3 Experimental set-up

2 Experimental set-up and procedure

The CLPHP was formed from 477 cm copper tubes that made 16 bends with an inner and outer diameter of 2 mm and 3 mm, respectively. This internal diameter should be smaller than critical diameter, which ensures that the physical behavior sticks to the pulsating mode. The critical diameter insurance that liquid slugs and vapor bubbles do not agglomerate causing phase separation, if the device is kept isothermally in a non-operating era. The formula is emanated from the critical Bond number criterion as Eq. (1), [1, 6].

$$D_c = 2\sqrt{\frac{\sigma}{g\left(\rho_{liq} - \rho_{vap}\right)}} \tag{1}$$

Maximum allowable set-up needed critical diameter for DW, methanol, ethanol and acetone comparing to manufactured set-up in filling temperature (26 °C) is shown in Fig. 4.

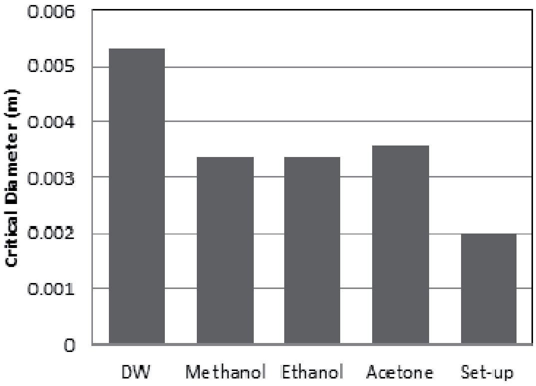


Fig. 4 Set-up diameter and critical diameter for working fluids

The U-turns at one end are set into an evaporator block. The remaining part of the CLPHP is cooled by forced air cooling by an axial fan, AC 230 V, 18W, capacity 190 m³/h, arranged in a wind tunnel of size 13·13·40 cm^3. Average air velocity was 4 m/s with ambient air temperature 26 °C ± 1 °C. The evaporator block, which was made of aluminium, has the size 15·4·4 cm^3. To accommodate the U-turns of the CLPHP, a preformed cavity with the size 14·2.5·1.6 cm^3 was machined into the aluminium block. After locating the CLPHP U-turns vertically into this cavity, a tin based solder alloy (lead and tin) was poured in and allowed to solidify. Four holes were laterally drilled into this aluminium block to accommodate four cylindrical cartridge AC heaters (100W, 230V, L = 4 cm, D = 1 cm) by mechanical fit. Additionally, three holes were also laterally drilled halfway through to locate the thermocouples (K-Type, OD = 5 mm, L = 4 cm) to measure the average temperature of the evaporator block. Thermocouples were coated with silicone powder for more accuracy. The evaporator block was then embedded in a wooden box filled with asbestos to provide thermal insulation. CLPHP evacuate till 0.2 bars by a vacuum pump and then working fluid is injected into. 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 sharply, this means dry-out occurred in the evaporator and the performance limit of the CLPHP was reached. Dry-out point is clearly specified in following figures by a sharp slope.

There are some important data to evaluate the thermal performance of PHPs, such as heat load, heat flux, average evaporator temperature and thermal resistance [6]. Here the thermal resistance is chosen which is defined as below:

$$R_{sys} = \frac{\Delta T_e}{Q} \tag{2}$$

With

$$\Delta T_e = T_e - T_a \tag{3}$$

Where T_a is the laboratory temperature and T_e is the average temperature of the evaporator block, calculated as:

$$T_e = \frac{1}{3}\sum_{k=0}^{3} T_{e,k} \tag{4}$$

Lower thermal resistance means better heat transfer, because it means lower T_e which indicate more heat transfer from the evaporator block.

3 Results and discussion

3.1 Effect of working fluid on evaporator temperature and thermal resistance

The variation of evaporator wall temperature and thermal resistance of the CLPHP for different working fluids at a pressure of 0.2 bars and a heat input of 50W to 220W with the filling ratios of 20 %, 40 %, 50 %, 60 % and 80 % are shown in Fig. 5 to Fig. 14, respectively. From the figures it can be seen that the evaporator wall temperature is higher in case of DW and lower in the case of acetone due to higher saturation temperature for DW and lower for acetone. This resulting in less vapor existence in the case of DW and more vapor plugs in the case of acetone while entering into the condenser and consequently further amount of heat will be released due to latent heat by acetone and cause the evaporator temperature increased less, but the dry-out point occurs soon for acetone because of lower saturation temperature that by determination of the proper filling ratio this obstacle could be solved. Meanwhile, lower surface tension of acetone comparing to others is a reason to consist of more liquid slugs leading to more pulsating mode. It is also observed that the system takes more time to reach the steady state in case of DW compared to acetone. Figure 15 shows that the CLPHP has the maximum performance limit and the lowest thermal resistance for FR = 60 %. Although FR = 80 % has similar behavior to FR = 60 %, but, FR = 60 % shows a little better trend, especially in power of 100 to 150 watts and could be cost effective than 80 %. It is worthwhile to mention that in low heat input, for example, in 50 to 100 watts the lower filling ratios have better performance and could be acceptable (Fig. 15). In the case of FR = 20 %, dry-out occurs at a very low heat input (about 175 W for acetone), with a low evaporator temperature of only about 98 °C. A reasonable explanation is that for FR = 20 % 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. Some articles showed that thermal resistance sharply decrease with increasing in heat input [6, 7] but here the thermal resistance almost decreases or remain constants with increasing in the heat input. This makes CLPHP mechanism a controversial field for researchers. The state-of-the-art emphasis a comprehensive theory of the complex thermo-hydrodynamic phenomena governing the operation of PHPs is not available yet.

3.2 Effect of working fluids mixing on performance

The variables of evaporator temperature and thermal resistance with the heat input for mixing of working fluids are shown in Fig. 16 and Fig. 17. DW with acetone, DW with Ethanol and DW with methanol in FR = 60 % were mixed with fifty present of each one by volume. From Fig. 16 it is clear that the mixture of DW with acetone has lower resistance but in comparison with pure acetone in FR = 60 % there is no outstanding difference in resistance and dry-out postponing to make working fluid combination as an optimization method. It seems that the pure working fluid in appropriate FR is suitable.

3.3 Effect of evacuation level on performance

Figure 18 and Fig. 19 show that the variation of evaporator temperature and thermal resistance with the heat input for acetone in an optimized filling ration that is 60 % under the different evacuation level. For making different evacuation levels the CLPHP was firstly evacuated till 0.2 bars and then by a regulating valve and a pressure gauge which are displayed in Fig. 3 desired pressures were set. From Fig. 19 it is clear that the more evacuation shows the lower values of thermal resistance compared to others. This shows that the heat transfer rate in the CLPHP has better performance and pulsating condition with more speed has properly worked. The progress of dry-out point in less evacuation level could be because of increasing in starting pulsating temperature and then inability of cooling fan for condensing of vapor which finally result to instability and reaching to dry-out point.

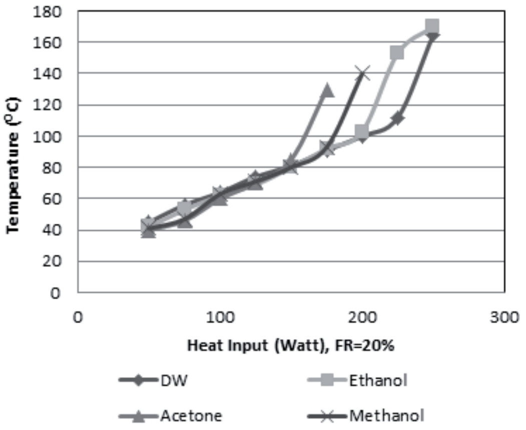


Fig. 5 Evaporator wall temperature vs. heat input for FR = 20 %

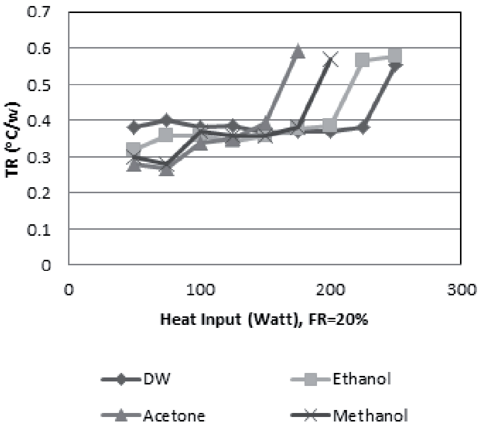


Fig. 6 Thermal resistance vs. heat input for FR = 20 %

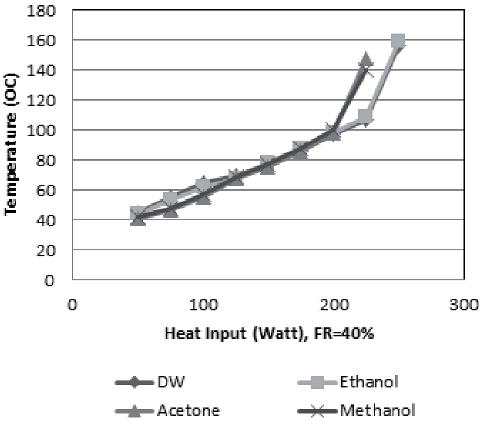


Fig. 7 Evaporator wall temperature vs. heat input for FR = 40 %

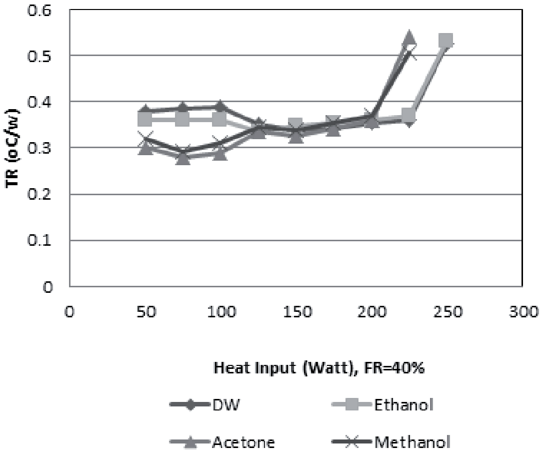


Fig. 8 Thermal resistance vs. heat input for FR = 40 %

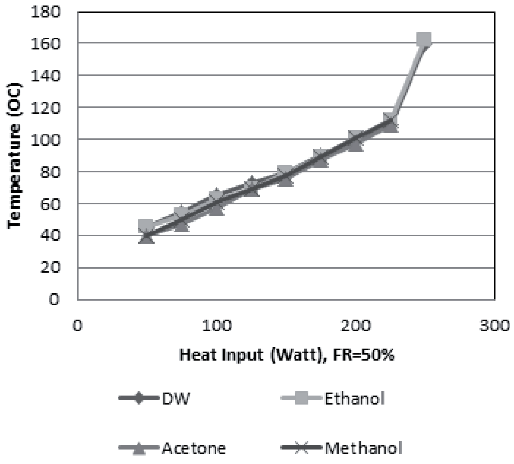


Fig. 9 Evaporator wall temperature vs. heat input for FR = 50 %

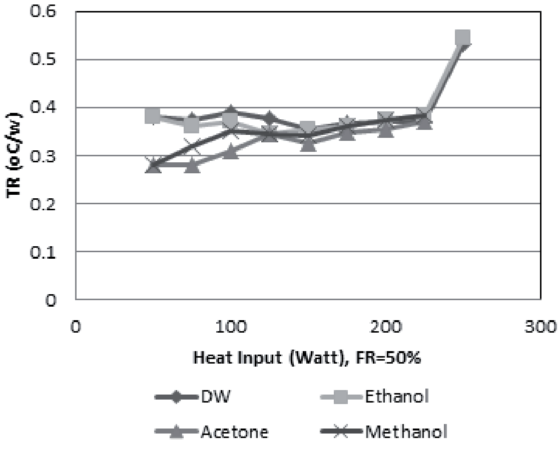


Fig. 10 Thermal resistance vs. heat input for FR = 50 %

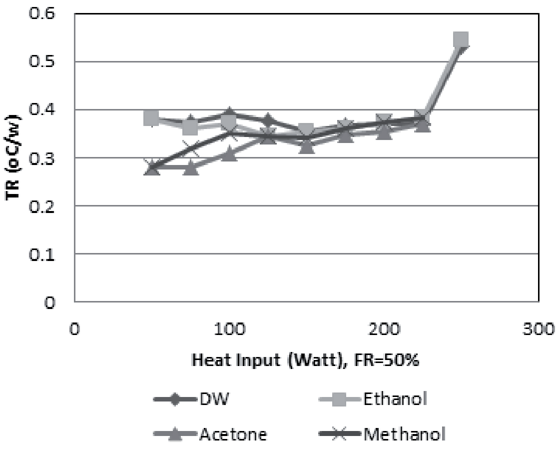


Fig. 11 Evaporator wall temperature versus heat input for FR = 60 %

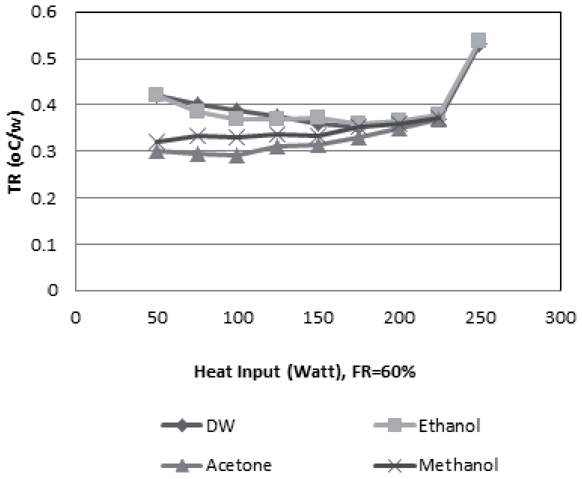


Fig. 12 Thermal resistance vs. heat input for FR = 60 %

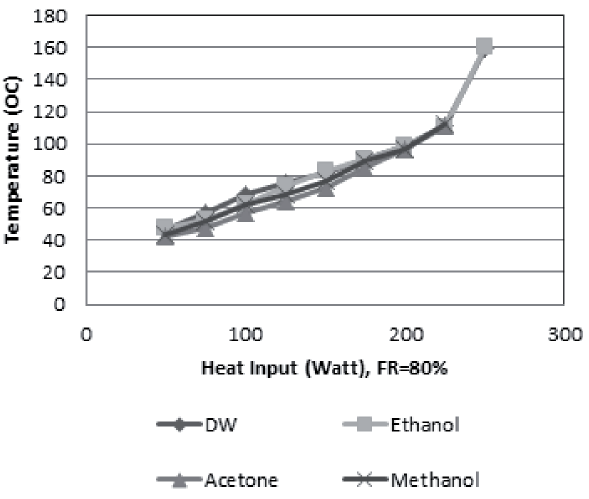


Fig. 13 Evaporator wall temperature vs. heat input for FR = 80 %

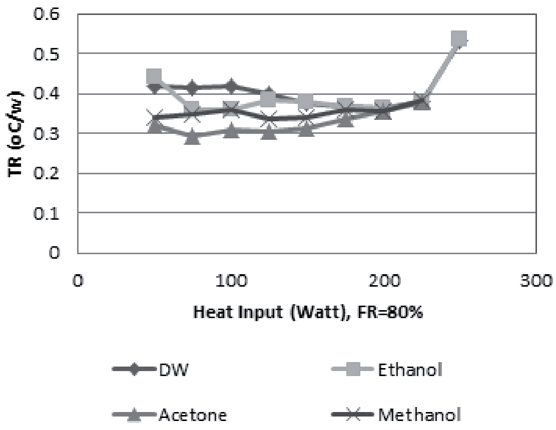


Fig. 14 Thermal resistance vs. heat input for FR = 80 %

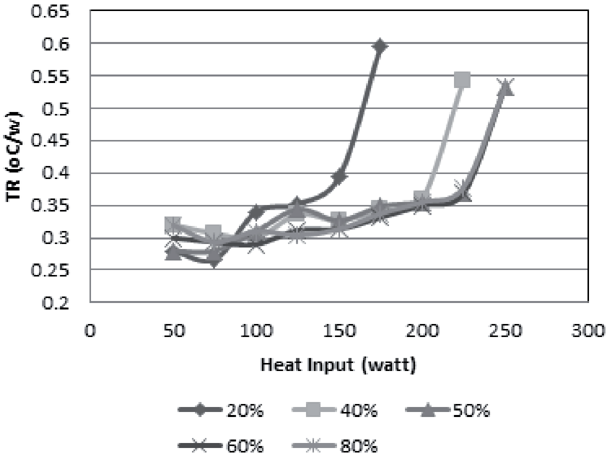


Fig. 15 Thermal resistance vs. heat input for acetone in different FR

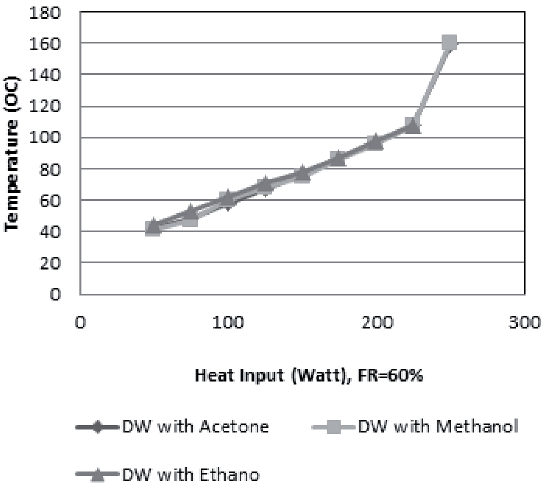


Fig. 16 Evaporator wall temperature vs. heat input in mixing of working fluids for FR = 60 %

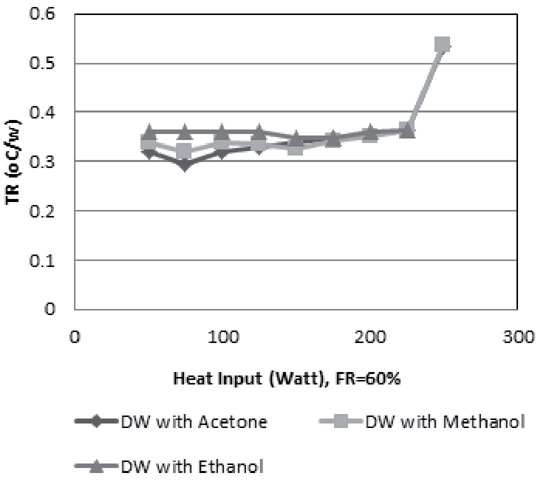


Fig. 17 Thermal resistance versus heat input in mixing of working fluids for FR = 60 %

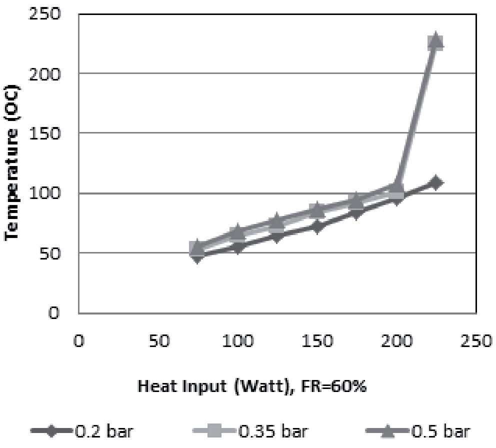


Fig. 18 Evaporator wall temperature vs. heat input for FR = 60 % in different vacuum level

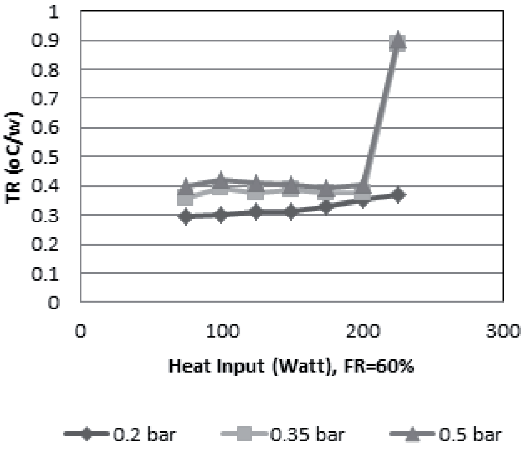


Fig. 19 Thermal resistance vs. heat input for FR = 60 % in different vacuum level

4 Conclusion

An experimental study was performed to investigate the effects of filling ratio, heat load, mixing of working fluids and evacuation level on performance of a closed loop pulsating heat pipe. The main results are:

- The thermal resistance at steady state is found to be lower for acetone compared to DW, ethanol and methanol.
- Acetone is observed to be more suitable working fluid for the CLPHP operation in filling ratio of 60 %.
- The operation of a CLPHP is found to be better at more evacuation level. Because the pulsating condition with more speed take place.
- The combination of working fluids has no outstanding effect on performance of CLPHP.

The reason for better operation of acetone could be related to its lower saturation temperature and surface tension, consequently resulting in the production of more pulsating mode.

Acknowledgement

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Nomenclature

PHP	pulsating heat pipe
CLPHP	closed loop pulsating heat pipe
Sys	system
TR	thermal resistance
DW	distilled water
FR	filling ratio
cm	centimetre
D_c	critical diameter
V	volt
W	watt
AC	alternative current
L	length
OD	outer diameter
D	diameter
Q	heat input
T_a	ambient temperature
T_e	evaporator temperature
g	gravity acceleration

Greek symbols

ρ_{liq}	liquid density
ρ_{vap}	vapor density
σ	surface tension

Subscripts

liq	liquid
vap	vapour
a	ambient
e	evporator

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