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Review on Thermal Performance of Oscillating Heat Pipe With Different Working Fluids

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Abstract

Pulsating heat pipe (PHP) or oscillating heat pipe (OHP) has drawn attention as a highly efficient two-phase heat transferring device that does not need the wick structure to return the condensate to evaporator section like many other types of heat pipes. Also, it can transfer the heat through liquid-vapor slug oscillations set up without any aid from external power. There are many parameters such as geometric parameters, working fluids, orientations, number of turns etc. affecting the OHP's performance. But among all, replacement of base fluid with better heat transfer fluid is direct and most effective method to improve the thermal performance of OHP. Many experiments have been carried out by researchers on OHP charged with different working fluids such as alcohols (methanol, ethanol, 2-propanol), acetone and refrigerant (R-123). Some investigators employed ferrofluid (magnetic nanofluid) and self-rewetting fluid (SRWF) in OHP to operate it in horizontal mode effectively. Nowadays, high heat transfer capability of nanofluid has attracted researchers to use it as working fluid in OHP. This paper reviews the work done by various researchers for heat transfer enhancement, startup characteristics and flow theories for OHP employed with different working fluids. Possible limitations in using any particular working fluid have also been pointed out in this paper.

Keywords: Pulsating/ Oscillating Heat Pipe, Thermal Performance, Working Fluid

Introduction

Heat pipe is a highly efficient passive device used to transmit heat. It allows high transfer rates over considerable distances with minimal temperature drops, exceptional flexibility, simple construction and easy control all without need of external pumping power [1]. The oscillating heat pipe (OHP) or pulsating heat pipe (PHP) is a relatively new member in the family of passive two-phase heat transfer devices i.e. heat pipes which was first introduced by Akachi et al. [2] in 1990. As compared to conventional heat pipes, there is no additional capillary structure in OHPs, which means the countercurrent flow between the liquid and vapor is almost non-existent inside them. As a result, the OHPs are not subjected to the entrainment limit affecting the heat transport capability in conventional heat pipes [6]. It is considered as one of the promising technologies for transferring high heat transfer within small spaces. It has great potential to be used in wide areas, such as spacecraft thermal control, high power-density electronic equipment cooling, heat recovery, solar energy collecting, drying, and chemical reactors, etc. due to its potential heat transport capability, simple structure, compact sizes and low cost of manufacturing.

A PHP (Figure 1) consists of meandering capillary tube bent into many U-turns. These tubes are mainly divided into three sections; evaporator section, condenser section and middle adiabatic section. Initially, the tubes are evacuated and then partially filled with working fluid which distributes randomly in the OHP forming liquid-vapor slugs and plugs. When the evaporation section is heated, imbalance in pressure forces is caused due to the initial non-uniform distribution of slugs/plugs that causes transportation of fluid to the condenser. After rejecting the heat in the condenser section, fluid is returned to the evaporation section. This cycle is repeated and at steady state, the oscillating motion of slugs and plugs gets setup between evaporator and condenser sections causing high heat transfer through both latent and sensible heat transfer of working fluid.

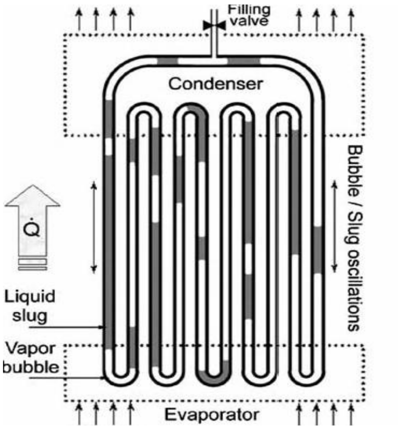


Figure 1: Closed loop pulsating heat pipe [13].

Factors Influencing the Performance of OHP

After studying the available literature, it is found that there are many factors influencing the OHP performance and hence they need to be considered while designing the OHP. These factors are given below-

1. Geometric parameters (Internal diameter of OHP tube etc.)
2. Working fluid

3. Filling ratio of the working fluid
4. Number of turns
5. Orientation of the device
6. Evaporator and condenser section capacity, etc.

Though the above factors influence the performance of OHP, change of the base fluid with better heat transfer fluid is the direct and most effective way to improve thermal performance of OHP. The investigations done on OHP by using different fluids can be categorized into experiments done with working fluid as alcohols, acetone, refrigerant, nanofluids, ferrofluid, binary fluid and self-rewetting fluids (SRWF). In alcohols, experiments are mainly carried with ethanol, methanol and 2-propanol as working fluids. During analysis, effects of filling ratio, heat input, and orientation of the OHP etc. against the use of different working fluids were checked. Work on one of the important design parameters of OHP by various researchers is reviewed in this paper.

Literature Review

Experiments performed on oscillating heat pipe with different working fluids-

Alcohol (methanol, ethanol, 2-propanol) and acetone as working fluid

Roger R. Riehl [3] tested an open loop pulsating heat pipe (OLPHP) with water, methanol, acetone, 2-propanol and ethanol as working fluids. The tests were conducted for both vertical and horizontal orientations with constant filling ratio of 50%. He found that at vertical orientation OLPHP was not too sensitive regarding the working fluid while among all working fluids acetone gave the best results. At horizontal orientation, methanol showed better performance while, with water, the performance was not too good at both the orientations. For different working fluids, the effective thermal conductance varied ± 19% at vertical orientation and ± 53% at horizontal orientation. From all tests he concluded that acetone, methanol and ethanol showed great potential for using working fluids in OLPHPs.

Haizhen Xian et al [4] conducted experiments on OHP filled with water and ethanol to check the effects of filling ratio, inclination angle and operating temperature on thermal performance and startup characteristics of the OHP. They observed that minimum temperature difference (ΔT min), which was needed to keep the heat pipe in working condition, varied when the filling ratio and inclination angle were changed. This variation was irregular for ethanol OHP while variation in ΔT min of the water OHP were quite small. They also found that the variation in ΔT min was maximum at the horizontal inclination angle at the same filling ratio. During the experiments, it was found that the maximum effective conductivity of the ethanol OHP reached up to 111kW/mK, while that of the water OHP reached up to 259kW/mK. This showed that the ethanol OHP was more affected by the filling ratio and the inclination angle but the influence law was irregular.

Next, they found that the startup temperatures of ethanol OHP and water OHP varied from 40°C to 50°C and 40°C to 60°C, respectively, without considering the horizontal operating mode (Table 1). The filling ratio and the inclination angle had some influence on startup temperature of ethanol filled OHP while in case of water filled OHP, inclination angle had no effect on startup temperature when the filling ratio was small but it increased with the increased inclination angle when the filling ratio increased to 60%. In overall performance of water filled OHP was better and it showed more stable heat transfer characteristics than the ethanol OHP.

Table 1: Startup temperatures under varied operating conditions [4].

Inclination angle (deg)	**Water**			**Ethanol**		
	α=40% (^{0}C)	α=50% (^{0}C)	α=60% (^{0}C)	α=50% (^{0}C)	α=40% (^{0}C)	α=60% (^{0}C)
0	Not run	79	69	Not run	69	79
20	40	40	55	40	50	40
60	40	40	55	45	50	50
90	40	40	60	50	50	40

K. Rama Narasimha et al [5] investigated a closed loop PHP with a single U turn. They carried the experiments for different working fluids (water, methanol, ethanol and acetone), heat input and for different evacuation levels (P= 1, 0.8, 0.7 bar). They found that for acetone, the temperature difference between evaporator and condenser at steady state was lower as compared to that for water, ethanol and methanol. Also, they observed lower value of thermal resistance and higher value of heat transfer coefficient in case of acetone compared to water, ethanol and methanol. When PHP was operated at atmospheric conditions, thermal resistance and temperature difference between evaporator and condenser became lower while heat transfer coefficient was higher. Hence, acetone seemed to be more suitable working fluid for PHP while atmospheric conditions were better for the operation of a single loop PHP (Figure 2).

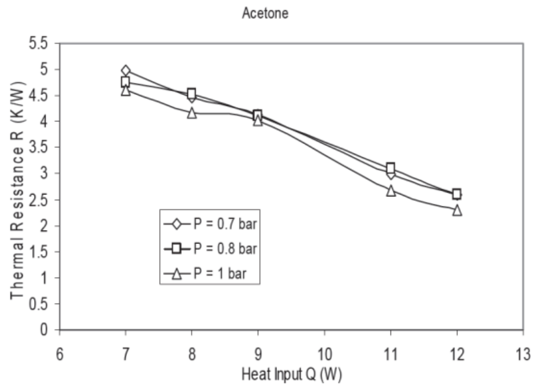
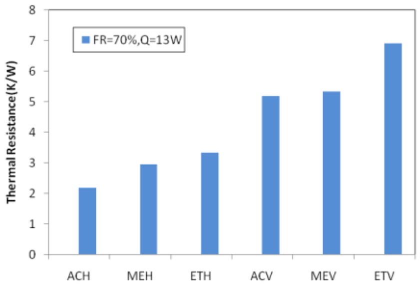


Figure 2: Effect of vacuum and atmospheric pressure on thermal resistance for acetone [5].

Jian Qu et al [6] analysed a CLOHP for different working fluids (pure water and ethanol), variable inner diameters (1.2, 2, and 2.4 mm), filling ratios (40%, 50% and

60%) and variable evaporator lengths. They checked the suitability of above parameters with respect to the working fluid. They observed that the 2 mm ID and 2.4 mm ID CLOHPs had better thermal performance when charged with water as compared with ethanol, while ethanol was preferred for the 1.2 mm ID CLOHP. For water, the thermal performance of CLOHPs was enhanced at 50%, 40% and 40% for 1.2 mm ID, 2 mm ID and 2.4 mm ID relatively while in case of ethanol filling ratio of 40% was suitable in all cases. They also developed an empirical powerlaw correlation based on dimensionless groups, such as the Bond number, Morton number, and Prandtl number, describing the flow and heat transfer characteristics to predict the thermal performance of vertical CLOHPs.

R. Naik et al [7] carried out experiments on a single loop PHP and studied the effects of heat input, working fluid, fill ratio and orientation on the performance of PHP. During the experiments, they used acetone, methanol and ethanol as working fluids with filling ratios of 60%, 70% and 80%. In both horizontal and vertical orientations of operation of PHP, the temperature difference between evaporator and condenser at steady state was found to be less for acetone as compared to that for ethanol and methanol.



(Where AC-acetone, ME-methanol, ET-ethanol, H-horizontal orientation, V-vertical orientation)

Figure 3: Effect of orientation on Thermal Resistance for different fluids at Q = 13 W and FR = 70% [7].

From Figure 3, Acetone is observed to be most promising working fluid for PHP operation under different operating conditions. Among all filling ratios, 60% filling ratio is found to be more suitable to operate the PHP (Figure 4). Also it was observed that use of single loop PHP is possible in horizontal orientation as it produced lower thermal resistance and higher heat transfer coefficient for the considered conditions.

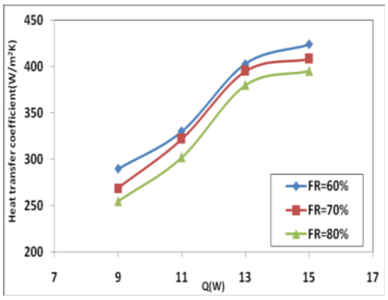


Figure 4: Effect of filling ratio on Heat Transfer Coefficient in horizontal orientation for Acetone [7].

Himel Barua et al [8] analyzed a CLPHP filled with two different fluids (water and ethanol). They checked the effects of filling ratio and heat input on thermal resistance, evaporator temperature and condenser temperature of the CLPHP for water and ethanol as working fluids. They found when heat input was lower, water showed better performance than ethanol at wide range of filling ratio while at higher heat input (beyond 70 W), both working fluids showed same thermal performance. In case of water, at both lower and higher heat input, thermal resistance had lower value for lower filling ratio and optimum heat transfer was obtained at nearly 30% filling ratio. Whereas ethanol showed best performance at high filling ratio (beyond 50%) when heat input was low and for high heat input it was effective at all filling ratio.

When filling ratio and heat input kept same, water showed higher evaporation temperature than ethanol. For water, as the filling ratio was increased, evaporation temperature continued to decrease and the lowest temperature was obtained at nearly 70% filling ratio. For further increase in filling ratio, increment in temperature was observed. Similar observation was made for condenser temperature; it decreased as filling ratio was increased and continued to increase beyond certain filling ratio. While in case of ethanol, both evaporation and condenser temperatures continued to decrease up to 80% filling ratio and then remained constant for further increment in filling ratio.

Bhawna Verma et al [9] had done an experimental investigation to check the effects of working fluids on the start-up and thermal performance of PHP. Methanol and de-ionized water were used as working fluids. The minimum startup powers for DI water and methanol were obtained at filling ratios of 50% and 40%, respectively. Also, the optimum filling ratios in terms of minimum startup power and minimum thermal resistance for DI water and for methanol were 50% and 40%, respectively. The minimum thermal resistances were observed at vertical orientation for both the working fluids. For water the heat transfer coefficient was slightly more at the evaporator side while it was appreciably more at the condenser side as compared to methanol. At optimum filling ratio, the minimum thermal resistances of water charged PHP at 45° inclination and horizontal orientation was found to be 0.55°C/W and 0.81°C/W respectively while that of methanol charged PHP, it was 0.52°C/W and 0.63°C/W, respectively. This showed that PHP worked efficiently at all orientations if methanol is used as working fluid.

Hua Han et al. [10] had done a comparative study of the oscillation characteristics and the heat transfer performance of a closed loop PHP charged with deionized water, ethanol and acetone, for different heat inputs and different filling ratios. They found that for the same filling ratio the PHP charged with the working fluid of lower boiling point & lower latent heat of vaporization was easier to dry out.

Refrigerant (R-123) As Working Fluid

Khandekar et al. [11] experimentally studied the performance of a closed-loop copper PHP with a 2mm diameter and 10 parallel channels. To maximize heat transfer, each working fluid had a slightly different optimum charge ratio (water = 30%, ethanol =20%, and R-123=35%) due to differences in surface tension, latent and specific heats, and the value of (dp/dT)sat. The small number of turns in the PHP setup did not allow operation at horizontal orientation.

Honghai Yang et al. [12] performed an experimental study on the operational limitation of closed loop oscillating heat pipe (CLPHP) in which R123 was employed as the working fluid. The effects of filling ratio, operational orientation, inner diameter 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. Performance limits for CLPHP with 2mm ID were about 540 W for +90, 450 W for 0 and 380 W for -90, respectively, while for the CLPHP with 1 mm ID tubes, orientation played almost no role; this was because surface tension dominates the fluid flow in the smaller tube. A filling ratio of 50% was optimum for both CLPHPs to obtain best performances in all orientations.

Table 2: Maximum heat loads and heat fluxes at dry out limit for both CLPHPS (three heat modes; fr=50%) [12].

	ID = 1 mm			**ID = 2 mm**		
Heat mode	$+90^0$	0^0	-90^0	$+90^0$	0^0	-90^0
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

Charoensawan et al [13] performed parametric experimental investigations on copper closed-loop PHP, including the variation of parameters like internal diameter, number of turns, working fluid and inclination angle. The working fluids employed were water, ethanol and R-123 with the charge ratio of 50% and the tests were conducted at both 0^o and 90^o orientations. The results indicated that gravity strongly affects the PHP performance unless the former has a certain critical number of turns. When the turns were less than a certain number of turns the PHP did not operate at horizontal orientation. Use of different working fluid was beneficial under different operating conditions but selection of correct working fluid was affected by several other parameters (inner diameter etc.) also.

Nanofluid as working fluid

Nanofluid is a new kind of working fluid with special properties which improve heat transfer characteristics. Nanofluids are prepared by suspending nanoparticles less than 100 nm of metallic or non-metallic substances uniformly stably in a conventional heat transfer liquid (base fluid). Thermo physical and transport properties of the conventional fluids are improved by adding nanoparticles in the base fluid [15]. Due to high heat transfer capability of nanofluids many researchers used nanofluid as working fluid PHP.

Ma et al [14] have successfully done experimentation on an OHP charged with nanofluid consisting (HPLC) grade water and 1.0% volume fraction of diamond nanoparticles of 5-50 nm with filling ratio of 50%. They found when the input power reached 100W, the temperature difference between the evaporation and the condensation sections were reduced from 42°C to 25°C, which significantly improved the heat transfer capability of the OHP. Due to oscillating motion in the OHP caused by thermal excitation, the diamond nanoparticles remained suspended in the base fluid, which resulted in increased heat transfer of the OHP. They also found that when the operating temperature increases, the thermal resistance is significantly decreased and approached to 0.03°C/W at a power input of 336 W.

Lin et al [15] investigated a PHP with an inner diameter of 2.4 mm filled with silver nanofluid solution, and compared the result with that of pure water. They carried out tests with 20 nm silver nanofluid at different concentrations (100 ppm and 450 ppm) at various filling ratios (20%, 40%, 60%, and 80%, respectively) under different input heating power. The heat pipe performed better for 100 ppm concentration of silver nano-fluid water solution since higher concentration lead to the higher viscosity which reduced liquid slug movement. Also, they found the best filling ratio was 60% as low filling ratio caused easy dry out while higher filling ratio decreased bubble movement and hence the heat transfer. At 60% filling ratio and the heating power of 85W, the average temperature difference and the thermal resistance of the evaporator and condenser decreased by 7.79 and 0.092°C/W, respectively.

S. Wannapakhe et al [16] investigated the effects of inclination angles, aspect ratios (evaporator length to inner diameter of capillary tube) and concentrations of silver nanofluid on the heat transfer rate of a closed-loop oscillating heat pipe with check valves (CLOHP/CV). They found that CLOHP/CV perform better for 0.5 %w/v concentration of silver nanofluid; also the best inclination for using CLOHP/CV was 90^0 from the horizontal axis.

Jian Qu et al. [17] checked the thermal performance of an OHP charged with base water and Al_2O_3 spherical particles of 56 nm in diameter. They studied the effects of mass fractions of alumina particles, filling ratios, and power inputs on the total thermal resistance of the OHP. They found that the alumina nanofluids improved the thermal performance of the OHP significantly with an optimal mass fraction of 0.9% (Figure 5). Compared with pure water, the maximal thermal resistance was decreased by 0.14 °C/W (or 32.5%) when the power input was 58.8W at 70% filling ratio and 0.9% mass fraction. The major reason for the improvement of thermal performance of the OHP was found to be the change of the surface condition on the evaporator due to nanoparticle settlement.

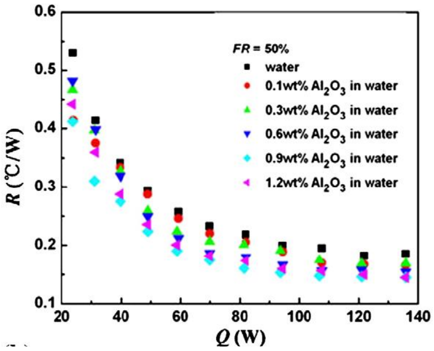


Figure 5: Thermal resistance comparison for the OHP charged with $Al_2O_{3/}$ water nanofluid [17].

Ji et al. [18] performed study on the particle size effect of Al_2O_3 on OHP. Four different size particles with an average diameter of 50 nm, 80 nm, 2.2 μm and 20 μm were experimentally tested respectively. The OHP achieved the best heat transfer performance of a thermal resistance of 0.113°C/W when charged with 80 nm particles and water at an operation temperature of 25°C and a power input of 200W.

Use of all nanofluids in OHP does not lead to an improved thermal performance but it will depend on the change of surface condition at the evaporator and condenser due to different nanoparticle deposition. This has been experimentally proved by Jian Qu and Huiying Wu [19]. They checked the thermal performance of two same OHPs charged with SiO2/water and Al2O3/water nanofluids respectively. For the alumina nanofluid-charged OHP, nanoparticles mostly deposited at evaporator thus enhanced the heat transfer of OHP (at 0.9 wt % concentration thermal resistance and evaporator wall temperature increased by 0.057 ^{0}C/W (or 25.7%) and 5.6 ^{0}C (or 8.7%), respectively) by increasing surface nucleation sites. While in case of silica nanofluid-charged OHP, nanoparticles deposited at both evaporator and condenser which decreased the surface nucleation sites and contact angle, and thus heat transfer was deteriorated (at 0.6 wt % concentration thermal resistance and evaporator wall temperature increased by 0.075 ^{0}C/W (or 23.7%) and 3.5 ^{0}C (or 5.5%) respectively.

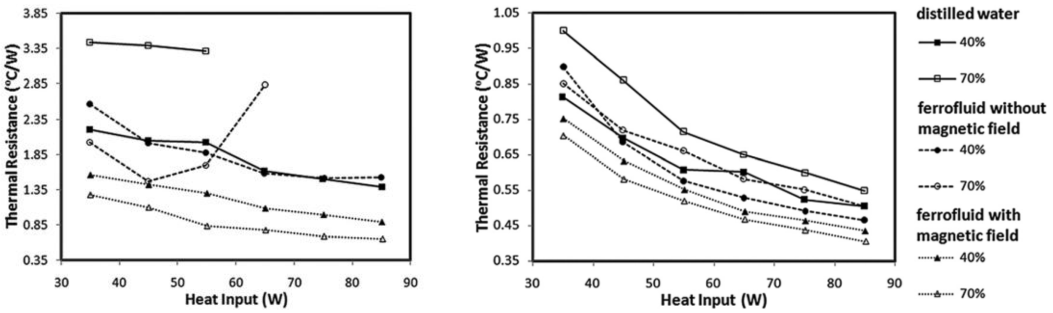
Wang et al. [20] studied the thermal performance of PHP charged with functional thermal fluids (microcapsule fluid FS-39E and nanofluid Al_2O_3), and compared it with that of pure water. The heat capability of the PHP significantly enhanced for both of the functional thermal fluids. The results show when bottom heating mode was used, microcapsule fluid FS-39E was the best working fluid & its best concentration was 1wt% while Al_2O_3 nanofluid was the best working fluid for horizontal heating mode & its best concentration was 0.1wt%.

Roger and Santos [21] conducted experiments on open loop PHP filled with water-copper nanofluid, with concentration of 5% by mass of copper nanoparticles. They observed the higher thermal conductance for the PHP filled with nanofluid as compared with pure water. As copper nanoparticles increased the water thermal conductivity, the film evaporation effect was more predominant than nucleate boiling for low heat loads. But, when the heat loads were higher, nanoparticles acting as nucleation sites improved the nucleation boiling, resulting in the generation of the pulsating flow.

Ferrofluid as working fluid

Ferrofluid is a kind of nanofluid in which nanoparticles having affinity to magnetic field have been dispersed into the base fluid. Such magnetic nanofluid can be used to improve the thermal performance of PHP.

Maziar Mohammadi et al [22] tested a PHP charged with water based ferrofluid and checked the effects of charging ratio, heat input, orientation, ferrofluid volumetric concentration, and magnetic field on the thermal performance of PHP. They found in the presence of magnetic field, thermal resistance of PHP always decreased and in the horizontal mode, magnetic force played the role of gravity which made PHP to operate in horizontal mode also (Figure 6a). In the presence of a magnetic field, the best thermal performance was achieved at the higher charging ratios (70%) in all orientations due to the increased magnetic effect (Figure 6a and 6b).



(a) (b)

Figure 6: Thermal resistance as a function of heat input at 40% and 70% charging ratios and in a) horizontal mode and b) vertical mode [22].

Binary mixture and self-rewetting fluid (SRWF) fluid as working fluid

Koji Fumoto et al [23] checked the performance improvement of PHP using self-rewetting fluid as working fluid. They conducted the experiments for the evaporator temperature range of 25–110°C, filling ratio of 0–50 vol %, and concentrations of 1-butanol and 1-pentanol in the working fluid of 0 wt %, 0.1 wt %, 0.25 wt %, 0.5 wt %, and 1.0 wt %. They observed lower thermal resistance of the PHP for self-rewetting fluid solution of 1 wt % or less as the working fluid compared with that of pure water. Also, they found that maximum heat transport capability of PHP increased four times as compared with that of pure water for maximum heater temperature of 110 °C. Since the largest heater power of pentanol aqueous solution was approximately 1.2 times higher than that of the butanol aqueous solution at the same solution concentration, pentanol aqueous solution made self-pulsating motion at a lower temperature difference than that of butanol aqueous solution and pure water.

Pramod R. Pachghare et al [24] done the experiments on CLPHP by using pure and binary mixtures as working fluids and checked the effects of heat input on it. In pure working fluids methanol, ethanol, acetone, water are used while in binary mixtures water-methanol, water-ethanol and water-acetone are used as working fluids. In all the cases, thermal resistance decreased as the heat input increased. From Figure 7, it is clear that for pure working fluids, thermal resistances increased in the sequence of acetone, methanol, ethanol and water while for binary mixtures it increased in the sequence of water-methanol, water-acetone and water-ethanol. Among all pure and binary mixtures working fluids, pure acetone showed the best thermal performance.

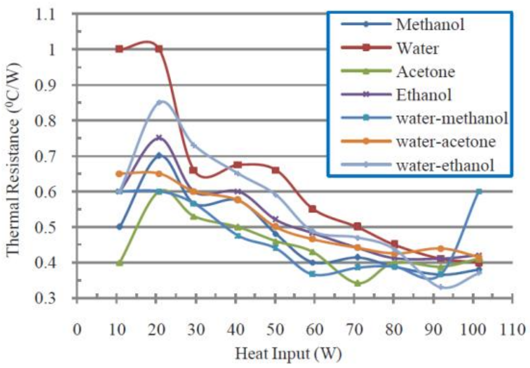


Figure 7: Variation in thermal resistance with heater power at different working fluids [24].

Yanxin Hu et al [25] investigated micro oscillating heat pipe (MOHP) charged with self rewetting fluid. During the experiments, they used different heat transfer lengths as 100,150,200 mm and different inner diameters as 0.4, 0.8 and 1.3 mm. They found that as compared to deionised water, the capillary resistance of 0.1 wt% heptanol solution was much smaller. In horizontal orientation, the MOHP charged with SRWF showed better thermal performance as compared with water. This was due to their property of increasing surface tension with increasing temperature. Also, SRWF prevented the dry out phenomenon since they could spontaneously wet the hotter region. While in vertical orientation, SRWF showed the thermal enhancement effect only for smaller diameter. Variation of surface tension with temperature for different concentrations of heptanol solution has been shown in Figure 8.

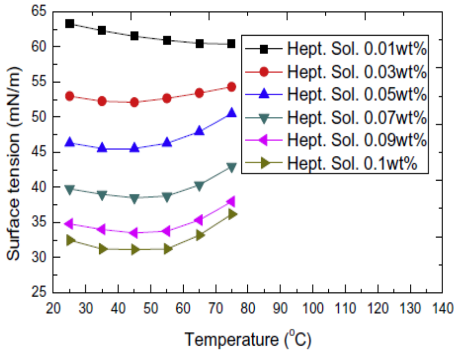


Figure 8: Relationship between surface tension and temperature of the SRWT fluid [25].

Table 3: Summary of experiments on oscillating heat pipe with different working fluids

Author	**Working fluid**	**Parameters studied**				**Conclusion**
		Inclina-tion angle	**Filling ratio**	**Heat input**	**Other**	
Roger [3]	water, methanol, acetone, 2-propanol and ethanol	90,0	50	5-50W		-At vertical orientation PHP was not too sensitive regarding the working fluid but among all working fluids acetone showed the best results. -At horizontal orientation, methanol showed better performance.
Xian et al [4]	water and ethanol	0,20,60, 90	40,50, 60		-different operating temperatures (69, 79,88^{0}C) -Startup characteristics	Water filled OHP showed better and more stable heat transfer characteristics than ethanol filled OHP.
K. Rama et al [5]	(water, methanol , ethanol and acetone	90	60	7-12W	different evacuation levels (P= 1, 0.8, 0.7 bar)	Acetone seemed to be more suitable working fluid for PHP and atmospheric conditions were better for the operation of a single loop PHP.

Jian Qu et al [6]	water and ethanol	90	40,50, 60	10-130W	Variable tube diameters (ID=1.2,2, 2.4 mm)	For water the thermal performance of CLOHPs was enhanced at 50%, 40% and 40% FR for1.2 mm ID, 2mm ID and 2.4 mm ID respectively while in case of ethanol filling ratio of 40% was suitable for 1.2 mm ID
R. Naik et al [7]	acetone, methanol and ethanol	90,0	60,70, 80	9-15W		-Acetone is observed to be most promising working fluid for PHP operation under different operating conditions. -Among all filling ratios, 60% filling ratio is found to be more suitable to operate the PHP.
Himel Barua et al [8]	water and ethanol	90	28,41. 30,50, 63, 70, 82.50, 100	5-70W	Effect on evaporation and condenser temperatures	-At lower heat input, water showed better performance than ethanol. -Optimum filling ratio for water was 30% while for ethanol it was beyond 50%. -At higher heat input (beyond 70W) both working fluids showed same thermal performance.
Verma et al [9]	methanol and deionized water	0,45,90	10-100 (in the step of 10)	10-100W		-Optimum filling ratios in terms of minimum startup power and minimum thermal resistance for water and methanol were 50% and 40% respectively. -The minimum thermal resistances were observed at vertical orientation for both the working fluids. -Use of methanol found to be efficient at all orientations.
Hua Han et al. [10]	deionized water, ethanol and acetone	90	20,35, 45,55, 62, 70, 90	5-100W		Fluid with lower boiling point and lower latent heat of vaporization dried out easily.
Khandekar et al. [11]	water, ethanol, and R-123	0,90	7-100	5-65W		-Optimum filling ratios for water , ethanol and R-123 were 30%, 20% and 35% respectively. -Horizontal operation not possible.
Honghai Yang et al. [12]	R123	-90,0,90	30,50, 70	10-400W	Variable tube diameters (ID=1,2 mm)	-At all orientations 50% filling ratio was optimum. -OHP with smaller ID tubes (1mm) can be operated at all orientations since surface tension of fluid dominates the fluid flow.

Charoensawan et al [13]	water, ethanol and R-123	0,90	50	200-1100		To operate OHP at 0^o, we require certain critical number of turns.
Ma et al [14]	(HPLC) grade water and diamond nanofluid (1.0% volume fraction)	90	50	50-325W	Variable condenser operating temperature (10-70^0C)	Diamond nanoparticles remained suspended in the base fluid during oscillations, which resulted in increased heat transfer of the OHP.
Lin et al [15]	silver nanofluid solution and pure water	90	20,40, 60,80	5-85W		-Better performance observed for 100 ppm concentration silver/water nanofluid solution. -Filling ratio of 60% found to be optimum.
S. Wannapakhe et al [16]	Silver/ water nanofluid	0,20,40, 60,80,90	50		Variable operating temperatures (40,50, 60 ^0C)	CLOHP/CV performed better for 0.5 %w/v concentration of silver nanofluid and inclination of 90^0 from the horizontal axis.
Jian Qu et al. [17]	water and Al_2O_3 /water nanofluid	90	50,60, 70	20-140W		-Alumina nanofluids improved the thermal performance of the OHP significantly with an optimal mass fraction of 0.9%. -Filling ratio of 70% found to be optimum.
Ji et al. [18]	water and Al_2O_3/ water nanofluid	90	50	5-200W	Variable nanoparticle size (50nm, 80nm, 2.2µm, 20µm)	Best heat transfer performance with thermal resistance of 0.113°C/W is achieved when charged with 80 nm Al_2O_3 particles and water at an a power input of 200W.
Jian Qu et al. [19]	SiO_2/ water and Al_2O_3/ water	90	50	20-140W		For all the given concentrations heat transfer enhances with Al_2O_3 /water nanofluid while it decreases for SiO_2/water nanofluid.

Wang et al. [20]	(microcapsule fluid FS-39E and nanofluid Al_2O_3) and water	0,90	50	10-80W		Microcapsule fluid FS-39E with the concentration of 1wt% was the best working fluid for bottom heating mode while Al_2O_3 nanofluid with concentration of 0.1wt%.was the best working fluid for horizontal heating mode.
Roger and Santos [21]	Water and water-copper nanofluid	-90,0,90	50	10-50W		Addition of nanoparticles increased the film evaporation and number of nucleation sites, as a result thermal conductance of OHP increased.
Maziar et al [22]	Water and water based ferrofluid	0,90	40,70	35-85W	Variable magnetic field	-Better thermal performance of PHP at higher filling ratios (70%) for all orientations. -Magnetic field played the role of gravity in horizontal mode.
Koji et al [23]	Water and self-rewetting fluids of 1-butanol and 1-pentanol solutions	90	20,25,30,40,50	0-140W		-SRWF with concentration of 1wt% or less improved the evaporator characteristics. -Pentanol aqueous solution showed better thermal performance as compared to butanol aqueous solution and pure water.
Pramod R. Pachghare et al [24]	methanol, ethanol, acetone, water while in binary mixtures water-methanol, water-ethanol and water-acetone	90	50	10-100W		- For the pure working fluids, thermal resistances increased in the sequence of acetone, methanol, ethanol and water while for binary mixtures it increased in the sequence of water-methanol, water-acetone and water-ethanol. -Out of all working fluids, pure acetone showed the best thermal performance.

Yanxin Hu et al [25]	Deionised Water and self-rewetting fluids (SRWFs) of heptanol solution	0,90	50	10-120W	Variable tube diameters (ID=0.4,0.8,1.3 mm) and heat transfer lengths (100,150, 200 mm)	As compared to water, o.1 wt% heptanol solution showed better thermal performance in horizontal orientation while in vertical orientation thermal enhancement occur only for smaller diameter.

Working fluid selection

Thermo-physical properties of working fluid are directly affecting the thermal performance of oscillating heat pipe; Work done by [11,26] suggests that the working fluid for OHP should be selected based on the following properties:

Surface tension

If the fluid with higher surface tension is used then maximum allowable diameter of the OHP will increase which in turn increase the pressure drop in the tube. As a result, performance of OHP will improve but an increased pressure drop will require greater bubble pumping and thus a higher heat input to maintain pulsating flow. Hence, the fluid with low surface tension should generally be preferred for OHP as it will start OHP with low input power and maintain the pulsating flow easily. But the low surface tension fluid should be used along with lower diameter OHP, otherwise it will dry out early.

Latent heat of vaporization

A fluid with low latent heat will evaporate more quickly at a given temperature and produce higher vapour pressure. This will increase the liquid slug oscillation velocities and hence improve the thermal performance of OHP. Thus fluid with low latent heat of vaporization should be used as it will cause quick bubble generation and collapse. Also, in OHP, sensible heat is the major mode of heat transfer.

Specific heat

A fluid having high specific heat will increase the amount of sensible heat transferred. Because sensible heat is a predominant mode of heat transfer in OHP, a fluid with high specific heat is preferred.

Viscosity

If the dynamic viscosity of working fluid is high then it will flow slowly and hence the heat transfer will be poor. So the fluid with low dynamic viscosity is preferred as it will reduce shear stress along the wall and will consequently reduce pressure drop in the tube. Also, this will reduce the heat input required to maintain a pulsating flow.

(dP/dT)sat
Fluid should have high value of (dP/dT)sat so that for small change in evaporator temperature, there will be a large change in saturated pressure inside the bubbles which will help in the bubble pumping action. Hence improvement in the performance of PHP will occur by enhanced oscillatory motion of liquid slugs.

Conclusion

In this paper, the work done on variation of oscillating heat pipe performance by the application of different working fluids has been reviewed. It has been seen that different working fluids seem to be beneficial at different operating conditions. Among different alcohols (methanol, ethanol, propanol), methanol shows better performance as compared to pure water for most of the conditions. However, if we compare thermal performances of alcohols (methanol, ethanol, propanol), binary mixtures (water-methanol, water-ethanol, water-acetone) and acetone then acetone seems to be more suitable working fluid for OHP. But use of acetone in OHP is limited for low temperature range because of its low dry out limit. Ferrofluid application in OHP has the advantage of making OHP operation possible at all orientations since role of gravity will be played by magnetic field. However, if we need to operate OHP in horizontal orientation, then self-rewetting fluid (SRWF) will be the better option for working fluid of OHP rather than increasing the number of turns of OHP. Nowadays outstanding heat transfer capabilities of nanofluids have attracted the researchers to use them as working fluid in OHP but still further development is needed for better understanding of flow regimes and heat transfer mechanism of nanofluid filled OHP.

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