

# Closed Loop Pulsating Heat Pipe with a Hydrocarbon as Working Fluid: A Review

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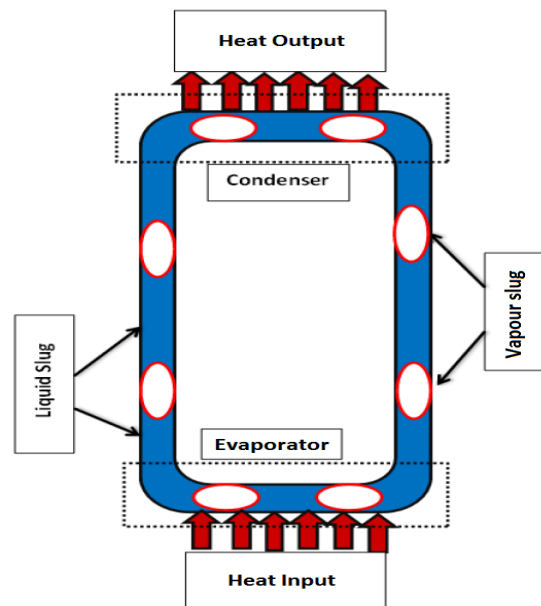
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**Abstract:** *The objective of this paper is to investigate the characteristics of closed loop pulsating heat pipe with hydrocarbon as working fluid and to study the effect of various operating parameter affecting the functioning of closed loop pulsating heat pipe. Working fluid is a very important factor which significantly influences the thermal performance of the closed loop pulsating heat pipe since the working fluid acts as heat transferring medium between a heat source and a heat sink. Thermal performance of the heat pipe subsequently depends on thermodynamics properties of the working fluid inside the heat pipe. Thermodynamics properties involving in heat transfer and two-phase flow consist of latent heat, specific heat capacity, viscosity, surface tension, density, etc. The hydrocarbon working fluid which are usually available are ethanol, methanol, acetone and propanol.*

**Keywords:** closed loop, heat pipe, hydrocarbon, thermal performance, working fluid.

## 1. Introduction

The closed-loop pulsating heat pipe is a type of small heat transfer device with a very high thermal conductivity. It was invented to meet the requirement for smaller heat transfer devices. It can transfer sufficient heat for heat dissipation applications in modern electronic devices. The Closed loop pulsating heat pipe was made of a long copper capillary tube, bent into an undulating tube and connected at the ends to form a closed-loop with no internal wick structure. Working fluid is partially filled in the tube. The closed loop pulsating heat pipe has a condenser, evaporator section and may also present an adiabatic section. As any other two-phase passive thermal control device, heat is acquired from the source through the evaporation section transferring it to the working fluid where the slug/plug pumping action will be generated. The fluid then flows by the adiabatic section towards the condensation section. On a closed loop configuration, the fluid is allowed to circulate and after being condensed, the fluid returns to the evaporation section to complete the loop. The tube is evacuated and consequently partially filled with working fluid. Since an inner diameter of the tube is very small and then meets a capillary scale, the inside working fluid forms into liquid slugs alternating with vapour plugs along the entire length of the tube [1].



**Figure 1:** schematic diagram of closed loop pulsating heat pipe

When one end of the closed-loop pulsating heat pipe, called 'evaporator section', is subjected to heat or high temperature, the working fluid, which is in liquid slug form, will evaporate, expand, and move through the no heat transferring zone, or 'adiabatic section', toward a cooler Section, 'condenser section' namely. Then, the vapour plugs will condense, collapse, and release the heat into the environment. Therefore, the vapour plug evaporating in the evaporator section will consequently flow to replace the vapour plug collapsing in the condenser section. Due to this mechanism, the working fluid can circulate and continuously transfer heat in a cycle. The structure of the closed loop pulsating heat pipe is as shown in Figure 1.

Identification of working fluid type by only one thermodynamics property cannot be done successfully. It can be found from literature reviews on past studies that most of the studies on effect of working fluids on thermal performance of Closed loop pulsating heat pipe frequently defined the latent heat as a quantitative property to identify a type of working fluid because heat transfer mechanism inside the Closed loop pulsating heat pipe can be maintained due to evaporation and condensation of the working fluid, which directly relate to the latent heat. However, it was found that when latent heat of working fluid increased, thermal performance of the vertical closed loop pulsating heat pipe has possibility to change in both ways, i.e., increase and decrease. Results from the past studies that the thermal performance increased as an increase of the latent heat are concluded as follows: When working fluid changed from ethanol to water,

The selection of the working fluid used in pulsating heat pipes is dependent on a number of variables. The approximate temperature range the system will be exposed to is the most critical in determining the proper working fluid. Using an approximate temperature range of 50 to 150 degrees Celsius in turn means many potential working fluids are possible options. Additional requirements need to be examined as well and are listed below:

- Thermal stability
- Wet-ability
- Reasonable vapour pressure
- Compatibility with heat pipe materials
- High thermal conductivity and latent heat
- Reasonable freezing point
- Low vapour and liquid viscosities

From the literature studies it was found that distilled water is most frequently used as the working fluid. Water was chosen for its thermodynamic attributes that make it more appealing than others, such as methanol. It has a high latent heat of vaporization of 2260 kJ/kg which has the potential to spread significantly more heat with less fluid flow. Latent heat is defined as the heat required converting a solid into a liquid or vapour, or a liquid into a vapour, without a change in temperature. This characteristic leads to low pressure drops and high power throughput.

Working Fluid a first consideration in the selection of a suitable working fluid is the operating vapour temperature range. Within the approximate temperature band, **50°C to 150°C** several possible working fluids may exist. A variety of characteristics must be examined in order to determine the most acceptable of these fluids for the application considered. For most commercial electronics cooling applications, the thermodynamic attributes of water make it better than any other fluids for both wicked and pulsating heat pipes. Its high latent heat spreads more heat with less fluid flow. This results in low pressure drops and high power throughput.

Although water's high surface tension allows it to generate a large capillary force and allows the wicked heat pipe to operate in any orientation, it may have adverse effects on the

operation of a pulsating heat pipe. In other words, the high surface tension may cause additional friction and hinder the two-phase flow oscillations in the pulsating heat pipe. Methanol with a lower surface tension (about 1/3rd of water) is a good substitute particularly if the heat pipe is used for sub **0°C** applications.

For the proper working fluid selection, the Clausius-Clapyeron relation could be applied [2], where high values for the magnitude of the derivative  $dP/dT$  (slope) must be achieved. This represents that a small change in the saturation temperature will result in a large influence in the saturation pressure, which will directly affect the pumping forces of the pulsating heat pipe during its operation. Other important parameters should also be evaluated, such as:

$$\frac{dP}{dT} = \frac{\text{latent heat of vapourisation}}{T \times (v_f - v_l)} \quad \text{eq}^n (1)$$

Where i and f are the initial and final phase

### 1.1 Latent Heat of Vaporization:

High values of vapourisation are desirable and important regarding the Clausius-Clayperon relation, which can reflect little temperature drop driving force [2]. On the other hand, this parameter should present a reduced value in order to result in faster bubble generation and collapse; the pulsating heat pipe process is more likely to be due to sensible heat

### 1.2 Tube Diameter

The pulsating action (plug/slug) is the motion force for the pulsating heat pipe, which is directly influenced by the inner tube diameter. The factors that influence the plug/slug formation in reduced diameters must be observed for this application, such as the correct working fluid selection, surface tension and shear stress effects, etc. Without this pumping action, the device will operate as a solid bar conducting heat from one end to another [5]. As an important parameter for the proper pulsating heat pipe operation, the critical bubble diameter is directly related to the selected working fluid and can be estimated from the Bond number as

$$B_o = \frac{g(\rho_l - \rho_v) D_i^2}{\sigma} \quad \text{eq}^n (2)$$

The bond number should be less than or equal to 2

This variable should be used as an upper limit for the maximum tube inner diameter, as an important parameter for the vapour plug formation. If the conditions for the vapour plug formation are satisfied, the pulsating heat pipe would present a satisfactory operation. Another factor that directly influences the pulsating heat pipe performance is the number of turns, as the increase of this parameter will increase the pulsating heat pipe performance and thus higher heat fluxes could be dissipated. From the literature studies for filling ratio of 50 % and vertical orientation, it was found that acetone presented the best results. On the other way, water has presented the worse performance.

### 1.3 Working Fluid Filling Ratio

Another critical parameter which affects the performance of a pulsating heat pipe is the fill ratio of the working fluid. The fill ratio is defined as a percentage of the total inner volume of the system. There has been significant research already performed on the operational limits of a Pulsating Heat Pipe and how it is affected by the fill ratio. At a 0% filling ratio, which means no working fluid is present, a heat pipe system behaves as a pure conduction mode heat transfer device [5].

At a 100% filled heat pipe system the operation observed is similar to a single phase thermosyphon. In this situation the desired pulsating effect is nonexistent, however studies have been performed that have shown substantial heat can be transferred due to liquid circulation in the tubes by thermally induced buoyancy. The ideal working range of a Pulsating Heat Pipe is between approximately 20 to 70% filled ratio. Within this range the system performs like an accurate pulsating structure. The ideal range differs for different systems, orientations, working fluids, and operating parameters [7].

### 1.4 High value of $dP/dT$

Ensuring that a small change in  $T_{\text{evaporator}}$  generates a large corresponding to saturation pressure inside the generated bubble which aids in the bubble pumping action of the device. The same is true in reverse manner in the condenser [8].

### 1.5 High Specific Heat

It is desirable, given the fact that sensible heat is playing the major role in heat transfer in the pulsating mode of pulsating heat pipe operation; although there are no specific studies which explicitly suggest the effect of specific heat of the liquid on the thermal performance. It is to be noted that if a flow regime change from slug to annular takes place the respective roles of latent and sensible heat transport mechanism may considerably change [9].

### 1.6 Low Surface Tension

Low surface tension in conjunction with dynamic contact angle hysteresis may create additional pressure drop. The closed loop pulsating heat pipe can be tested by using different working fluids: isopropyl alcohol, propanol, ethanol, methanol, acetone and water. These fluids can be selected according to their Clausius-Clapyeron relation and also for the maximum saturation pressure at the evaporation section temperatures. The pulsating heat pipe was under vacuum before charging it with any working fluid, which was able to hold a vacuum level of  $10^{-3}$  mbar.

### 1.7 Reliability

If the heat pipe material(s) are compatible with the working fluid, they can be expected to provide highly reliable heat transfer performance within their operating limits for years..

The copper/water materials used in heat pipes employed in notebooks technology.

## 2. Effect of Working Fluid on Thermal Performance

Figure below shows the plot of thermal resistance with heat input for different working fluid at 60 % fill ratio. From the figure it is clear that the thermal resistance decreases with increases in heat input. As the temperature difference between evaporator and con denser is less for acetone, the thermal resistance is also very less. It indicates that acetone is best working fluid compared to other working fluids in heat transfer capability.

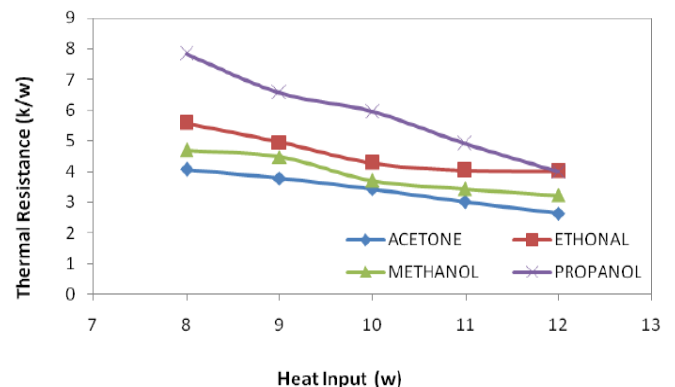


Figure 2: Effect of working fluid on thermal performance

## 3. Effect of Working Fluid on Heat Transfer Coefficient

Figure below shows the plot of heat transfer coefficient with heat input for different working fluid at 60 % fill ratio. Figure below shows heat transfer coefficient increased with increased in heat input for all working fluids. It is seen that acetone is having higher heat transfer coefficient compared to all other working fluids. As the temperature difference between evaporator and condenser is decreases for acetone the heat transfer coefficient will increases.

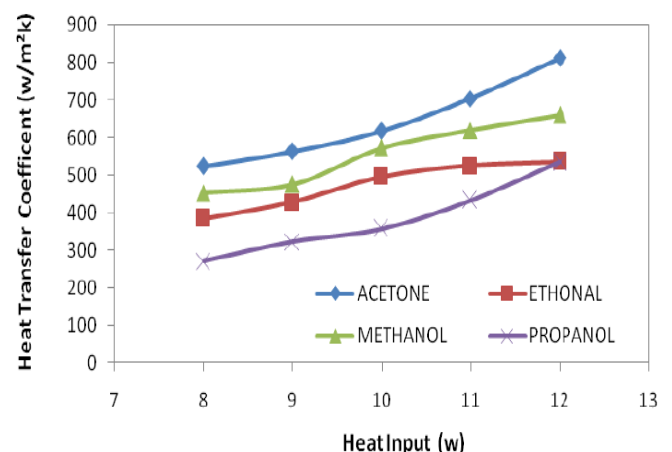


Figure 3: Effect of working fluid on heat transfer coefficient

### 4. Pure Working Fluids of Closed Loop Pulsating Heat Pipe

Fig. show  $T_e$  and  $T_c$  of pure working fluids pulsating heat pipe with the filling ratio of 60% and different power inputs. The thermal resistances have the results of  $R_{acetone} < R_{methanol} < R_{ethanol} < R_{water}$ . For power input less than 60W,  $T_e$ , water is higher than  $T_e$  of other pure working fluids and  $T_c$ , water is lower than  $T_c$  of other pure working fluids. For power input larger than 60W,  $T_e$ , methanol is lower than  $T_e$  of other pure working fluids. From 20W to 100W,

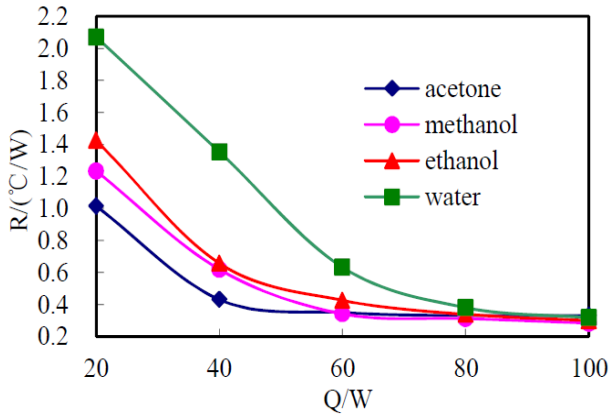


Figure 4: Thermal resistance of pure working fluids of closed loop pulsating heat pipe at different heat Input

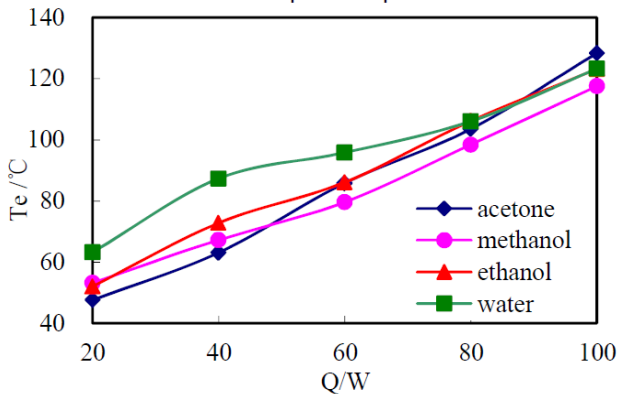


Figure 5: Evaporator temperature of pure working fluids of pulsating heat pipe at different power input

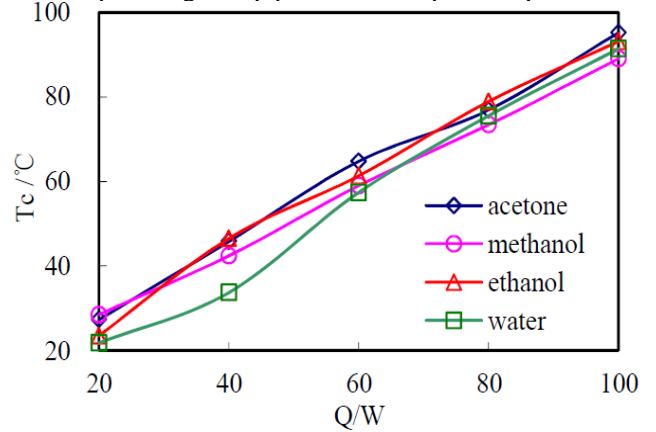


Figure 6: Condenser temperature of pure working fluids of closed loop pulsating heat pipe at different power input

### 5. Working Fluids and Temperature Ranges

Each heat pipe application has a particular temperature range in which the heat pipe needs to operate. Therefore, the design of the heat pipe must account for the intended temperature range by specifying the proper working fluid [13]. Life of a heat pipe can be assured by selecting a container, materials that are compatible with one another and with the working fluid of interest. Performance can be degraded and failures can occur in the container wall if any of the parts (including the working fluid) are not compatible. For instance, the parts can react chemically or set up a galvanic cell within the heat pipe. Additionally, the container material may be soluble in the working fluid or may catalyze the decomposition of the working fluid at the expected operating temperature. This situation is more advantageous than underfilling the heat pipe, which may significantly reduce the maximum heat transfer. With extreme overfill, however, any excess fluid might collect as liquid in the condenser section and increase the thermal resistance, thereby decreasing the heat transport capability of the heat pipe.

Table 1: Thermo-physical properties of various working fluid

Working fluid	Saturation temperature $t_{sat}$ / °C	Specific heat $C_p$ / kJ/kgK	Thermal conductivity $k_w$ / mK	Latent heat $h_{fg}$ / kJ/kgK	$\frac{dp}{dT}_{sat} \times 10^3$ / Pa/°C	$\nu \times 10^6$ / Pa.s	$\rho \times 10^3$ / N/m
Methanol	64.7	2.48	0.212	1101	3.55	0.60	22.6
Ethanol	78.3	2.39	0.172	846	3.51	1.15	22.8
Acetone	56.2	2.35	0.170	523	3.1	0.32	23.7
Water	100	4.18	0.599	2257	1.3	1.01	72.8

#### 5.1 Temperature Range

The temperature range is from 200 to 550 K. Most heat pipe applications fall within this range. Commonly used fluids are ammonia, acetone, the Freon compounds, and water. Water, which is perhaps the most widely used working fluid, has good thermo physical properties such as large heat of vaporization and surface tension, and has the added benefit of being safe to use during handling.

Table 2: Working fluid and temperature ranges of various working fluids

Working fluid	Melting point At 1 atm in K	Boiling point At 1 atm in K	Temperature ranges in K



Methane	90.6	111.4	91-150
Ethane	89.9	184.6	150-240
Pentane	143.1	309.2	252-393
Acetone	180.0	329.4	273-393
Methanol	175.1	337.8	283-403
Ethanol	158.7	351.5	273-403
Heptanes	182.5	371.5	273-423
Water	273.1	373.1	303-350

**Table 3:** Compatibility of metals with working fluids for heat pipes

Working fluid	Compatible Material	Incompatible Material
Water	Stainless Steel, Copper, Silica, Nickel, Titanium	Aluminum
Ammonia	Aluminum, Stainless Steel, Cold Rolled Steel, Iron, Nickel	
Methanol	Stainless Steel, Iron, Copper, Brass, Silica, Nickel	Aluminum
Acetone	Aluminum, Stainless Steel, Copper, Brass, Silica	
Heptane	Aluminum	

## 6. Conclusion

From the literature studies it was found that methanol, ethanol and acetone presented higher thermal conductance when compared to the other fluids. The analysis made on these results point the better performance achieved with acetone, methanol and ethanol during all tests, which show the great potential in using these working fluids. From the literature studies it was observed that results, for filling ratio of 60 % and vertical orientation, acetone presented the best results. On the other way, water has presented the worse performance.

The device can be tested with different working fluids, which can be used to compare the performance. The results gathered in this investigation have the objective to compare the thermal performance of the pulsating heat pipe with different working fluids. The temperature difference between evaporator and condenser is lower for acetone compared to other working fluids. When heat input increases the thermal resistance will decrease and heat transfer coefficient will be increases. When heat input increases the fluid circulation velocity is also increases. Acetone is the most suitable working fluid for pulsating heat pipe operation when compared to other working fluid.

## 7. Future Scope

Analysis need to be done on closed loop pulsating heat pipe hydrocarbon fluids like methane ethane, pentane, acetone, methanol, ethanol, heptanes by comparing their results so as to know which working fluid which will have higher performance under the given set of operating condition and various filling ratio. It is expected that the performance of hydrocarbon fluid may be different at different filling ratio. There is need to do thermal analysis of closed loop pulsating heat pipe with software packages like ANSYS and need to study the position of vapour slug at particular intervals of time and temperature variation inside the channel of closed loop pulsating heat pipe with hydrocarbon as working fluid.

Additional research is required to fully understand the operating principles behind closed loop pulsating heat pipes as well as to better understand the heat transfer characteristics. Some key areas of focus would include decreasing the time required for pulsating action of working fluid.

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