Technology of Oscillating Heat Pipe (OHP) and their Applications

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Abstract

The oscillating heat pipe (OHP) is accepted as the high effectiveness, it can transfer heat by itself with latent heat of the working fluid in the tube. The working fluid inside the OHP will arrange in slug-train units due to the effect of surface tension. The heat can be transported from the evaporator section to the condenser section by means of the local axial oscillations and phase changes in the working fluid. Currently, OHPs are a few applications for an air to air heat exchanger because a lack of useful information for a design and selection of the OHP as heat exchanger. This review article presents knowledge of OHP technology, and their applications for an air to air heat exchanger. The various research aspects relating to heat transfer characteristic studies in OHPs are summarized and analyzed. In addition, examples of previous works that the application of OHP for an air to air heat exchangers were described. Finally, the parametric on effectiveness of OHP heat exchanger are described. The result of this article is additional information for design of the OHP heat exchanger with optimum conditions.

Key word: heat pipe, heat exchanger, pulsating, flux, air pre-heater

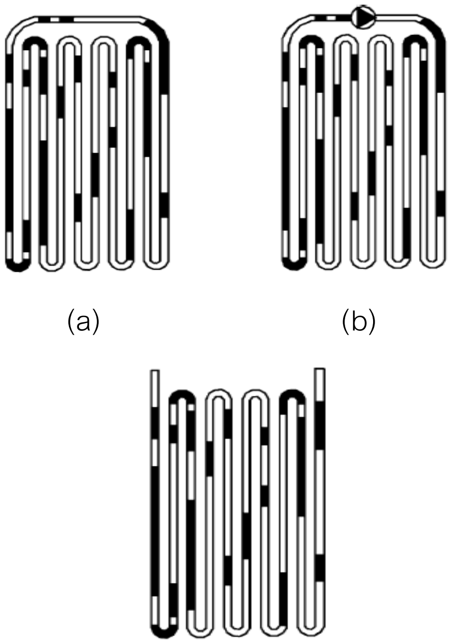
1. Introduction

The OHPs, also referred to as pulsating heat pipes (PHPs), are a relatively new development in the field of heat pipe technology. Originally developed and patented by Hisateru Akachi in 1990 [1]. Generally, OHP consists of three parts, which include the evaporator, adiabatic and condenser sections. It is made from a long continuous capillary tube bent into many turns, and it constrains more working fluid. Their operation is based on the principle of oscillation for the working fluid and a phase change phenomena in a capillary tube.

The advantage of using an OHP is that large quantities of heat can be transported through a small cross-sectional area. The OHP is a very effective heat transfer device. It has a very simple structure and a fast thermal response. It is different from the conventional heat pipe in design and working principle. In addition, no wick is required to assist the condensed working fluid to flow back to the evaporator section. Due to the effect of surface tension, the working fluid will arrange in slug-train units in the OHP. Heat is transported from the evaporator section to the condenser section by means of the local axial oscillations and phase changes in the working fluid. Fluid flow inside the OHP is very complex due to phase changes and interactions between the slugs and plugs.

Three different types of long capillary tubes are commonly employed as shown in Fig. 1. The first is a closed-loop oscillating heat pipe (CLOHP), which is connected at both ends of the tube to form a closed loop. The second is a CLOHP with a check valve (CLOHP/CV), which makes the working move in a specified direction.

The last is a closed-end oscillating heat pipe (CEOHP), which is closed at both ends.



(a) (b)

(c)

Fig. 1. Types of oscillating heat pipes (a) CLOHP (b) CLOHP/CV (c) CEOHP [2].

The heat transfer of OHP occurs because of self-exciting oscillation which may be driven by fast fluctuating pressure waves caused by nucleate boiling and condensation of the working fluid. As the criterion to find the maximum inner diameter of an OHP, assumed that where the vapor bubble is formed alternately with the liquid plug within the tube depended on the properties of the working fluid as:

$$d_{max} \leq 2\sqrt{\sigma/(g(\rho_l - \rho_v)} \,. \qquad (1)$$

Where σ is the surface tension of working fluid, g is the gravitational acceleration, σ_l is the liquid density and σ_v is the vapor density. If $d < d_{max}$, surface tension forces dominate and stable liquid plugs are formed. However, if $d > d_{max}$, the surface tension is reduced and the working fluid will stratify by gravity and oscillations will cease. The OHP may operate as an interconnected array of two-phase closed thermosyphons (TPCT).

Nowadays, the OHPs are applications for an air to air heat exchanger but a lack of useful information for a design and selection of the OHP heat exchanger. Therefore, the technology of OHPs involves their heat transfer characteristics, and their applications will also be discussed.

2. OHPs heat transfer characteristics

Since the late 1990s, numerous experimental and analytical investigations have been conducted by researchers to better understand OHPs. These investigations have focused on the mechanisms behind OHPs as well as the heat transfer characteristics. As mentioned previously, there are three distinct types of OHPs. An analysis of the heat transfer characteristics for each device will be discussed in more detail.

Many researchers analyzed the heat transfer to improve the thermal performance of OHPs. The researches was published that related to the OHPs: Khandekar et al. [3, 5], Charoensawan et al. [4], Charoensawan and Terdtoon [6], Lin et al. [7], Khandekar and Groll [8], Rittidech et al. [2, 9, 11], and Bhuwakietkumjohn and Rittidech [10]. Based on their studies, the geometric characteristics with working fluids of OHPs for these researches are compared in Table 1. The geometric characteristics of OHPs in this table are a useful data for the designers. Many factors affect to thermal performance of the OHPs. The parameters are filling ratios and type of working fluids, temperature of heat source and heat sink, inlet cold air velocity flow into condenser section, inlet hot air velocity flow into evaporator section, material type and tube diameter, evaporator length, condenser length, adiabatic length and number of turn. These parameters are considered as controlled or variable parameters depend on the purposes of the studies. From the previous research works, it can be compared in Table 2.

2.1 Heat transfer characteristic of CLOHP

The CLOHP operates under the same principle as the conventional OHP is previously discussed. It consists of a long capillary tube is bent with n number of turns. However, unlike other OHPs, the ends of the CLOHP are joined for a closed loop system. The CLOHP tends to have better thermal performance than other OHP devices owing to the possibility of fluid circulation. Many experimental investigations have been conducted to systematically investigate the heat transfer characteristics of a CLOHP, and some results of previous works will be discussed as follows. Khandekar et al. [3, 5], Charoensawan et al. [4], Charoensawan and Terdtoon [6], Lin et al. [7] and Khandekar and Groll [8] have been presented the various parameters depend on thermal performance of CLOHPs. By measuring the flow rate as well as the inlet and outlet temperature of the coolant flowing through the condenser section, it is possible to calculate the heat transfer rate for the CLOHPs. An example of CLOHP was studying, as shown in Fig. 2.

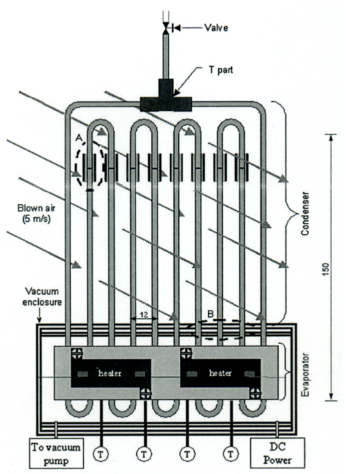


Fig. 2. The schematic of the tested CLOHP [3].

The evaporator section part of the CLOHP is made up of an aluminum block which heated by two electrical heaters, while air-cooling is applied by blowing air directly on the bare copper tubes by a centrifugal blower and connecting wind tunnel arrangement at average air velocity of 5 m/s and temperatures ranging from 24 to 28^{o}C. From the results of previous works, it can be concluded that the heat load input, volumetric filling ratio, type of working fluid, internal diameter, number of turns and inclination angle, are affected to the thermal performance of CLOHP. If the CLOHP operates in orientation, the effect of gravity on slug flow, the effect of the total number of meandering turns (n) on the perturbations and the input heat flux, which affects dynamic instability, all affects the CLOHP performance in respect to its orientation. It can be explained by the Bond Number (Bo). Bo is the ratio of buoyancy force per surface tension force. It approaches a critical number, approximately equal or less than 2, the surface tension forces dominate the forces from gravity. However, the critical number varies for different tube material and working fluid contact angles. It can be seen from view B in Fig. 3, ethanol slugs and bubbles in a glass tube under isothermal conditions, that gravity does impact the performance of a CLOHP, from the unsymmetrical shape of the bubble.

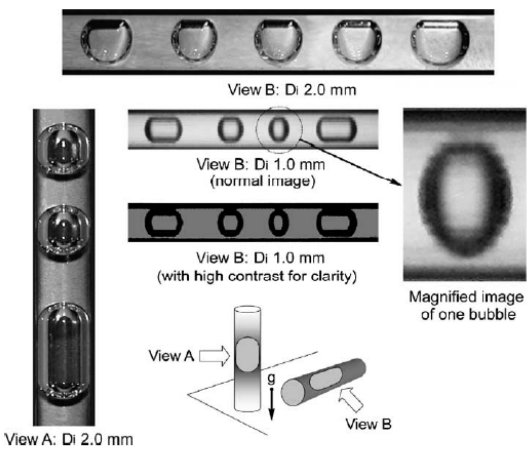


Fig. 3. Images of ethanol slugs and bubbles in glass tube for vertical and horizontal CLOHP [4].

Table 1. Comparison of the geometric characteristics of OHPs.

Types	Dimension of tube	Working fluid/FR	Number of n	Authors
CLOHP	d_i = 2 mm, d_o = 3 mm, L_e = 30 mm, L_t = 120 mm	Water/Ethanol/ R123 FR : 0-100%	4	Khandekar et al. [3]
	d_i = 1 or 2 mm L_e = L_c = L_a = 5, 10 and 15 m.	Water/Ethanol/R-123 FR : 50%	5, 7,11, 16 or 23	Charoensawan et al. [4]
	d_i = 2 mm, L_e = 50 and 150 mm	R123	11, 28	Khandekar et al. [5]
	d_i = 1, 1.5 or 2 mm L_e = 50 and 150 mm	Water/Ethanol FR : 30, 50 or 80 %	5, 11, 16 or 26	Charoensawan and Terdtoon [6]
	d_i = 0.4, 0.8, 1.3 and 1.8 mm., L_t = 100, 150 and 200 mm	Water FR: 50%	4	Lin et al. [7]
	d_i = 2 mm	Ethanol FR : 20 - 80 %	1	Khandekar and Groll [8]
CLOHP/CVs	d_i = 1.77 or 2.03 mm L_e = L_c = L_a = 50, 100 or 150 mm	Water/ethanol/ R123 FR : 50%	40	Rittidech et al. [9]
	di = 2.4 mm, L_c = 50 and 100 mm.	Silver nano-ethanol FR : 50%	2	Bhuwakietkumjohn and Rittidech [10]
CEOHP	d_i = 0.66, 1.06 and 2.03 mm, L_e = L_c = L_a = 5, 10 and 15 cm	Water/ethanol/ R123 FR : 50%	14	Rittidech et al. [2]
	d_i = 0.002 m, L_e = L_c = 19 cm	Water/ R123 FR : 50%	8/32	Rittidech et al. [11]

The calculation of the heat transfer rate for CLOHP is presented by Khandekar et al. [5]. The equation based on non-dimensional numbers for prediction the thermal performance of CLPHPs such that:

$$q = 0.54(\exp(\beta))^{0.48} Ka^{0.47} Pr_l^{00.27} Ja^{1.43} n^{-0.27} . \qquad (2)$$

Where β is an inclination angle, Ka is Karman number, Pr is Prandtl number, Ja is Jacob number and n is the number of turn. Eq. (2) with the standard deviation of ±30% is suggested by the researchers [5].

2.2 Heat transfer characteristic of the CLOHP/CV

The CLOHP/CV provides a high rate of heat transfer through the addition of one or more check valves with prevents bidirectional flow, as shown in Fig. 4. The liquid forms U-shaped columns in individual turns of the OHP and the oscillations form waves.

Table 2. Comparison of the studied parameters for the OHPs.

Type	Control parameters	Variable parameters	Authors
CLOHP	- cold air, V = 5 m/s - cold air, T = 24-28^{o}C	- filling ratios: 0-100 % - heater inputs: 5≤Q≤60W	Khandekar et al. [3]
	- cold water, T = 20^{o}C - hot water, T = 80^{o}C - filling ratio: 50%	- incline angles: 0-90 ^{o} - working fluids: water, ethanol, R123	Charoensawan et al. [4]
	- d_i = 2 mm - cold water, T = 20^{o}C - hot water, T = 80^{o}C - filling ratio: 50% - working fluid: R123	- incline angles: 0-90 ^{o}	Khandekar et al. [5]
	- cold air, V = 0.4 m/s - cold air, T = 25^{o}C	- d_i: 1-2 mm - L_e: 50 and 150 mm - number of turns: 5-26 - working fluids: water/ethanol - filling ratios: 30-80%	Charoensawan and Terdtoon [6]
	- working fluid: water - filling ratio: 50% - number of turn: 4	- d_i: 0.4-1.8 mm - L_t: 100-200 mm - heater input: 8≤Q≤32W	Lin et al. [7]
	- working fluid: ethanol - d_i = 2 mm	- FR: 20 - 80 %	Khandekar and Groll [8]
CLOHP/CVs	- working temperature: 50^{o}C - number of turn: 40 - filling ratio: 50%	- working fluids: water/ethanol - R_{cv} and L_e/d_i - d_i = 1.77-2.03 mm	Rittidech et al. [9]
	- working fluid: silver nano - filling ratio: 50% - d_i = 2.4 mm	- L_e = 50-100 mm - evaporator temperatures, T_e = 80-125^{o}C	Bhuwakietkumjohn and Rittidech [10]
CEOHP	- filling ratio: 50% - working temperature: 50^{o}C	- working fluids: water/R123 - L_t: 5-15 m - d_i: 0.66-2.03 mm	Rittidech et al. [2]
	- filling ratio: 50% - hot gas velocity: 3.3 m/s	- working fluids: water/R123 - hot air, T_h = 60, 70 or 80^{o}C	Rittidech et al. [11]

Under these conditions, the effective heat-transfer is limited by the amplitude of the waves. When the amplitude of oscillatory flow is sufficient and the heat transfer area is not included as part of the waves, the effective working fluid supply to the heat transfer area cannot be obtained and the heat transfer is not maintainable. This operating limit can be overcome by the implementation of check valves in the CLOHP design. The check valves regulate the flow such that it becomes unidirectional and the heat transfer area in not restricted by the amplitude of the oscillating flow. The check valves themselves, are a floating type of valve consisting of a stainless steel ball and copper tube. Within the tube are a conical valve seat at bottom and a ball stopper at the top. The ball is free to move between the valve seat and stopper, but when it is in contact with the valve seat it prevents reverse flow of the working fluid.

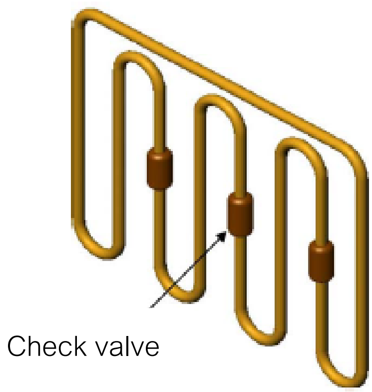


Fig. 4. The CLOHP/CVs [9].

In research on CLOHP/CV: Rittidech et al. [9] reported the heat transfer characteristics of a vertically oriented CLOHP/CV with 40 turns, an inner diameter of 2.03 mm and different working fluids. Part of the experiment is to determine the effect from the ratio of check valves (R_{cv}) on the overall heat flux. R_{cv} is defined as the number of turns divided by the of check valves. The experiment tested a CLOHP/CV with 2, 5, 8 and 20 valves. From the results, it can be concluded that the greater the ratio of check valves, the higher the heat flux and that the maximum heat flux of each working fluid was obtained at the maximum ratio of check valves. This is owing to the fact that an increase in the R_{cv}, which occurs as the number of check valves decreases, the effect from gravity on the ball also decreases. It can be concluded that as the aspect ratio increases, the heat flux decreases.

The dimensionless parameters have an effect on the heat flux for a CLOHP/CV in a vertical mode are the R_{cv}, L_e/d_i, Bo, Weber Number (We), Froude Number (Fr), Jacob Number (Ja), Prandtl Number (Pr), density ratio ($_v$/ $_l$) and Kutateladze Number (Ku). These parameters can be used to predict the heat flux of a CLOHP/CV in a vertical position such that:

$$q = 0.0004\left[Bo^{2.2}Fr^{1.42}Ja^{1.2}Pr^{1.02}\left(\frac{L_e}{D_i}\right)^{0.5}\right]^{0.107}$$

$$\times\left[\left(\frac{\rho_v}{\rho_l}\right)^{0.98}R_{cv}^{1.4}We^{0.8}\right]^{0.107}\times\left[\rho_v h_{fg}\left(\frac{\rho_l-\rho_v}{\rho_v^2}\right)\right]^{\frac{1}{4}}. \quad (3)$$

The Eq. (3) is suggested for prediction the heat flux of CLOHP/CV with the standard deviation of ±30%. The equation is useful for the designers to calculate the heat transfer rate of CLOHP/CV in during design.

In addition, the internal flow patterns and heat transfer characteristics of a CLOHP/CV is presented by Bhuwakietkumjohn and Rittidech [10]. This result, the silver nano-ethanol mixture gave higher heat flux than ethanol. When the temperature at the evaporator section was increased from 85°C to 105°C and 125°C. It was found that, the flow patterns occurred as annular flow + slug flow, slug flow + bubble flow and dispersed bubble flow + bubble flow respectively. These all flow patterns are important in understanding the heat transfer phenomena.

2.3 Heat transfer characteristic of CEOHP

The advantages of a CEOHP are its heat transferring properties in any orientation, its quick response and its internal wickless structure. Out of all the types of OHPs, CEOHPs are the least complicated operating mechanism. An experimental investigation has been conducted to investigate the heat transfer characteristics of a CEOHP at normal operating condition by Rittidech et al. [2], as shows in Fig. 5.

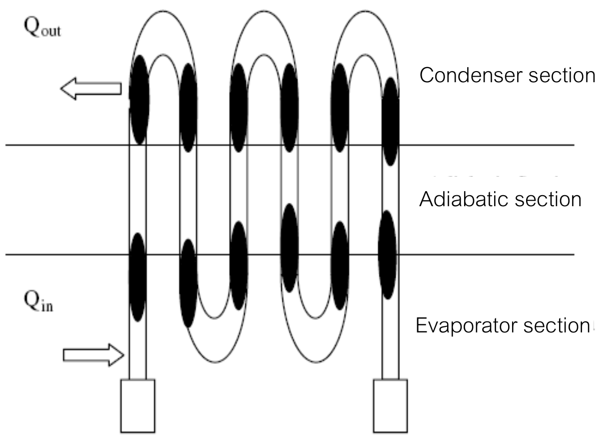


Fig. 5. The CEOHP [2].

The results will be discussed as follows: the heat transfer in a CEOHP is such that, as heat is supplied at the evaporator, the vapor bubbles originate in the evaporator section through latent heat. These bubbles move to the condenser with buoyancy force producing pumping action. Most of the bubbles that flow into the condenser section collapse and the latent heat is released. The heat is transferred through a phase change which is independent of temperature difference. The heat flux depends only on the evaporation, buoyancy force and condensation mechanism. It was noted that the inner diameter must be less than the maximum inner diameter found using Eq. (1), and greater than the inner diameter found experimentally, or the CEOHP will not be able to transfer heat. It was also concluded that the larger the inner diameter, the higher the heat flux. For the experiment, the evaporator, adiabatic and condenser sections were all of equal length, they found the heat flux at the input was equal to the heat flux at the output of the CEOHP. In addition, it is observed that as the evaporator length increased, the heat flux decreased for all working fluids. It can be concluded that as the evaporator length decreased, the effective length between the condenser and evaporator also decreases, which allows the heat to be efficiently transferred by the working fluid. The effect of the number of turns (n) on the heat flux of a CEOHP in a horizontal orientation was also considered. They presented that the number of turns has a direct effect on the heat flux. From this study it was noted that the maximum heat flux for R123 and ethanol were obtained using a CEOHP with 14 turns. It can be concluded that if there is an optimal number of turns, the heat flux will increase and then decrease with an increase in the n number. Moreover, they formulated an equation to predict the heat flux of a horizontal CEOHP is such that:

$$q = 0.0052\left[\left(\frac{D_i^{4.3} L_t^{0.1}}{L_e^{4.4}}\right) n^{0.5} \left(\frac{\rho_v}{\rho_l}\right)^{-0.2} Pr_v^{025}\right]^{0.116} \times \left[\rho_v h_{fg}\left(\frac{\rho_l - \rho_v}{\rho_v^2}\right)\right]^{\frac{1}{4}}. \qquad (4)$$

Where $D_i^{4.3} L_t^{0.1} / L_e^{4.4}$ indicates the size of the CEOHP. For example, if it is very high then the tube would be larger and the evaporator section would be short, resulting in a high heat flux. If the value is low, then the tube would be small and the evaporator section would be long with a low heat flux. The n indicates the number of turns or the number of capillary tubes connecting the evaporator and condenser sections. The ρ_v/ρ_l indicates the vapor and liquid density ratio at the working pressure of the working fluid. The Pr_v is the Prandlt number ofvapor, for a low Pr_v the heat transfer of the vapor slug will be much higher than its momentum transfer, i.e. the vapor slug will be able to transfer the thermal energy to condenser section efficiently. The Eq. (4) can be used to calculate the heat flux of a horizontal CEOHP with a standard deviation of ± 30%. However, this equation does not include the parameters of oscillation and circulation phenomena within the CEOHP; this is an area for future research

3. Air to air heat exchanger with OHP

In recently, applications of OHPs for air to air heat exchangers are conducted by Rithidech et al. [11] and Meena et al. [12]. For Rithidech et al. [11] designed, constructed and tested the CEOHP for air pre-heater which using in energy thrift of dryer. Meena et al. [12] applied CLOHP/CV for reduced relative-humidity in drying system. Notice, there is no found the recent published on the application of the CLOHP.

For understanding on the potential of OHP heat exchanger, the knowledge about thermal performance of CLOHP/CV or CEOHP air to air heat exchanger will be described. If there is a negligible heat which loss from the heat exchanger to the surroundings. The performance of the heat exchanger can be represented by its effectiveness (ε). Fig. 6 shows a schematic of the air flow arrangement and the corresponding parameters for CEOHP. The CEOHP air-preheater of [11] was employed copper tubes: 32 sets of capillary tubes with an inner diameter of 0.002 m, an evaporator and a condenser length of 0.19 m, and each of which has 8 meandering turns. The evaporator section is heated by hot-gas, while the condenser section is cooled by fresh air.

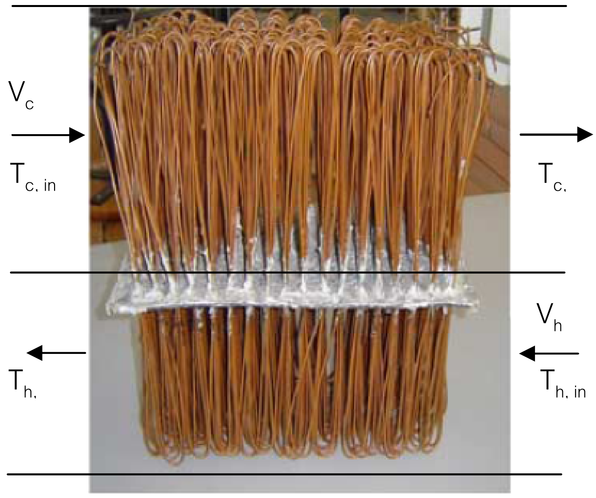


Fig. 6. The CEOHP air pre-heater [11].

The ε of the CEOHP or CLOHP/CV heat exchanger defined as;

$$\varepsilon = \frac{(T_{c,out} - T_{c,in})}{(T_{h,in} - T_{c,in})} \text{ when } (\dot{m}_c C_{p,c})_c < (\dot{m}_h C_{p,h})_h, \qquad (5)$$

or

$$\varepsilon = \frac{(T_{h,in} - T_{h,out})}{(T_{h,in} - T_{c,in})} \text{ when } (\dot{m}_h C_{p,h})_h < (\dot{m}_c C_{p,c})_c . \qquad (6)$$

The Eq. (5) or (6) was used to calculate the effectiveness of CEOHP and CLOHP/CV in the studies of [11] and [12] respectively. The average effectiveness values of both studies are 0.50 and 0.68, respectively. This result, it can be confirmed that the effectiveness calculation of CEOHP or CLOHP/CV air to air heat exchanger is accepted. Therefore, designers can be used these Eq. for the calculation of the effectiveness of CEOHP or CLOHP/CV heat exchanger.

In addition, the average effectiveness of conventional two-phase closed thermosyphon (CTPCT) for air to air heat exchangers [13-14] were compared with the OHPs as shown in Fig. 7. Clearly, the CLOHP/CV has the highest effectiveness.

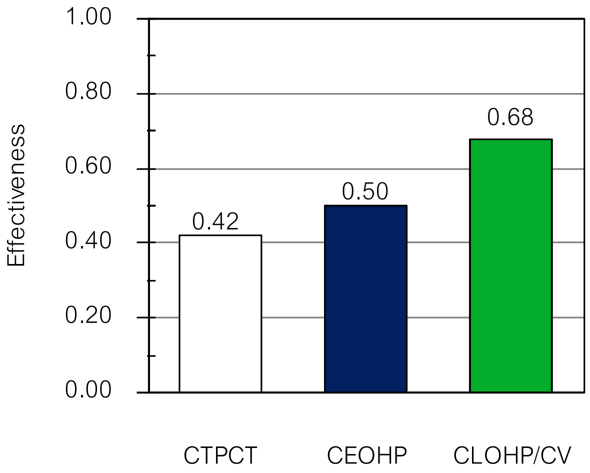


Fig. 7. Comparison of the effectiveness between CTPCT and OHPs.

4. The parametric on effectiveness of OHPs heat exchanger

There are five main parameters: (i) the length of evaporator, (ii) hot-air inlet-temperature, (iii) hot-air inlet-velocity, (iv) working fluids and (v) ratio of check valves, are significant effect on effectiveness of OHPs heat exchanger. These parameters are will be discussed as follows.

4.1 The effect of evaporator length

In case of the evaporator, adiabatic and condenser are of equal length. The heat flux decreases with a decrease of the evaporator length owing to when the evaporator length is shortly, the effective length between the condenser and the evaporator section also decreased. Therefore, heat could be efficiently transferred by the working fluid which the vapor bubble moves to condenser with very high speed. It is concluded that, if the length of evaporator is shortly, the effectiveness also increased due to the decreases of evaporator length with an increase of heat flux.

4.2 The effect of hot-air inlet-temperature

The hot-air inlet temperature increases at a lower velocity, the effectiveness also rises because the air outlet-temperature increases. The difference of temperature between the inlet and the outlet air also increased and the actual heat transfer rate will be high. It is concluded that, if the hot air inlet temperature increases with a lower velocity, the effectiveness also increase due to increase the actual heat transfer rate.

4.3 The effect of hot-air inlet-velocity

When the hot-air inlet-velocity increases with temperature, the heat transfer rate also rises. This is because, when the hot-air inlet-velocity decreases with temperature, the air outlet-temperature also increases. Thus, the temperature difference between the inlet and outlet air also increases and the actual heat transfer rate will be high. It is concluded that, if the hot-air inlet-velocity is lower at the highest temperature, then heat transfer rate increases.

4.4 The effect of working fluids

In case of water, R123 or ethanol was used as working fluids. If the working fluid changes from water and ethanol to R123 as the effectiveness increases because the R123 has a lower latent heat of vaporization.

4.5 Effect of the ratio of check valves

For the CLOHP/CV, the effectiveness increases with ratio of check valves owing to the fact that an increase in the ratio of check valves, which occurs as the number of check valves decreases.

5. Conclusion

The developments of OHPs have been carried out. The knowledge of the OHPs based on the recent published studies is discussed. The investigations focused on the heat transfer characteristics, thermal performance and applications of the three types of OHPs are detailed and described. It can be concluded that:

- The basic structure of a typical OHP consists of meandering capillary tubes having no internal wick structure. It can be designed in at least three ways: (i) closed loop oscillating heat pipe (CLOHP), (ii) closed loop oscillating heat pipe with additional flow control check valves (CLOHP/CV), and (iii) closed-end oscillating heat pipe (CEOHP).
- The designers can use the Eq. (1) to calculate the inner diameter of OHPs.
- The heat transfer rate of all the types of OHPs can be calculated from the correlations of dimensionless which described in this article: Eq. (2), (3) and (4) for CLOHP, CLOHP/CV and CEOHP respectively.
- The example of CEOHP air-preheater is presented for additional information on design an OHP air to air heat exchanger. The equation for calculation of its effectiveness was suggested.
- The parametric on the effectiveness of OHPs air to air heat exchanger is described to give awareness for the designers to select the OHP air to air heat exchanger with the optimum parameters. The optimum parameters in turn lead to energy saving in terms of cost.
- This review article helps the researchers to carry out their research in this field.

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