Energy Research Journal 1 (2): 96-103, 2010
ISSN 1949-0151

Establishment, Verification and Application of a Correlation to Predict the Maximum Heat Flux of a Horizontal Closed-Loop Pulsating Heat Pipe

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Abstract: Problem statement: In heat pipe design, it was very important to be sure that the desired heat pipe would not operate in the MHF state. In the case of a vertical CLPHP, the MHF state and maximum heat flux could be predicted by using the correlation, while, in the case of a horizontal CLPHP, there had been no study presented how to calculate the maximum heat flux. Therefore, it was necessary to establish the correlation. **Approach:** To establish a correlation to predict the maximum heat flux of a horizontal closed-loop pulsating heat pipe and to verify a reliability of the correlation which was used to predict the maximum heat flux of the heat pipe used in an actual application especially when geometrical variables, working fluid properties and also heating and cooling medium types were extremely different from variables, properties and mediums used in the study to establish the correlation. The correlation to predict the maximum heat flux of a horizontal CLPHP was established after actual cause and trends of various parameters obtained from past quantitative and qualitative studies were determined and analyzed. After that, the correlation was calculated to predict the maximum heat flux of a closed-loop pulsating heat pipe which was applied to be a flat plate solar collector. The closed-loop pulsating heat pipe was made from a copper capillary tube with the evaporator section length of 1.0 m, the condenser section length of 0.2 m and the inner diameter of 1.06 mm and bent into 75 turns. R134a was filled as working fluid. **Results:** The correlation was successfully established after analysis on trends of effects of geometrical variables on the maximum heat flux and analysis on sequence and cause of the maximum heat flux state were done. It was seen that the maximum heat fluxes calculated from the correlation were higher than actual heat fluxes that the heat pipe could transfer entire range of operation, in turn; they were higher than the heat fluxes at the normal operating state. **Conclusion:** It was found that the maximum heat flux of a horizontal closed-loop pulsating heat pipe could be accurately predicted with a coefficient of determination and standard deviation of 0.68 and ±35% respectively. In addition, the correlation has been verified that it could be reliably used to predict the maximum heat flux although variables were not in a range used in experiments for the correlation establishment.

Key words: Horizontal closed-loop pulsating heat pipe; correlation; maximum heat flux;

INTRODUCTION

The Closed-Loop Pulsating Heat Pipe (CLPHP) is a heat transfer device which has very high thermal conductivity and can operates without a requirement of any external power. It was firstly introduced by Akachi *et al*. (1996). The CLPHP is made of a long capillary tube, bent into an undulating tube and connected at the ends to form a closed loop with no internal wick structure. After inside air is evacuated, working fluid is partially filled in a tube. Because 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 vapor plugs along the entire length of the tube. This internal flow pattern is well known as “slug-train”. The structure and working fluid formation are shown in Fig. 1. Heat can be transferred by means of the replacement mechanism and incomplete condensation (Soponpongpipat *et al*., 2009). When one end of the CLPHP is subjected to heat

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or high temperature, the working fluid, which is in liquid slug form, will evaporate, expand and move toward a cooler section. Then, the vapor plug will condense, collapse and release the heat into the environment. Therefore, the vapor plug evaporating in the evaporator section will consequently flow to replace the vapor plug collapsing in the condenser section. Due to this mechanism, the working fluid can circulate and continuously transfer heat in a cycle.

Generally, if liquid quantity in the evaporator section is sufficient to transfer heat input, the CLPHP can be normally transfer the heat and an operation with this condition is defined as "normal operating state".

However, when heat input gradually increases until liquid quantity in the evaporator section is not sufficient to transfer that heat, dry-out of liquid film will occur at a tube surface inside the evaporator section (Yang *et al*., 2008; Kammuang-lue *et al*., 2009). This may lead damages to be on the tube and environment if the heat input is further increased. State in which the CLPHP cannot normally operate is defined as "maximum heat flux state" or "MHF state" and the highest heat flux that the CLPHP can transfer while it is operating in the normal operating state is called "maximum heat flux" or "$\dot{q}_{max}$".

In applications with using a CLPHP, it is necessary to have a heat pipe design in order to obtain heat transfer rate as desire by calculation on the correlation presented in (Khandekar *et al*., 2003). Moreover, the design has to correspond with actual system conditions e.g. evaporator and condenser section temperature, geometrical variables, working fluid type and also orientation of a heat pipe. In addition, it is very important to be sure that the desired heat pipe will not operate in the MHF state. In the case of a vertical CLPHP, the MHF state and maximum heat flux can be predicted and calculated by means of the correlation presented in (Kammuang-Lue *et al*., 2009). Otherwise, in the case of a horizontal CLPHP, there has been no study presented how to calculate the maximum heat flux.

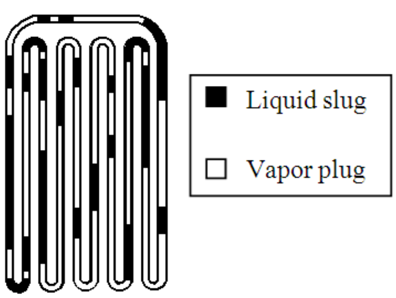

Fig. 1: Closed-loop pulsating heat pipe

There have been a quantitative study conducted on trends of effects of geometrical variables on the maximum heat flux and a qualitative study visually investigated on sequence and cause of the MHF state of a horizontal CLPHP. It can be concluded from the study that the MHF state of a horizontal CLPHP occurs due to dry-out of the liquid film in the evaporator section after the two-phased working fluid circulation changes its internal flow pattern from slug-train to stratified flow, because the surface tension of the working fluid decreases combined with the effect of the gravitational force (Kammuang-Lue *et al*., 2008).

Since a mathematical tool to calculate the maximum heat flux of a horizontal CLPHP is still limited, this study has been conducted. The objectives of this study are to establish a correlation to predict the maximum heat flux of a horizontal CLPHP and to verify a reliable of the correlation which is used to predict the maximum heat flux of the CLPHP used in an actual application.

MATERIALS AND METHODS

Experimental setup and procedure: The CLPHP used in the verification of the correlation is shown in Fig. 2. The CLPHP was made of a long copper capillary tube with the inner Diameter (D_i) of 1.06 mm and bent into 75 turns (N). The evaporator section Length (L_e) was 1.0 m. The condenser section Length (L_c) was 0.2 m. There was no adiabatic section Length (L_a = 0). R134a was selected as the working fluids. The filling ratio was 50% by total volume. The evaporator section was installed in a solar collector part which was made from

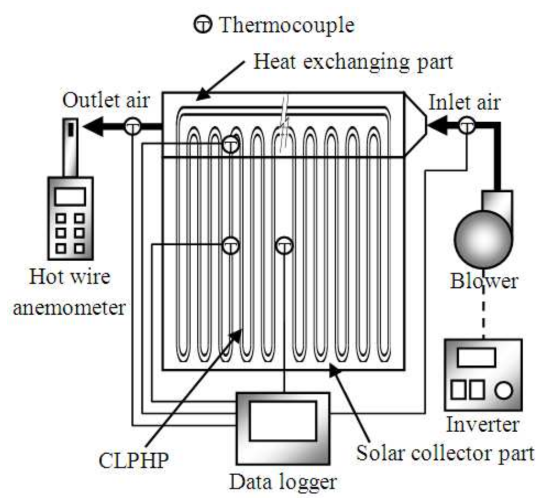

Fig. 2: Experimental setup for the verification of the correlation

wood with sizing of 1.0 m width, 2.0 m length and 0.17 m height. A transparent glass was closed as a top cover in order to allow solar radiation to pass into the collector part. The condenser section was installed in a heat exchanging part which was made from zinc with sizing of 0.2 m width, 2.0 m length and 0.17 m height. Both parts were firmly connected to completely form a flat plate solar collector. It was oriented in the horizontal plane. Fresh air at the ambient temperature was used as heat exchanging medium at the condenser section. A squirrel cage blower, of which revolution speed can be adjusted by using an inverter, was used to blow the air. Flow rate of the air was constantly controlled at 1.0 m sec^{-1} measuring by using a hot wire anemometer (Testo, 435-2, accuracy ±0.02 m sec^{-1}) at an outlet of the heat exchanging part and directly adjusted at the inverter. At specified points, the temperature was monitored by a data logger (Yokogawa, MW-100, accuracy ±0.1°C). Twenty Chromel-Alumel thermocouples (Omega, Type K, accuracy ±0.5°C) were installed on the outer surface of the capillary tube to measure the variations in temperature at every part of the heat pipe. They consisted of one point for measuring an ambient temperature, 5 points on the middle of each tube in the evaporator section, 5 points in the condenser section and 5 points on the bottom surface of the solar collector part. Two thermocouples were also placed on each inlet and outlet tube of the heat exchanging part to measure the variations of the air temperature in order to calculate the heat flux at specified times by means of the calorific as Eq. 1. The advantage of this way of measuring is that the actual throughput heat along the CLPHP could be obtained:

$$\dot{q} = \frac{\dot{m}_a c_{pa} (T_{out} - T_{in})_a}{A_c} \quad (1)$$

Where:

$\dot{m}_a$ = The mass flow rate of the air
c_{pa} = The specific heat of the air
$(T_{out} - T_{in})_a$ = The difference in temperature of the air
A_c = The inner surface area of the tube in the condenser section

The procedure was initially started from placing the flat plate solar collector on completely shade-free space. When the sun was fully shiny, the blower was started to blow the air through the heat exchanging part. Temperature at all points were recorded every a minute. The experiment was conducted until intensity of the sun light decreased to non-useful level. After that, the heat fluxes at the normal operating state were determined from Eq. 1 by using measured temperature differences between inlet and outlet air across the heat exchanging part in order to compare with the maximum heat flux obtained from the established correlation. Comparisons between these two types of the heat flux are stated in a section of verification and application of the correlation.

RESULTS

In a development of mathematical models or correlations to predict the maximum heat flux, it is important to determine and analyze actual cause and trends of various parameters obtained from quantitative and qualitative experiments. This causes the established correlation to correspond with actual physics and to be able to accurately predict the maximum heat flux. From the past quantitative and qualitative study (Kammuang-Lue *et al*., 2008), results can be obtained as follows.

Effect of evaporator section lengths on maximum heat flux: In the study on the effect of evaporator section lengths on the maximum heat flux, it was found that, when the evaporator section length increases, the maximum heat flux decreases as shown in Fig. 3. From the experiments in the case of 15-turn CLPHP, when the evaporator section length increased from 50-100 and 150 mm, the maximum heat flux decreased from 25.0-12.6 and 9.5 kW m^{-2} respectively, using R123 as working fluid. The maximum heat flux decreased from 23.7-9.2 and 7.7 kW m^{-2} respectively, using ethanol as working fluid. And the maximum heat flux decreased from 52.6-10.0 and 0.2 kW m^{-2} respectively, using water as working fluid.

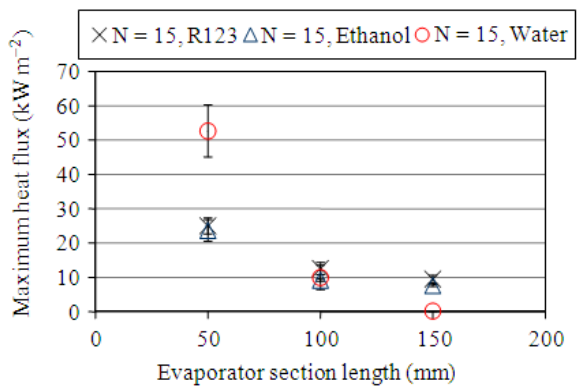

Fig. 3: Effect of evaporator section lengths on maximum heat flux

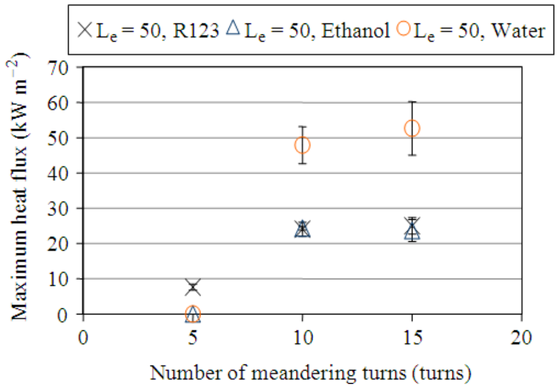

Fig. 4: Effect of number of turns on maximum heat flux

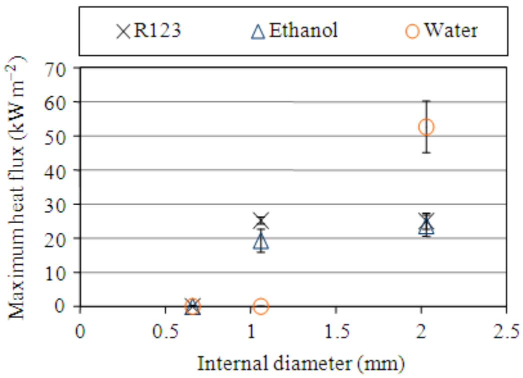

Fig. 5: Effect of internal diameters on maximum heat flux

Effect of number of turns on maximum heat flux: The study on the effect of the numbers of meandering turns on the maximum heat flux found that, when the number of meandering turns increases, the maximum heat flux increases as presented in Fig. 4. In the experiments in the case of 50 mm CLPHP, when the number of meandering turns increased from 5 turns to 10 turns and 15 turns, the maximum heat flux increased from 7.6-24.1 and 25.0 kW m^{-2} respectively, using R123 as working fluid, it increased from 0-24.3 and 23.7 kW m^{-2} respectively, using ethanol as working fluid and it increased from 0-47.9 and 52.6 kW m^{-2} respectively, using water as working fluid.

Effect of internal diameters on maximum heat flux: It was found in the study on effect of internal diameters on the maximum heat flux that when the internal diameter increases, the maximum heat flux increases as shown in Fig. 5. From the experiments, when the internal diameter increased from 0.66-1.06 and 2.03 mm, the

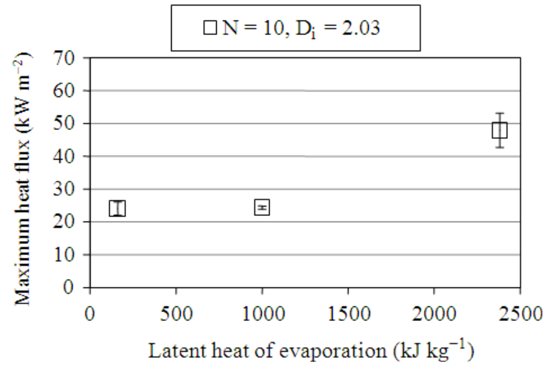

Fig. 6: Effect of working fluids on maximum heat flux

maximum heat flux increased from 0-25.2 and 25.0 kW m^{-2} respectively, using R123 as working fluid. The maximum heat flux increased from 0-19.3 and 23.7 kW m^{-2} respectively, using ethanol as working fluid. And the maximum heat flux increased from 0-0 and 52.6 kW m^{-2} respectively, using water as working fluid.

Effect of working fluids on maximum heat flux: It was found in the study of the effect of working fluids on the maximum heat flux that, when the working fluid is changed from R123 to ethanol and water, in turn, the latent heat of evaporation increases, the maximum heat flux increases as presented in Fig. 6. It could be found that when the latent heat of evaporation increased from 161-1,000 and 2,382 kJ kg^{-1}, the maximum heat flux increased from 24.1-24.3 and 47.9 kW m^{-2} respectively.

Cause of maximum heat flux state: From the qualitative study or visualization, it can be concluded that the cause of a CLPHP to operate at MHF state is as follows: the MHF state of the horizontal CLPHP occurs due to dry-out of the liquid film in the evaporator section. This is a consequential result from the two-phased working fluid circulation changing its internal flow pattern from slug-train to stratified flow, because the surface tension of the working fluid decreases combined with the effect of the gravitational force.

Correlation to predict the maximum heat flux: In addition to the phenomena inside the CLPHP, which are an internal factor that causes the CLPHP to operate in the MHF state, there are external factors, consisting of the working fluid types and the geometrical sizes of a CLPHP. These factors also affect to the maximum heat flux. Initially, a relation of various factors affecting the maximum heat flux can be written as:

$\dot{q}_{max,0}$ = f(inside phenomena, thermophysical properties of working fluid, geometrical sizes) (2)

The first term in Eq. 2 is the internal phenomena. The horizontal CLPHP can changes its operation from normal operating state to MHF state because the CLPHP receives an increased heat input or it has higher evaporator section temperature until the surface tension of working fluid decreases. In addition, the gravitational force affects the working fluid formation more dominantly in the case of a horizontal CLPHP. The internal flow pattern consequently changes from slug-train to stratified flow and dry-out finally takes place. The study of dimensionless groups, which can be used to describe the above mentioned phenomena, found that, there is a group which expresses the proportion of the surface tension to the gravitational force. That is dimensionless group of Bond number (Bo), as shown in Eq. 3:

$$Bo = \left(\frac{g(\rho_l - \rho_g) D_i^2}{\sigma} \right)^{0.5} \quad (3)$$

Moreover, when the phenomena inside the CLPHP at a transition to the MHF state are considered, it can be seen that, some sections of the liquid passage in which the temperature increases, but does not reach the saturated temperature where it can vaporize, is quickly pushed back into the condenser section due to quick expansion of vapor plug. At this point, this liquid can transfer heat out of the evaporator section by means of sensible heat. Thus, the established correlation must be included a dimensionless group, which can describe the proportion of the latent heat of evaporation to the sensible heat. That is dimensionless group of Jacob number (Ja) as Eq. 4 and this group can be also a representation of the working fluid properties in the second term of Eq. 2:

$$Ja = \left(\frac{h_{fg}}{c_{p,l} \Delta T_{e-c}} \right) \quad (4)$$

The last term in Eq. 2 is various geometrical variables affecting to the maximum heat flux. Consideration of the evaporator section and the ratio of geometrical size, i.e., aspect ratio (L_e/D_i), is also important. This ratio is classified into one of many dimensionless groups, which can be used to describe the appearance of the evaporator section of the CLPHP. In addition, the meandering turn is also a parameter, which can describe the appearance of the CLPHP. However, the number of meandering turns cannot be directly used as an absolute dimensionless parameter, since it still has a unit of cycles or turns. Because the sets of evaporator, adiabatic and condenser sections of the CLPHPs used in past study were identical, therefore, the ratio of the total length to the length of any section, which was the evaporator section length in this study, (L_t/L_e) can be used to determine how many meandering turns of the CLPHP is. This ratio is called the dimensionless group of meandering turns.

The maximum heat flux, which is a parameter appearing on the left-hand side of Eq. 2, can be substituted by the clearly known dimensionless group of Kutateladze (Ku), as shown in Eq. 5:

$$Ku_{max,0} = \frac{\dot{q}_{max,0}}{h_{fg}\rho_v} \left[\sigma g \frac{(\rho_l - \rho_v)}{\rho_v^2} \right]^{-0.25} \quad (5)$$

When the dimensionless groups consisting of Bond number, Jacob number, aspect ratio, meandering turns and Kutateladze are combined, the relationship in Eq. 2 can be rewritten as:

$$Ku_{max,0} = f(Bo, Ja, L_e/D_i, L_t/L_e) \quad (6)$$

The 54 results from the quantitative experiment, which were all obtained after the initial working condition, are brought into the calculation. The least squares curve fitting method is used in order to find the best coefficient and power of relationship in Eq. 6. Consequently, the correlation to predict the maximum heat flux of a horizontal CLPHP is established as in Eq. 7:

$$Ku_{max,0} = 0.004849 (Bo)^{0.5696} (Ja)^{-0.1396} \left(\frac{L_e}{D_i} \right)^{-1.5341} \left(\frac{L_t}{L_e} \right)^{1.3733} \quad (7)$$

Verification and application of the correlation: When the correlation to predict the maximum heat flux has been completely established, not only the correlation must be verified how it can predict the maximum heat flux accurately close to the one obtained from the actual experiment as above discussion, but also should be verified on a reliability of the correlation which is used to predict the maximum heat flux of the CLPHP used in an actual application especially when geometrical variables (L_e, L_a, L_c, N and D_i), working fluid properties and also heating and cooling medium types are extremely different from variables, properties and mediums used in the study to establish the correlation. The verification of the correlation and demonstration how to use the correlation for calculation actual application are presented in this topic. The correlation would be used to predict the maximum heat flux of a flat plate solar collector with a CLPHP installed inside. It could be seen that, various parameters concerning with the heat pipe were obviously different from the ones used in the correlation establishment i.e., the evaporator section length which was very long and was not equal to the condenser section length, quite high number of meandering turns and the CLPHP receiving heat from the sun light and releasing heat to air instead of water. Note that, the verification in this topic was not compared with the maximum heat flux obtained by increasing heat input until the CLPHP reached the MHF state as that of the past quantitative study. However, it was compared with actual heat flux that the CLPHP could transfer. This is because the application of the correlation is emphatically demonstrated and also due to a heating limitation.

In general CLPHP design, the calculation procedure to determine the maximum heat flux or the performance limit of a designed CLPHP is as follows. The geometrical sizes of the heat pipe are initially defined such as L_e, L_a, L_c, N and D_i. Then, working fluid type is selected to obtain various thermophysical properties e.g. the latent heat of evaporation, the specific heat and the surface tension. Subsequently, working conditions consisting of outer tube surface temperature in the evaporator and the condenser section are defined.

After that, all above parameters are substituted into Eq. 7 and the maximum heat flux of the designed CLPHP is determined. Finally, this maximum heat flux ($\dot{q}_{max,0}$) was compared with the desired heat flux ($\dot{q}_{normal,0}$) obtained from a design at the normal operating state. If the maximum heat flux is higher than the desired heat flux, it is shown that the CLPHP with those of design conditions is safe to operate. Otherwise, the design conditions have to be redefined.

The verification was started from using actual measured outer tube surface temperature in the evaporator and the condenser section as the initial condition in the calculation. Comparison between the heat fluxes calculated from Eq. 1 and the maximum heat fluxes predicted from Eq. 7 is shown in Fig. 7.

It could be seen from Fig. 7 that, the maximum heat fluxes predicted from the establish correlation were higher than the actual heat fluxes measured from the experiment entire the test duration.

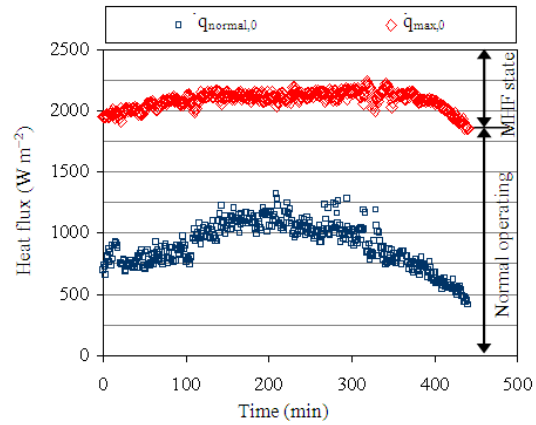

Fig. 7: Comparison of $\dot{q}_{max,0}$ from the correlation with $\dot{q}_{normal,0}$ from the actual experiment

DISCUSSION

Effect of evaporator section lengths on maximum heat flux: When the evaporator section length increases, the maximum heat flux decreases. This is because when the evaporator section length increases, the distance for heat to transfer between the liquid film and the tube's surface increases. The liquid film, which surrounds the vapor plug and contacts the top surface of the tube, dries out and the internal flow pattern changes from slug-train to stratified flow more easily. This consequently causes the maximum heat flux to decrease. This trend corresponds with a trend of the heat flux at the normal operating state obtained from earlier studies (Charoensawan *et al*., 2008).

Effect of number of turns on maximum heat flux: From the results, when the number of meandering turns increases, the maximum heat flux increases. This is because when the number of meandering turns increases, the working fluid has sufficient driving force to circulate continuously. The working fluid in liquid state can flow more continuously into the evaporator section to receive and transfer heat. Probability of dry-out to occur is lower. This consequently causes the maximum heat flux to increase. This trend corresponds with a trend of the heat flux at the normal operating state obtained from earlier studies (Charoensawan *et al*., 2008).

Effect of internal diameters on maximum heat flux: When the internal diameter increases, the maximum heat flux increases. Since, when the internal diameter increases, the cross section area proportion of vapor to liquid state working fluid decreases, in turn, the area in which the liquid film surrounding the vapor plug contacts the heating surface decreases. Therefore, the CLPHP can transfer more heat since it starts an operation. This consequently causes the maximum heat flux to increase.

Effect of working fluids on maximum heat flux: When the latent heat of evaporation increases, the maximum heat flux increases. Because, when the latent heat of evaporation increases, the working fluid requires higher heat input in order to change its phase. Thus, the CLPHP can transfer an increasing amount of heat until the volume of the vapor flow is large enough to cause a dry-patch, which is long enough to consequently cause a change in internal flow pattern from slug-train to stratified flow. Subsequently, this causes the maximum heat flux to increase.

Reliability of the correlation compared with the quantitative data used in the correlation establishment: In order to verify reliability of the correlation, the maximum heat flux calculated from Eq. 7 is also compared to the maximum heat flux obtained from the actual quantitative experiment as shown in Fig. 8. It is found that a coefficient of determination (R^2) and Standard Deviation (STD) is 0.68 and ±35% respectively. It should be noted that the thermophysical properties used in this correlation are considered at the working temperature or can be calculated from $(T_e + T_c)/2$.

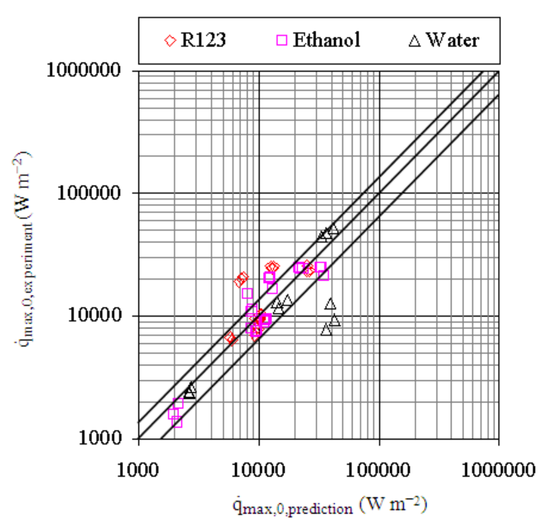

Fig. 8: Comparison of $\dot{q}_{max,0}$ from the correlation with $\dot{q}_{max,0}$ from the quantitative experiment

Reliability of the correlation used in actual application: From Fig. 7, since, it was very confident that the CLPHP used in this study transferred heat in the normal operating state all the time. This could be seen from none of appearance in abnormal sign such as dramatically increasing in outer tube surface temperature in the evaporator section or instantly decreasing in the heat flux. Therefore, the actual measured heat fluxes could be acceptably supposed to be the heat flux at the normal operating state. This could be implied that, at these working conditions, the horizontal CLPHP installed in the flat plate solar collector still operated in the normal operating state and could transfer more certain heat quantity, which was equal to the difference between the maximum heat flux and the measured heat flux, before it reached the MHF state. Since the maximum heat fluxes obtained from the correlation are higher than the heat fluxes at the normal operating state entire the experimental range as they should theoretically be, it can be verify that, the correlation can be reliably predicted the maximum heat flux, although, values of the various variables substituted into Eq. 7 are extremely different from the values used in the quantitative experiment included in the establishment of this correlation.

CONCLUSION

The objectives of this study are to establish a correlation to predict the maximum heat flux of a horizontal closed-loop pulsating heat pipe and to verify a reliability of the correlation which is used to predict the maximum heat flux of the heat pipe used in an actual application especially when geometrical variables, working fluid properties and also heating and cooling medium types are extremely different from variables, properties and mediums used in the study to establish the correlation. From this study, the correlation to predict the maximum heat flux of a horizontal CLPHP was established as Eq. 7 with a coefficient of determination and standard deviation of 0.68 and ±35% respectively. In addition, the correlation has been verified that it can be reliably used to predict the maximum heat flux although variables are not in a range used in experiments for the correlation establishment. The correlation was calculated to predict the maximum heat flux of a horizontal closed-loop pulsating heat pipe which was applied to be a flat plate solar collector. It was seen that the maximum heat fluxes calculated from the correlation were higher than actual heat fluxes that the heat pipe could transfer entire range of operation, in turn, they were higher than the heat fluxes at the normal operating state.

ACKNOWLEDGEMENT

This research was supported and cooperated by Department of Mechanical Engineering, Faculty of Engineering and Industrial Technology, Silpakorn University (Sanam Chandra Palace Campus) and Department of Mechanical Engineering, Faculty of Engineering, Chiang Mai University. The authors would like to express their sincere appreciation for all of the support provided.

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