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Research Paper

Performance enhancement of thermosyphon heat pipe by ultrasonic wave

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Abstract

This study focuses on heat transfer phenomena associated with a thermosyphon heat pipe operated under an ultrasonic wave. The thermosyphon used in this experiment has a diameter of 3.35 cm and a length of 120 cm. The lengths of the evaporator and condenser sections are 52 cm, and the length of the adiabatic section is 16 cm. In this work, water is selected as the working fluid. This thermosyphon exchanges heat between 50-80ºC hot water and 25ºC cold water. The filling ratio of the working fluid is between 50% and 100%. The inclination angle of thermosyphon is 90° from the horizontal line. The ultrasonic probe is attached at the end of an evaporator section and generates waves with a frequency of 0, 8, 10 and 14 kHz. We find that the ultrasonic wave can increase the heat transfer rate of a thermosyphon up to 230% depending on the temperature of the heat source, the frequency of the ultrasonic wave and the filling ratio. In addition, boiling thermal resistance models were developed to describe the situations where ultrasonic waves are present or absent, and they are shown to agree well with the experimental data.

Keywords: Ultrasonic wave, Heat transfer enhancement, Thermosyphon, Heat Pipe, Heat transfer modelling, energy conservation in industry, Thailand

Introduction

The development of heat exchangers in order to recover energy from industrial waste heat has become an interesting topic for energy conservation programs. A thermosyphon heat pipe, one type of heat exchanger, has been used in many industrial processes because of its many advantages, such as its high thermal conductivity, low cost, and ease of construction

The thermosyphon heat pipe shown in Figure1 can be divided into three parts: the evaporator, adiabatic, and condenser. When heat is added to the evaporator section, the working fluid (water) inside the heat pipe is boiled and vaporized. The vapor carries heat from the heat source, flows to the condenser section, and rejects heat to the heat sink. The working fluid condensate returns to the evaporator section via gravity.

Normally, the performance of a thermosyphon heat pipe depends on the temperatures of the heat source and heat sink. In the case of a low temperature heat source, the working fluid inside the thermosyphon is normally difficult to boil, and the heat transfer between the evaporator surface and the working fluid proceeds only via the free convection mode. In this case, a poor heat transfer rate is obtained. In this paper, we use an ultrasonic wave to overcome this problem by activating the heat transfer rate of the evaporator section.

Figure 2 shows the concept used to enhance the heat transfer via ultrasonic waves. In Fig. 2(a), a thermosyphon is operated in conjunction with a low temperature heat source; in this situation, the working fluid does not boil. When an ultrasonic wave is applied to the end of the evaporator section, as shown in Fig. 2(b), the ultrasonic wave energizes the working fluid and creates a turbulent condition. Therefore, a higher heat transfer rate is obtained, and the working fluid easily evaporates. Ultrasonic waves could generate alternating low-pressure and high-pressure waves in liquids, thereby leading to the formation and violent collapse of small vacuum bubbles.

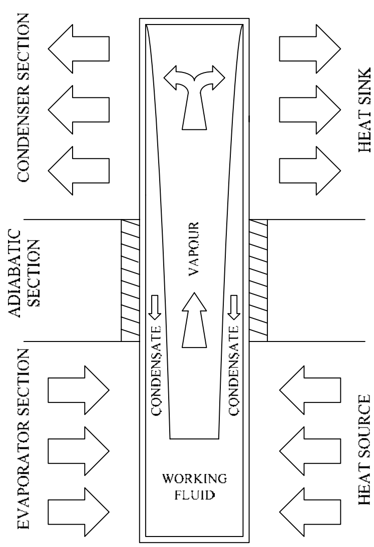


Figure 1. Schematic of the thermosyphon heat pipe.

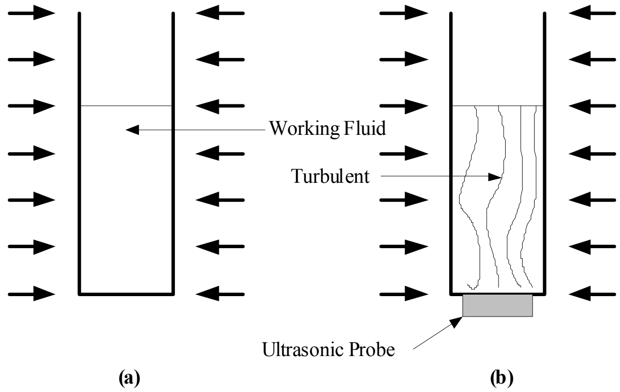


Figure 2. Effect of an ultrasonic wave on the working fluid;
(a) no ultrasonic wave **(b)** ultrasonic wave present.

Many studies have reported that ultrasonic waves can be used to enhance boiling heat transfer. Kim *et al*. [1] used ultrasonic waves to promote the pool boiling of water, and they found that the boiling heat transfer coefficient was increased by approximately 8%. Oh *et al*. [2] found that the vibrations due to the ultrasonic waves could enhance the phase change process of phase change material (PCM), and a shorter process time was obtained.

Although there are some applications of ultrasonic waves in heat transfer processes, in the case of a thermosyphon heat pipe, there is no report on the enhancement data. The aim of this study is to investigate the performance of thermosyphon heat pipes operating with ultrasonic waves. The results of the study can be applied to the design of high performance thermosyphon heat pipes for many applications, such as heat/coolness recovery equipment.

Experimental Setup

Fig. 3 shows a schematic sketch of the experimental apparatus. The thermosyphon heat pipe used in this experiment had a 3.35 cm outside diameter with a thickness of 1.3 mm and a length of 120 cm. The lengths of the evaporator and the condenser sections were 52 cm, and the length of the adiabatic section was 16 cm.

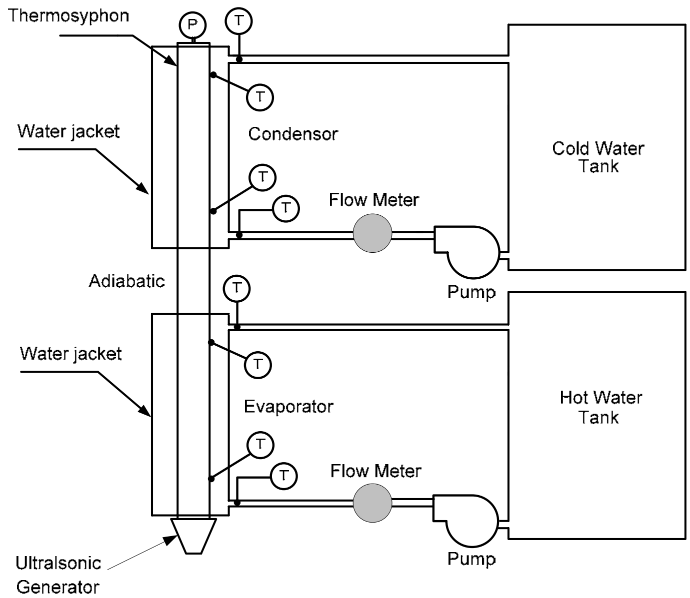


Figure 3. Schematic of the testing apparatus.

In this work, water was selected as the working fluid and the filling ratio was varied between 50% and 100% by volume of the evaporator section. The ultrasonic probe was attached at the end of the evaporator section, and waves with at frequencies of 0, 8, 10 and 14 kHz were generated. This thermosyphon heat pipe exchanged heat between 50-80ºC hot water and 25ºC cold water. Note that the inlet and the outlet temperatures of the water at the evaporator and the condenser sections were measured by K-type thermocouples and recorded by a temperature data logger. The mass flow rate of the cold and the hot water streams were measured by two calibrated rotameters and kept constant at 1.167 kg/s and 0.0035 kg/s, respectively. These data are used for calculating the performance of the thermosyphon heat pipe.

Data Reduction

From the experiment, the heat transfer rate of the thermosyphon heat pipe (Q) can be calculated from the conditions of the hot and cold water flowing in the water jacket at evaporator and condenser sections as

$$Q = \dot{m}_c Cp_c \left(T_{co} - T_{ci}\right), \tag{1}$$

$$Q = \dot{m}_h Cp_h \left(T_{hi} - T_{ho}\right), \tag{2}$$

respectively. $\dot{m}$ is mass flow rate of water, Cp is the specific heat of water, and T is defined as the water temperature. The subscripts c and h indicate cold and hot water, and the subscripts i and o are defined as the inlet and outlet conditions, respectively.

In the case where the evaporator section (shown in Fig.4) is considered, the outside surface temperature of the tube at the evaporator section (T_{eo}) and the inside temperature of the evaporator (T_{ei}) are measured. The heat transfer rate of the thermosyphon can also be calculated as

$$Q = \frac{T_{eo} - T_{ei}}{Z_{et} + Z_{ei}}, \tag{3}$$

where Z_{et} is the thermal resistance of the tube material and Z_{ei} is the boiling thermal resistance inside the evaporator. These parameters are calculated from

$$Z_{et} = \frac{ln(r_o / r_i)}{2\pi k_t L_e}, \tag{4}$$

$$Z_{ei} = \frac{1}{h_{ei} A_{ei}}, \tag{5}$$

where r_i and r_o are the inside and outside radii of the tube, k_t is the thermal conductivity of tube material, L_e is the length of the evaporator, h_{ei} is the boiling heat transfer coefficient of the working fluid, and A_{ei} is the area inside the evaporator section.

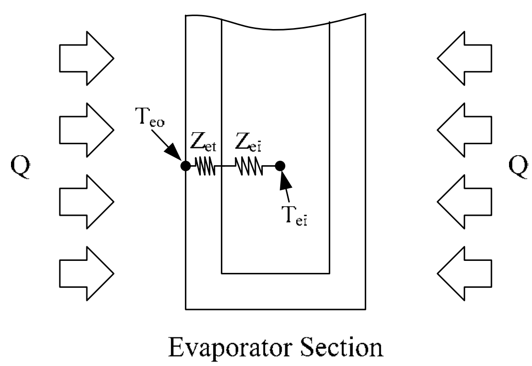


Figure 4. Thermal resistance of the evaporator section.

Results and Discussion

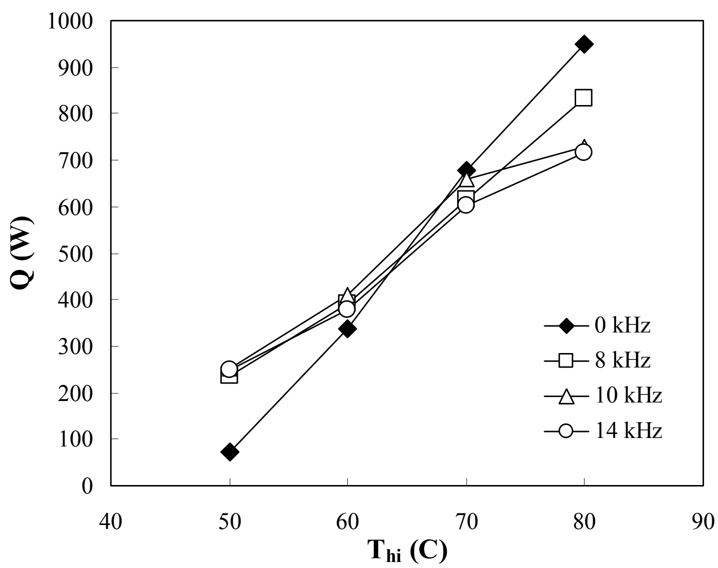
Heat transfer characteristics

Figure 5(a) shows the heat transfer rate of a thermosyphon when a working fluid with a 50% filling ratio is used. In this case, the inclination angle of the thermosyphon was 90° from horizontal. The inlet temperature of the hot water was varied between 50-80°C while the frequency of ultrasonic wave was 0 kHz (no wave), 8 kHz, 10 kHz and 14 kHz. The results from Figure 5(a) show the increase of the heat transfer rate with the inlet temperature of the hot water. Note that, in this case, the inlet temperature of the cooling water was kept constant at 25°C.

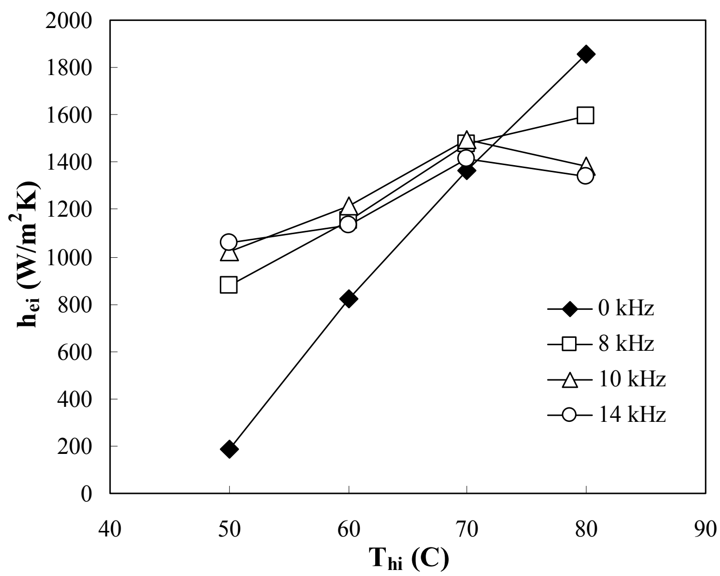
In addition, it was found that when the inlet temperature of the water is between 50-60°C, the heat transfer rate in the case without an ultrasonic wave is lower than the case with an ultrasonic wave around 230% (at 50°C) and 16% (at 60°C). However, when the inlet temperature of the water is higher than 70°C, the performance of no ultrasonic case is higher than those of having ultrasonic cases. These results can be explained as follows.

In the case of a low heat source temperature (lower than 70°C), the working fluid inside the thermosyphon is hardly to vaporize, and the heat transfer between the internal surface of the tube and the working fluid occurs via natural convection [3]. When the ultrasonic wave is applied to the bottom of the evaporator section, it promotes turbulence in the working fluid inside the tube, and part of working fluid can be evaporated. Therefore, an increase of the heat transfer rate is obtained.

However, when the heat source temperature is increased (in this case it was higher than 70°C), the working fluid reaches its boiling point (at its vapor pressure). Therefore, the working fluid can be boiled and vaporized easily, resulting in an increase of the heat transfer rate. Under these conditions, if the ultrasonic wave is applied to the evaporator section, it results in a lower heat transfer rate than in the case where no wave is present. This result may be due to the drying out of the heating surface of the evaporator section. Actually, when the working fluid is boiling, the ultrasonic wave can push the working fluid out of the heating surface easily, and the heat transfer surface is lost. This explanation is supported by data shown in Fig. 5(a) where, in the case when the inlet temperature of the water is higher than 70°C, a higher wave frequency reduces the heat transfer rate.



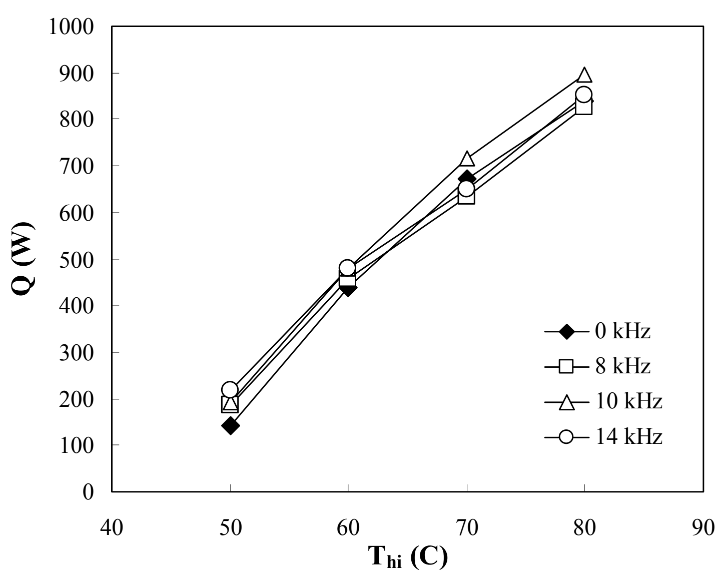
(a)



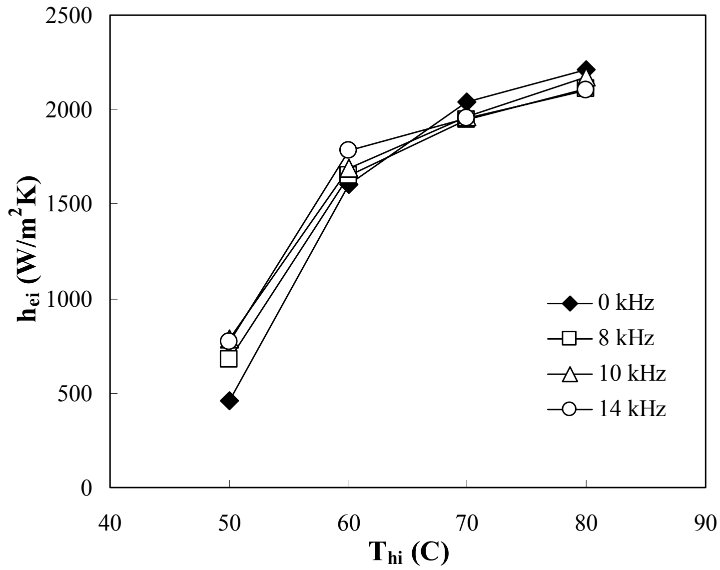
(b)

Figure 5. Heat transfer rate (a) and heat transfer coefficient (b) in the case of a 50% filling ratio at various conditions.

The heat transfer coefficient in this case is also shown in Fig. 5(b). These results agree with those of Fig 5 (a) and show that the ultrasonic wave increases the heat transfer coefficient by around 350% at 50°C and 38% at 60°C. However, for a hot water inlet temperature greater than 70°C, the heat transfer coefficient is reduced around 13-20% when an ultrasonic wave is present.



(a)



(b)

Figure 6. Heat transfer rate (a) and heat transfer coefficient (b) for the case of a 100% filling ratio at various conditions.

The effect of the filling ratio of the working fluid on the performance of thermosyphon is shown in Figs. 5-6. Since the ultrasonic enhancement technique can be applied with the thermosyphon heat pipe of solar collector which the filling ratio is higher than 50%. Because of this possibility, this part focuses on the effect of filling ratio, especially in case of a 100% filling ratio. As is shown in Fig. 6(a), the ultrasonic wave has an effect on the heat transfer of a thermosyphon heat pipe same as that of case 50% filling ratio. However, a 50% filling ratio has a stronger effect on the heat transfer rate than a 100% filling ratio. In the case of a 100% filling ratio, a heat transfer enhancement was found for a hot water inlet temperature of less than 60°C. For a hot water inlet temperature of around 50°C, the application of an 8 kHz, 10 kHz and 14 kHz ultrasonic wave can increase the heat transfer rate by approximately 33%, 37% and 56%, respectively. Moreover, when the hot water inlet temperature was higher than 70°C, the ultrasonic wave had no effect on the heat transfer rate of the thermosyphon. These results can be explained as follows.

In the case of a 100% filling ratio, the hydrostatic pressure at the bottom of the evaporator decreases the effect of turbulence produced by ultrasonic waves. Therefore, the heat transfer enhancement obtained when ultrasonic waves were used is lower than that measured when a fluid with a 50% filling ratio was used (in which case the hydrostatic pressure has a smaller effect). However, this hydrostatic pressure can also reduce the effect of dry-out of the heat transfer surface due to the ultrasonic wave.

From Fig. 6(b), we also find that the heat transfer coefficient agrees with the heat transfer rate. However, it should be noted that the heat transfer coefficient in the case of a 50% filling ratio is larger than that in the case of a 100% filling ratio, particularly when the inlet temperature of the hot water is higher than 60°C. This result may come from the boiling phenomenon that occurs in the thermosyphon. In the case of a 50% filling ratio, the boiling of the thermosyphon can be divided into two parts: pool boiling (at the liquid pool) and film boiling (at the condensate turn-down). However, in the other case, the boiling in the evaporator section only involves pool boiling. Actually, in the case of a low operation temperature (T_{hi} = 50°C), pool boiling has a stronger effect than film boiling; this is due both to the small amount of condensate turn-down and the heating surface lack of condensate. Therefore, under these operating conditions, the heat transfer coefficient for a fluid with a 100% filling ratio is higher than that of a fluid with a 50% filling ratio. However, when the temperature is increased, the effect of film boiling is dominant. Since the film boiling heat transfer coefficient is higher than the pool boiling heat transfer coefficient, the heat transfer coefficient in the case of a fluid with a 50% filling ratio is higher than that of a fluid with a 100% filling fraction.

Heat transfer modelling

This section is divided into two parts. In the first part, we derive an expression for the boiling heat transfer coefficient of the working fluid inside the thermosyphon without an ultrasonic wave. For the second part, the effect of the ultrasonic wave is included in the model so that we can predict the boiling heat transfer coefficient.

For the first part, we use the well-known ESDU model to predict the boiling heat transfer coefficient of a working fluid inside a thermosyphon [4]. The concept of this model involves separating the boiling processes of the working fluid into two parts: pool and film boiling. The total boiling heat transfer coefficients can be calculated as

$$h_{ei} = \frac{1}{Z_{ei} A_e}. \tag{5}$$

The thermal resistance of boiling (Z_{ei}) can be evaluated from

$$Z_{ei} = Z_p \qquad \text{for} \qquad Z_p < Z_f, \tag{6}$$

$$Z_{ei} = Z_p F + Z_f (1 - F) \qquad \text{for} \qquad Z_p \geq Z_f, \tag{7}$$

$$Z_p = \frac{1}{\Phi_1 g^{0.2} Q^{0.4} (\pi D_i L_e)^{0.6}}, \tag{8}$$

$$Z_f = \frac{0.235 Q^{1/3}}{D_i^{4/3} g^{1/3} L_e \Phi_2^{4/3}}, \tag{9}$$

$$\Phi_1 = 0.32 \frac{\rho_l^{0.65} k_l^{0.3} Cp_l^{0.7}}{\rho_v^{0.25} \lambda^{0.4} \mu_l^{0.1}} \left[\frac{P_v}{P_a}\right]^{0.23}, \tag{10}$$

$$\Phi_2 = \left(\frac{\lambda k_l^3 \rho_l^2}{\mu_l}\right)^{0.25}, \tag{11}$$

where Z_p and Z_f are the pool boiling and film boiling thermal resistances, respectively, F is the filling ratio, g is gravitational acceleration, Q is the heat transfer coefficient, D_i is the inside diameter of the tube, L_e is the evaporator length, ρ_l, k_l, Cp_l, μ_l are density, thermal conductivity, specific heat and dynamic viscosity of the liquid, respectively, ρ_v is the density of the gas, λ is the latent heat of vaporization, and P_v and P_a are the vapor and atmospheric pressures, respectively.

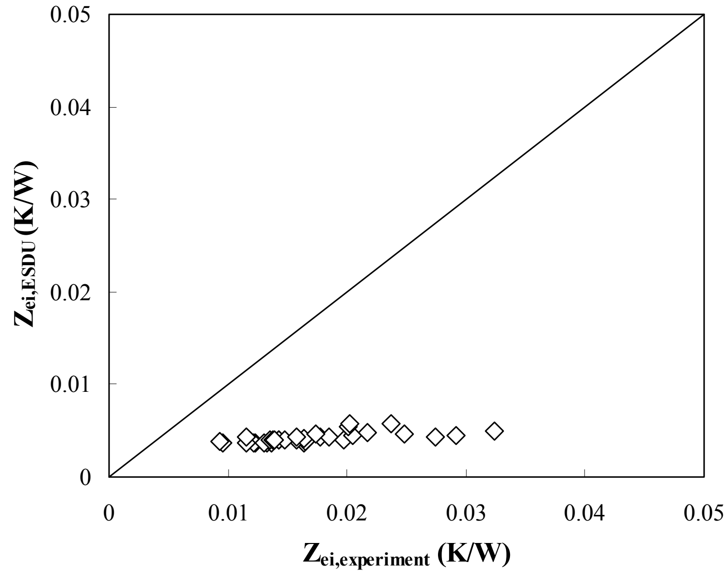


Figure 7. Comparison of the experimentally and theoretically obtained boiling thermal resistance.

In the case of a fluid with a 50% filling ratio, the thermal resistance from the experiment is compared with the ESDU model, and the results are shown in Fig. 7. It is found that the ESDU model cannot predict the experimental data. Actually, the ESDU model is used for predicting the thermal resistance in the case when the working fluid readily boils. However, in this experiment, the working fluid is hard to boil at the testing temperature range. Therefore, using the ESDU model for evaluating the thermal resistance will result in large errors. This observation is validated by investigating the case of low thermal resistances. Fig. 7 shows that when the thermal resistance is lower than 0.01 K/W, the experimental value is close to that predicted by the ESDU model. A low thermal resistance means high boiling performance. This means that the ESDU model is correct for high temperature heat sources.

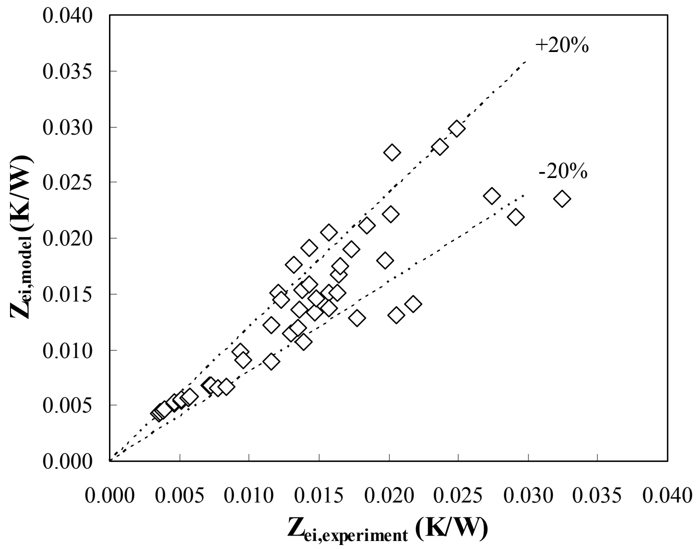


Figure 8. Comparison of the boiling thermal resistance between the experimental and model data in the case when no ultrasonic wave is present.

In this work, the model used to predict the thermal resistance in the case of no ultrasonic wave and the inlet temperature of the heat source was between 50 °C and 80 °C is also developed based on the ESDU model. This model can be described as

$$Z_{ei,no\_wave} = 0.9925\overline{F}^{3.2199} Z_{ei,ESDU}^{\delta}, \tag{12}$$

$$\delta = -0.2080 + 1.7175\overline{F}, \tag{13}$$

where $\overline{F}$ is equal to the ratio of the working fluid volume and the tube volume. It should be noted that the standard deviation of this model is 0.207, and this model can be predicted 75.5% of experimental data within ±20% variation. Fig. 8 shows a comparison of the thermal resistance obtained experimentally and numerically via the model given in equations (12)-(13).

When an ultrasonic wave is used to enhance the boiling of the working fluid inside the thermosyphon, the heat transfer correlation is also developed and the model is

$$Z_{ei,ul} = 0.9931\overline{F}^{2.7262}\left(\frac{f}{f_{\max}}\right)^{-1.6056} \beta^{\phi} Z_{ei,no\_wave}^{\theta}, \tag{14}$$

$$\phi = -0.2213\overline{F} + 1.1821\left(\frac{f}{f_{\max}}\right) - 0.6447, \tag{15}$$

$$\theta = 2.0520\overline{F} - 1.6056\left(\frac{f}{f_{\max}}\right) - 0.0562, \tag{16}$$

where f is the wave frequency, $f_{\max}$ is equal to 14 kHz, and β is the inclination angle (which is equal to 1.571 rad (90°)). It should be noted that the standard deviation of this model is 0.193, and this model can predict 88.6% of the experimental data to within ±20%. Fig. 9 shows a comparison of the thermal resistance obtained experimentally and numerically via the model given in equations (14)-(16).

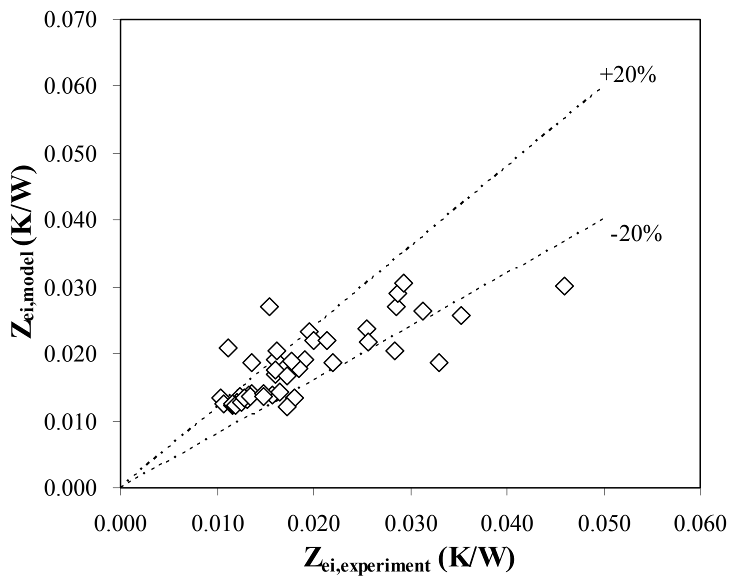


Figure 9. Comparison of the boiling thermal resistance between the experimental and model data in the case when an ultrasonic wave is present.

Energy ratio

The capacity of the ultrasonic wave to enhance the boiling heat transfer of a thermosyphon heat pipe is shown in terms of the energy ratio. This ratio is defined as the energy gain when using an ultrasonic wave compared to a normal thermosyphon divided by the energy consumption of the ultrasonic probe. The definition of energy ratio is written as

$$ER = \frac{Q_{ul} - Q_{no\_ul}}{E_P}, \tag{17}$$

where ER is the energy ratio, Q_{ul} and Q_{no_ul} are the heat transfer rates of the thermosyphon with and without an ultrasonic wave, respectively, and E_P is the energy consumption of the ultrasonic probe.

Figure 10 shows the energy ratio at various conditions. The results show that the ultrasonic wave can enhance the heat transfer in the temperature range of 50°C to 65°C or before the working fluid starts to boil. However, when the inlet temperature of water is higher than 65°C, the working fluid can boil by itself and using the ultrasonic wave gets the dry out of the heating surface. Therefore, the energy ratio is less than zero. Moreover, it is found that, at a frequency of 8 kHz, the energy ratio is the highest (in the temperature range of 50°C to 65°C). This result comes from the fact that the frequency of the wave does not have much of an effect on the enhancement, while the energy consumption of the ultrasonic probe increases with the frequency of the ultrasonic wave. Therefore, an ultrasonic wave can be used to enhance the heat transfer rate of a thermosyphon when a proper water inlet temperature (between 50°C and 65°C) and frequency of the wave (8 kHz) are used.

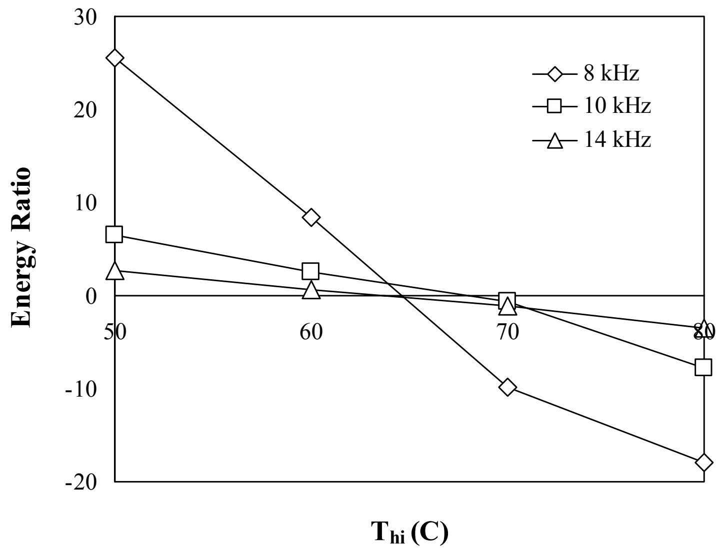


Figure 10. Energy ratio of the thermosyphon when using an ultrasonic wave.

Conclusion

From this study, it can be concluded that:

- The application of an ultrasonic wave to enhance the heat transfer rate of a thermosyphon works for inlet water temperatures lower than 65°C when the frequency of the wave is 8 kHz.
- The ultrasonic wave has more of an effect on the performance of the thermosyphon in the case of a 50% filling ratio than for a 100% filling ratio.
- The model for predicting the boiling thermal resistances in case of with and without ultrasonic waves are also developed and it can be predicted the boiling thermal resistance quite well.

Acknowledgements

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References

1. Kim, H.T., Kim, Y.G. and Kang, B.H. (2004), Enhancement of Natural Convection and Pool Boiling Heat Transfer via Ultrasonic Vibration, **International Journal of Heat and Mass Transfer**, Vol. 47, pp. 2831-2840.

2. Oh, Y.K., Park, S.H. and Cho, Y.I. (2002), A Study of the Effect of Ultrasonic Vibrations on Phase-Change Heat Transfer, **International Journal of Heat and Mass Transfer**, Vol. 45, pp. 4631-4641.

3. Nuntaphan, A., Tiansuwan, J., Kiatsiriroat, T. (2000), Heat Transfer Coefficients of Thermosyphon Heat Pipe at Medium Operating Temperature, 1st Regional Conference on Energy Technology Toward a Clean Environment, Chiang Mai, Thailand.

4. Engineering Data Science Unit No. 81038 (1983), Heat Pipes-Performance Enhancement of Two-Phase Closed Thermosyphon, ESDU Int. Plc., London, UK.

NOMENCLATURE

A_{ei}	Area inside the evaporator section (m^2)
Cp_c	Specific heat of cold water (J/kgK)
Cp_l	Specific heat of liquid (J/kgK)
Cp_h	Specific heat of hot water (J/kgK)
D_i	Inside diameter of the tube (m)
E_P	Energy consumption of ultrasonic probe
ER	Energy ratio
F	Filling ratio
$\overline{F}$	Ratio of the working fluid volume to the tube volume
f	Wave frequency (Hz)
$f_{\max}$	Maximum wave frequency (14 kHz)
g	Gravitational acceleration (9.81 m/s^2)
h_{ei}	Boiling heat transfer coefficient of the working fluid (W/m^2K)
k_l	Thermal conductivity of the liquid (W/mK)
k_t	Thermal conductivity of the tube material (W/mK)
L_e	Length of the evaporator (m)
$\dot{m}_c$	Mass flow rate of cold water (kg/s)
$\dot{m}_h$	Mass flow rate of hot water (kg/s)
P_a	Atmospheric pressure (Pa)
P_v	Vapor pressure (Pa)
r_i	Inside radius of the tube (m)
r_o	Outside radius of the tube (m)
Q	Heat transfer rate (W)
Q_{ul}	Heat transfer rate of thermosyphon (with ultrasonic wave)
Q_{no_ul}	Heat transfer rate of thermosyphon (without ultrasonic wave)
T_{ci}	Inlet temperature of the cold water (°C)
T_{co}	Outlet temperature of the cold water (°C)
T_{hi}	Inlet temperature of the hot water (°C)

T_{ho}	Outlet temperature of the hot water (°C)
Z_{et}	Thermal resistance of the tube material (K/W)
Z_{ei}	Boiling thermal resistance inside the evaporator (K/W)
Z_p	Pool boiling thermal resistance (K/W)
Z_f	Film boiling thermal resistance (K/W)
β	Inclination angle which equal to 1.571 rad (90°)
λ	Latent heat of vaporization (J/kg)
μ_l	Dynamic viscosity of liquid (Ns/m^2)
ρ_l	Density of liquid (kg/m^3)
ρ_v	Density of gas (kg/m^3)