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Performance of Brazed and Adhesive Bonded Pin Fins

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Abstract

A study to determine the magnitude of thermal contact resistance at the base plate - root of pin fin interface is presented. This is relevant to the performance of a heat sink/exchanger, if its fin and base plate is not made from one piece of metal. For instance, annular fins are usually fitted to tube, and thermal contact resistance does exist between the tube and the root of this fin. In this work, a 3 mm diameter and 60 mm height brass pin fins were adhesive bonded or brazed to an aluminium base plate. To determine the thermal contact resistance, the base plate was heated and temperatures at the root, middle and tip of the fins were recorded. Heat transfer coefficient for natural convection was evaluated using available correlations. Thermal contact resistance was calculated using the temperature difference and heat flow between fin's root and base plate. A finite difference heat transfer scheme was used to study the effect of heat transfer coefficient on the performance of fins. The thermal contact resistance for brazed fin was 28.5% less than the adhesive bonded fin. However, for the brazed and adhesive bonded pin fin, the differences in heat flow, fin efficiency and fin effectiveness was found to be 5%, 2 % and 2 times, respectively. The effect of thermal contact resistance on the performance of brazed and adhesive bonded fins is negligible if the heat transfer coefficient is less than 10 $Wm^{-2}K^{-1}$. These findings are useful to assist the design of heat sink equipped with fin that operates in natural heat convection region.

Keywords: Thermal contact resistance; fin efficiency; fin effectiveness; heat sink; heat exchanger.

INTRODUCTION

Extended surface such as fin is a structure that is usually employed to increase the effective surface area for heat transfer. Efficient heat dissipation is one of the key parameters to ensure a process occurs at its optimum level. For instance, the performance of thermoelectric generator is closely related to its heat exchanger effectiveness [1]. A fast transient response of thermoelectric generator is also affected by its heat exchange efficiency [2]. Fin is also used in melting process of phase change material [3] and in solar energy for dissipating heat from photovoltaic panel [4]. Issues on heat generated by light-emitting diode module [5] may utilize extended surface to maintain the lamp module's temperature.

Therefore, it is essential to improve the performance of a fin. Various methods have been used to increase the efficiency of fins. Addition of dimples improves the performance of fins array [6]. Optimum fins spacing also enhance the performance of annular fins on horizontal cylinder [7] or vertical cylinder [8]. Shapes of fin such as longitudinal fin on vertical cylinder also give a better performance [9]. Pin fins improve the efficiency in material use, hence reduce the mass of a heat transfer components [10]. Novel design of fin in heat exchanger may increase its performance in the region of natural heat convection [11].

Different fin design is required for the fin operating under the force or natural heat convection conditions. Another factor that influences the performance of a fin is the joining method between fin and base plate, where adhesive bonded fin has higher thermal contact resistance compared to soldered fin [12]. Various joining methods may be relevant if a complex geometry of fin is required, such as in [13]. Furthermore, the performance of fin in adsorption chiller's adsorber is compromised if thermal contact resistance does exist at the fin-base plate interface [14]. Performance of thermoelectric heat pump is significantly affected if the fin has low efficiency [15], particularly if air is used as heat transfer medium. Thus, the effect of thermal contact resistance at the base plate-fin interface is worth investigation to determine its effect to fin performance.

This paper presents the measurement of thermal contact resistance for adhesive bonded and brazed fins. Then, the finite difference heat transfer scheme of fin was used to predict the effect of thermal contact resistance on fin performance at various heat transfer coefficient.

METHODOLOGY

This section presents the experiment to determine thermal contact resistance and data analysis to obtain performances of fins. The method on prediction of fin performance at various heat transfer coefficient using finite-difference heat transfer scheme is briefly explained.

Experiment apparatus and procedures

The main component in this experiment was two pin fins made of brass, brazed or bonded onto aluminium base plate (Fig. 1). The pin fins has the height (L) of 60 mm and diameter of 3 mm. The first pin fin was bonded using Electrolube heat transfer compound onto the base plate while the second fin was brazed to the base plate.

A hot water reservoir was used to heat the base plate (Fig. 2). This hot water reservoir was made from 2 cm thick expanded polystyrene, with the volume of 48 liters. Type K thermocouples were used to measure the temperatures at the root, middle and tip of the fins, base plate, ambient air and hot water reservoir. A TC-08 Picologger temperature recorder was used to record the temperatures.

Hot water at the temperature of 85 °C poured into the hot water reservoir. Then, the lid of the reservoir and base plate was placed at its position as in Fig. 2. The temperatures were recorded at the interval of 1 second.

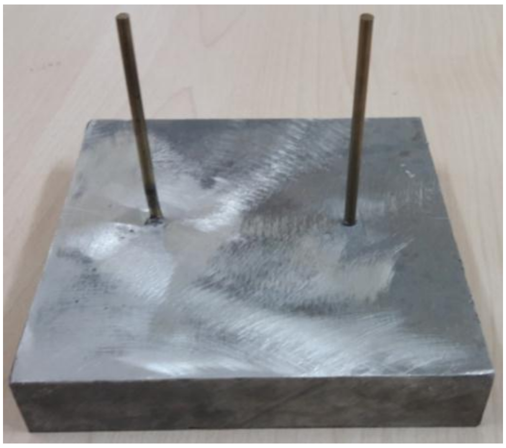

Figure 1: Brass pin fins brazed (left) and adhesive bonded (right) onto aluminium base plate

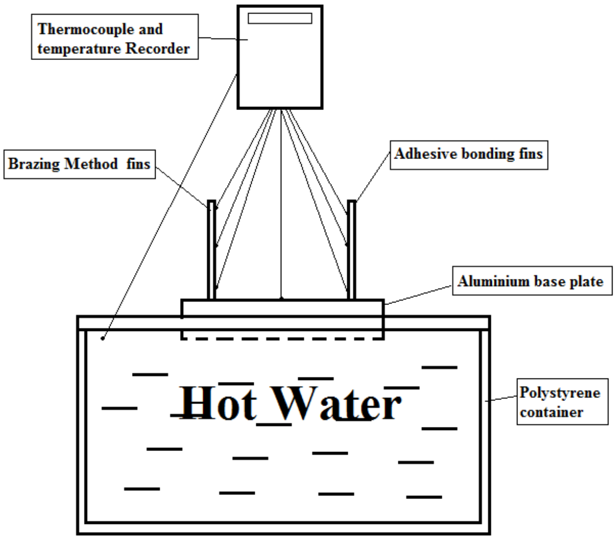

Figure 2: Schematic diagram of apparatus for thermal contact resistance experiment

Data analysis

The heat flow through the fin with adiabatic tip was estimated using Equation 1[16]:

$$Q = \sqrt{hp_f kA_c}(T_b - T_\infty)\tanh nL \tag{1}$$

where $n = \sqrt{\frac{hp_f}{kA_c}}$, h is heat transfer coefficient, p_f is the perimeter of the fin, k is the thermal conductivity, A_c is cross sectional area, T_b is the base temperature, T_∞ is the air temperature and L is the height of the fin. For the brazed and adhesive bonded fins, T_b was replaced with temperature at the root (bottom) of the fin.

The Nusselt number(Nu) was calculated using Equation 2[16]:

$$Nu = \left(0.825 + \frac{0.387\, Ra_L^{1/6}}{\left[1 + (0.492/Pr)^{9/16}\right]^{8/27}}\right) \tag{2}$$

where Nu is Nusselt number, Ra is Rayleigh number and Pr is Prandtl number. The surface temperatures of fin were taken at the average (60 readings) at root, tip and middle temperatures.

Heat transfer coefficient (h) was determined by Equation 3:

$$h = \frac{Nu\, k}{L} \tag{3}$$

The efficiency (η) of the fin was calculated using Equation 4:

$$\eta = \frac{\tanh nL}{nL} \tag{4}$$

Then, the effectiveness (ε) of the fin was determined using Equation 5:

$$\varepsilon = \frac{Q}{h\, A\, (T_b - T_\infty)} \tag{5}$$

The properties of air were determined once the fin was reached steady-state temperature (average of 60 readings).

Thermal contact resistance was evaluated using Equation 6:

$$R_c = \frac{T_b - T_{root}}{\left(\frac{Q}{A_c}\right)} \tag{6}$$

where R_c is thermal contact resistance and T_{root} is root (bottom) temperature of fin.

Finite difference heat transfer scheme of pin fins

This section presents a mathematical model that was used to predict the heat lost from a pin fin (Fig. 3). The fin has a diameter of 3 mm and height of 60 mm.

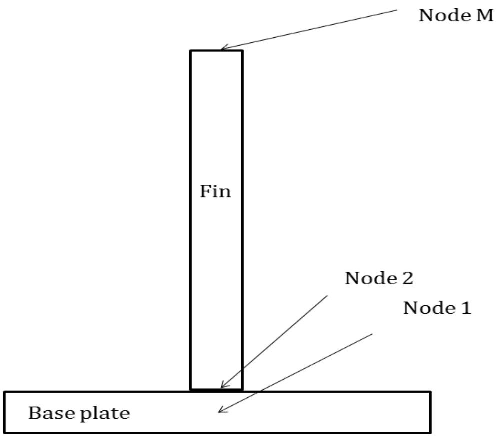

Figure 3: The schematic of fin model. Thermal contact resistance is between Node 1 and Node 2 for brazed and adhesive bonded fin

The heat equation (Equation 7) is for 1-dimensional heat conduction with constant thermal properties and constant volumetric heat generation [17]:

$$\frac{1}{\kappa}\frac{\delta T}{\delta t} = \frac{\delta^2 T}{\delta x^2} + \frac{\dot{q}_g}{k} \tag{7}$$

where κ is thermal diffusivity, k is the thermal conductivity and q_g is net heat generation per unit volume of the fin. Equation 7 was manipulated to yield Equation 8 for fin made from a single piece metal (no thermal contact resistance):

$$T_2^p = Fo\left(T_3^{p-1} + T_1^{p-1}\right) + (1 - 2Fo)\,T_2^{p-1} + \frac{\delta t\,\dot{q}_g}{\rho_f\,c_f} \tag{8}$$

where Fo is the Fourier number, the superscript p represents the calculation at the time step = p, ρ_f and c_f are the density and specific heat of the fin, respectively.

For the brazed and adhesive bonded fin, the temperature at node 2 at the next time step (p) follows from Equation 9:

$$T_2^p = T_2^{p-1} + 2Fo\left[T_3^{p-1} - T_2^{p-1} - Bi\,T_2^{p-1} + Bi\,T_1^{p-1}\right] + \frac{\dot{q}_g}{\rho_f\,c_f}\delta t \tag{9}$$

where Bi is the Biot number.

The temperature of node 1 (T_1) in Fig. 3 was maintained throughout the simulation. The end surface of the fin (node M) is assumed adiabatic and follows from Equation 10:

$$T_M^p = Fo\left(2T_{m-1}^{p-1}\right) + (1 - 2Fo)\,T_M^{p-1} + \frac{\delta t\,\dot{q}_g}{\rho_f\,c_f} \tag{10}$$

For internal nodes (m= 3 to m=M-1), temperature at node m at the next time step (p+1) follows from

$$T_m^p = Fo\left(T_{m+1}^{p-1} + T_{m-1}^{p-1}\right) + (1 - 2Fo)\,T_m^{p-1} + \frac{\delta t\,\dot{q}_g}{\rho_f\,c_f} \tag{11}$$

The volumetric heat generation (equivalent to heat loss through convection) was calculated using Equation 12:

$$\dot{q}_g = \frac{4\,h\left(T_\infty - T_m^p\right)}{D} \tag{12}$$

where D is the diameter of fin.

RESULTS

This section presents the results from experiment and finite difference heat transfer scheme

Determination of thermal contact resistance

Fig. 4 shows the temperature curves at the bottom (root), middle and tip of the fin. The temperature at the root of adhesive bonded fin was always lower than the temperature of brazed fin. This indicates the thermal contact resistance for adhesive bonded fin is higher than the brazed fin. By adopting Equations 1 through 6, the heat flow, efficiency and thermal contact resistance of those fins were obtained, and presented in Table 1. Adhesive bonded fin has a 28.5 % higher thermal contact resistance compared to brazed fin. However, the difference in heat flow and efficiency between these fins was 5 % and 2 %, respectively. These calculations confirmed that adhesive bonded fin has a lower thermal conductance, and less heat is dissipated by the fin.

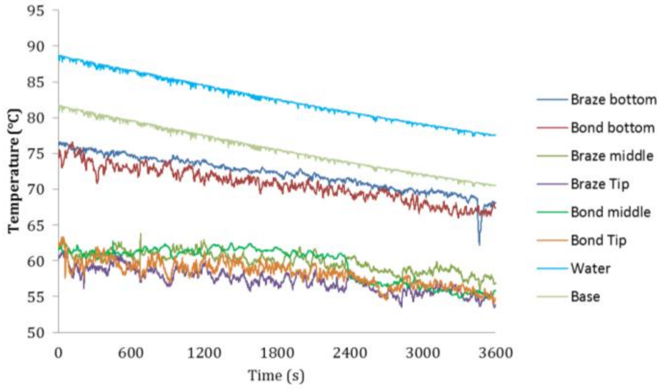

Figure 4: Temperature at various positions along fins, hot water reservoir and base plate throughout the experiment

Table 1: Performance of fins

Parameter	Bonding method		
	Brazed	Adhesive bonded	Single piece
h ($Wm^{-2}K^{-1}$)	7.623	7.582	7.778
Q (W)	0.1709	0.1662	0.1898
R_c (m^2KW^{-1})	1.654 x10^{-4}	2.126 x 10^{-4}	-
Efficiency, η	0.8262	0.8079	0.8996
Effectiveness,ε	66.1	64.63	71.96

Effect of heat transfer coefficient on fin performances

Natural heat convection is a mode of heat transfer that relies on differences in fluid's densities, in the absence of mechanical devices to force fluid to flow. It is essential to determine the changes in fin's performance at a range of heat transfer coefficient that is relevant to natural heat convection.

Thermal resistance of a fin may be defined as the magnitude of temperature difference to dissipate 1 Watt of heat at a specific heat transfer coefficient. Fig. 5 shows the thermal resistance was reduced at a higher heat transfer coefficient. The magnitudes of difference in thermal resistance for these three fins were constant for heat transfer coefficient in the range of 5 to 30 $Wm^{-2}K^{-1}$.

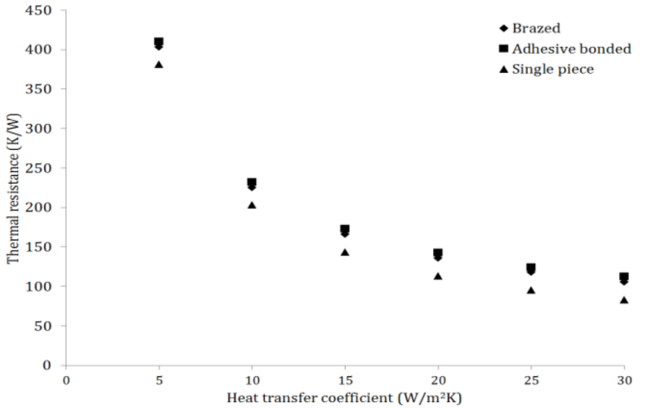

Figure 5: Thermal resistance of the fins with various joining methods at the base plate-fin interface

The magnitude of heat dissipated to ambient air is increases at higher heat transfer coefficients (Fig.6). There is no significant difference in the magnitude of heat dissipation between these three types of fin if the heat transfer coefficient is at 5 $Wm^{-2}K^{-1}$. However, the differences increased at higher heat transfer coefficient. The adhesive bonded pin fin had the lowest heat transfer at a higher heat transfer coefficient since it had the highest thermal contact resistance. This effect was more significant at higher heat transfer coefficient since the temperature drop at base plate-fin interface is expected to be higher if the heat flow through this interface is increased.

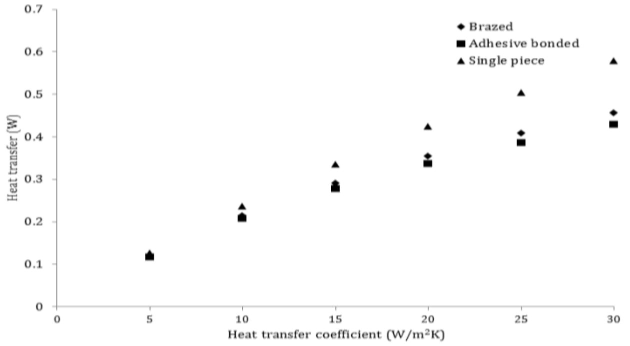

Figure 6: Heat dissipation of the fins with various joining methods at the base plate-fin interface

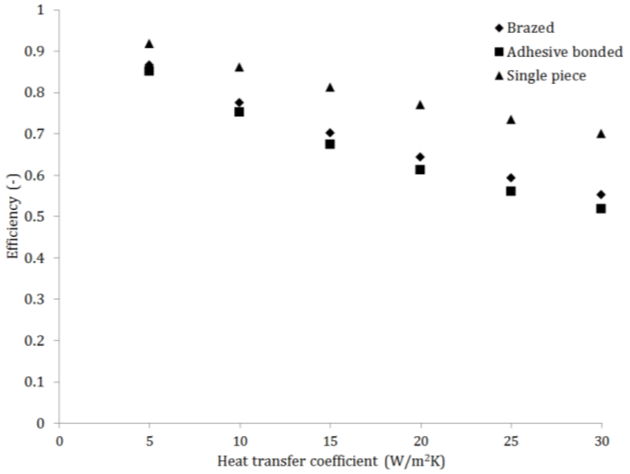

Figure 7: Efficiency of fins with various joining methods at the base plate-fin interface

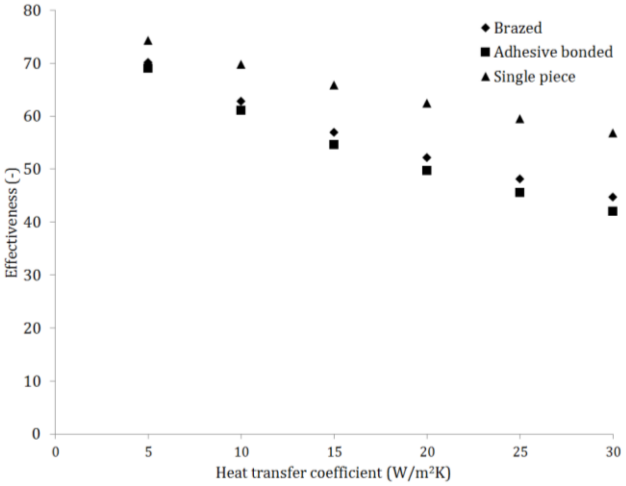

Figure 8: Effectiveness of brazed, adhesive bonded and single piece fins

Differences on the fin efficiencies were lower at a higher heat transfer coefficient (Fig. 7). The efficiency of brazed and adhesive bonded fins was reduced by ~ 30 %, if the heat transfer coefficient increased from 5 $Wm^{-2}K^{-1}$ to 30$Wm^{-2}K^{-1}$. For the fin made from a single piece metal with its base plate, the efficiency was only reduced by 22 %. This show the brazed and adhesive bonded fins are more sensitive to the changes in heat transfer coefficient. It is worth to evaluate thoroughly the range of heat transfer coefficient during the design stage to ensure fin has an optimum efficiency.

Similar trend to the fin efficiencies were observed for the fin effectiveness (Fig. 8). The reduction in fin's effectiveness for adhesive bonded, brazed and single piece fins were 38%, 36 % and 24 %, respectively. This finding shows the effectiveness of fins that is not fabricated from the same piece of metal with its base plate has a higher sensitivity to changes in heat transfer coefficient.

DISCUSSION

The rates of heat dissipation for fins with brazing and adhesive joining methods at its root are similar if the heat transfer coefficient is less than 10 $Wm^{-2}K^{-1}$. If a heat sink is designed to work at this range of heat transfer coefficient, the joining methods at the fin-base plate interface does not significant. So, this provides a flexibility to choose a cheaper joining method. Furthermore, this also enables more flexibility in the design of fin's geometry since the fin and its base plate does not need to be fabricated from a single piece of metal.

The results showed the brazed fin has a lower thermal contact resistance compared to the adhesive bonded fin. This finding is in agreement with [13] where the soldered fin has a lower thermal contact resistance relative to the adhesive bonded fin. One of the possible reasons is the thermal conductivity of adhesive is much lower than the thermal conductivity of filler, which is usually made from metal.

In future, it is worth to extend the finite difference heat transfer scheme to predict the performance of fin made from other materials such as copper or aluminium. However, it should be noted that other materials may have different thermal contact resistance although the same joining method is used. For further investigation, finite element method may be employed to determine the characteristic of heat transfer at the base plate-fin interface.

To improve the experimental method, thermoelectric module may be used to control the base plate temperature. Thermoelectric module equipped with control mechanism may able to control the base plate temperature at a constant, or any specified set point to within 0.1 Kelvin [18]. Furthermore, this method could be used to determine the rate of heat supplied to the base plate. Alternatively, the method employed in [15] on the utilization of sine wave temperature variation to determine thermal contact resistance could be adopted in the future.

CONCLUSIONS

Thermal contact resistances for brazed and adhesive bonded fin were determined. Brazed fin has a lower thermal contact resistance compared to the adhesive bonded fin. Differences in heat dissipation, efficiency and effectiveness between these fins were less than 5 %. Analysis on the effect of heat transfer coefficient on the fin performance indicated there were no significant differences in the magnitude of heat transfer if the heat transfer coefficient is less than 10 $Wm^{-2}K^{-1}$. This showed the thermal contact resistance was less significant at a low heat transfer coefficient, enabling adoption of less complex joining method in fabrication of heat exchanger/sink. Future work is on the improvement of experimental method and tests with various types of adhesives.

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NOMENCLATURE :

A_c	cross-sectional area of fin	m^2
Bi	Biot number	-
c_f	specific heat of fin	$kJkg^{-1}K^{-1}$
D	diameter of fin	m
Fo	Fourier number	-
h	heat transfer coefficient	$Wm^{-2}K^{-1}$
k	thermal conductivity	$Wm^{-1}K^{-1}$
Nu	Nusselt number	-
p_f	perimeter	m
Pr	Prandtl number	-
Q	heat flow	W
Ra	Rayleigh number	-
R_c	thermal contact resistance	m^2KW^{-1}
T	temperature	K
q_g	volumetric heat generation	Wm^{-3}

Greek letters

η	efficiency of the fin	-
ε	effectiveness of the fin	-
κ	thermal diffusivity	m^2s^{-1}
ρ	density	kgm^{-3}

Subscripts

f	fin
b	base
∞	air
M	total number of nodes
m	node number

Superscripts

p	time step

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