HEAT TRANSFER ENHANCEMENT BY COATED FINS IN THE MICROSCALE DOMAIN

by

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Micro-fins configuration is considered as a capable cooling method for micro-electronic components due to its space optimization and types of heat transfer. In this study micro-fins profile is selected according to the type of heat transfer and fabricated on copper and aluminum materials through wire-cut electric discharge machining process. The four numbers of square test pieces of dimensions of 4.5 cm × 4.5 cm and fin height, H, of 0.25 mm with different spacing, S, of 3.75 mm and 5 mm are considered for the experimentation. The fabricated test pieces such as aluminum, copper, painted aluminum, and painted copper are used in this experiments. This paper aims to improve the convective heat transfer coefficient by applying aluminum paint coating on a micro-fin structure. The paint coated copper test piece produces 20.62% higher heat transfer compared to aluminum test piece. On comparing the aluminum with aluminum paint coated test piece, the convective heat transfer rate found to increase by 49%. Coated aluminum test piece with 3.75 mm and 5 mm spacing shows higher radiation heat transfer compared to other micro-fin structures.

Key words: *natural convection, aluminum paint, micro-fin, heat transfer, heat sink*

Introduction

In recent years, the use of electronic gadgets has increased in too many folds and at the same time the heat ventilation in those devices poses a major problem for the electronics engineers. In electronic cooling, there are two different types of cooling methods are used, one is active cooling and another one is passive cooling system. In active cooling, external power source is required and in case of passive cooling it happens by itself, which obeys the natural conditions [1]. Researchers worldwide are pursuing research to improve passive cooling *i. e* the convective heat transfer through various means and aids. Philip *et al.* [2] have developed the micro-scale fin array structures on the aluminum alloy and studied the influence of surface finish on heat transfer performance. Based on the study, surface finish has a significant effect on heat transfer performance. Micheli *et al.* [3] have investigated and improved the thermal performance of horizontal micro-fins under natural convective condition. Shahzad *et al.* [4] have developed a carbon nanotubes structures on a patterned Si surface and enhanced the convective heat transfer. Ventola *et al.* [5] experimentally compared the heat transfer perfor-

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mance of laser etched surface and smooth surface heat sinks. Based on the study the laser etched surfaces shows a significant result compared to the smooth heat sinks. Taha *et al.* [6] studied the convective heat transfer behavior of a chemical vapor deposition (CVD) coated nickel wire at 650 °C. The coating of amorphous carbon and carbon nanofibers enhances the heat transfer. Nkurikiyimfura *et al.* [7] had reviewed the heat transfer characteristics using magnetic nanofluids (MNF). The review highlights the importance of MNF as heat transfer media in small scale cooling devices. Zhou and Tianquan [8] had developed a 3-D graphene growth on porous Al_2O_3 ceramics heat sink for thermal management using CVD technology for electronic applications. Mahmoud *et al*. [9] experimentally studied the effects of micro-fin dimensions on heat transfer coefficient for a horizontally mounted heat sink when operating under steady-state natural convective conditions. They concluded that the convective heat transfer coefficient decreases as fin height increased and found that the highest convective heat transfer coefficient value is recorded as 8 W/m^{2}K. Devdatta and Debendra *et al*. [10] extensively analysed the heat sink of a Pentium III chip through heat transfer equations. They reported that the use of paint coating significantly improved the radiation. Khan *et al*. [11] reviewed the heat transfer enhancement using surface coating. The review concluded that the porous metal coating on the surface enhance the heat transfer significantly. From the cited literature it is evident that researchers are using various methods to enhance the convective heat transfer and still there is no clear-cut understanding of convective heat transfer in nano/micro scaled structures. Hence, a new method for surface modifications must be developed to the practical applications. Hence, this research aims to study the convective heat transfer coefficient of different test pieces coated with aluminum paint. Different metal material such as aluminum and copper is considered for the experiment. The micro-fin is fabricated on metal materials through wire-cut electric discharge machining (WEDM) for different fin spacing. The fabricated micro-fin is coated with Al paint and its effects on the convective and radiative heat transfer is studied.

Experimental set-up

Micro-fin structure is fabricated on copper and aluminum material through WEDM process. Micro-fin dimensions such as fin height of 0.25 mm, fin thickness, *t*, of 3.75 mm and 5 mm, fin spacing of 3.75 mm, and 5 mm are considered for the study [9]. Totally four numbers of test pieces such as aluminum with 3.75 mm and 5 mm spacing, and copper with 3.75 and 5 mm spacing are considered for the experiments. Those test pieces are again coated with aluminum paint through spray paint technology to study the effect of paint coating on the convective and radiative heat transfer. All the test pieces were square shaped with length, *L*, and breadth of 4. The 5 cm and maintained with good surface quality. The test pieces were heated from the base by electric mat heater up to 10 Watts. The test piece is covered with fiber glass of dimension 10.8 cm × 4 cm × 0.4 cm and styropor block of dimension 23 cm × 20 cm × 9 cm, which restrict the heat transfer from undesirable sides. The surface and air temperature is noted and presented in the tab. 1. Figure 1 shows the micro-fin and heating arrangements used for the experiments.

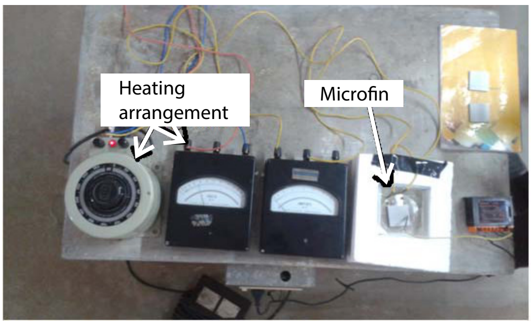

Figure 1. Experimental set-up

Results and discussion

Figure 2 shows the convective heat transfer coefficient plotted against the temperature difference at 3.75 mm spacing for coated and uncoated test pieces. Based on the fig. 2 it is clear that the convective heat transfer coefficient for the aluminum paint coated test pieces are more compared to uncoated test pieces. In general the heat transfer occurring at metal materials is classified into convection and radiation. The convection can transfer heat between the surface and the surrounding air, and the efficiency depends not only on the properties of the fluid, but also on the surface characteristics such as topography and geometry [12]. In common, aluminum material drives out more heat at higher temperatures [13, 14]. The paint coating of aluminum test piece dissipates much amount of heat, due to this, the local convective heat transfer coefficient and heat flux at the outlet gets increases.

According to fig. 2. It is evident that, the coated copper test pieces shows the highest heat transfer coefficient when compared to other test pieces. The highest convective heat transfer coefficient of paint coated copper and paint coated aluminum is found to be 21.29 W/m^{2}K and 16.90 W/m^{2}K, respectively. The paint coated copper test piece produces 20.62% higher heat transfer coefficient when compared to aluminum test piece. This is due to the reason that, at a small spacing of fin the air volume in between the fins will be minimal, so the fin surface and air will act as a barrier and produces high thermal resistance. This thermal resistance allows the heat to flow through the top surface of the fins. Moreover, the conductivity of copper is also high and hence convection rate in-

Table 1. Record of surface and air temperature

Micro-fin material	Time duration in hours	Fin spacing [mm]	Surface temperature T_{fin} [K]	Air temperature T_a [K]
Aluminum	1	3.75	111.5	53.8
	2	3.75	120.1	62.9
	3	3.75	130.4	73.7
	4	3.75	140.7	81.7
Aluminum	1	5	151.2	82.3
	2	5	159.9	91.7
	3	5	170	101.1
	4	5	177.7	101.1
Aluminum (with paint coating)	1	3.75	144.1	101.1
	2	3.75	149.1	109.8
	3	3.75	154.2	113.7
	4	3.75	157.1	115.9
Aluminum (with paint coating)	1	5	156.3	110.5
	2	5	171.9	122.8
	3	5	176.9	129.9
	4	5	179.4	137.2
Copper	1	3.75	149.2	93.1
	2	3.75	156.8	105.2
	3	3.75	173.8	119.3
	4	3.75	176.1	120.8
Copper	1	5	131.2	92.1
	2	5	149.5	110.9
	3	5	156.3	118.8
	4	5	161.2	124.5
Copper with aluminum paint coating	1	3.75	53.6	115.2
	2	3.75	163.2	124.3
	3	3.75	171.5	133.4
	4	3.75	191.4	137.8
Copper with aluminum paint coating	1	5	140.9	112.5
	2	5	156.2	123.4
	3	5	165.2	137.5
	4	5	181.3	148.4

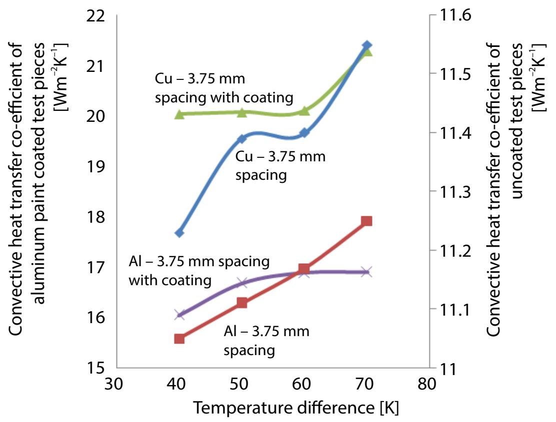

Figure 2. Convective heat transfer coefficient plotted against the temperature difference at 3.75 mm spacing

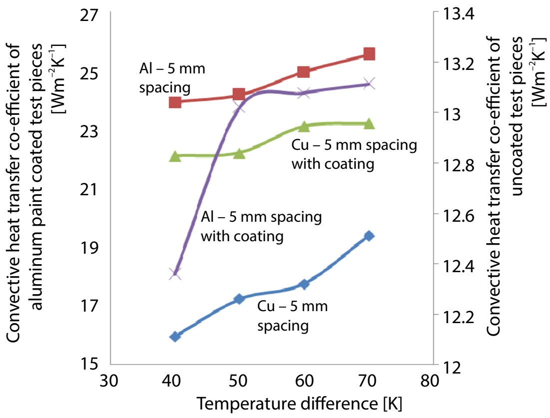

Figure 3. Convective heat transfer coefficient plotted against the temperature difference at 5 mm spacing

creases with the temperature. The temperature difference between air on the heated surface and the atmospheric air creates a thermal boundary-layer. This thermal boundary-layer will have a strong effect on the convective heat transfer [15].

Figure 3. shows convective heat transfer coefficient for copper and aluminum test piece for spacing of 5 mm and it is found to be 12.51 W/m^{2}K and 13.23 W/m^{2}K, respectively. Convective heat transfer coefficient is calculated from the eqs. (1)-(5) [16, 17]:

$$h_{\text{fin}} = \frac{K_{\text{air}}}{L}\text{Nu}^* \tag{1}$$

$$\text{Nu}^* = 1.18(\text{Ra}_r X_\mu)^{0.147} \tag{2}$$

$$\text{Ra}_r = \frac{g\beta(T_{\text{fin}} - T_a)r^3}{\nu\alpha} \tag{3}$$

$$X_\mu = \left(\frac{r}{H}\right)^4 \left(\frac{r}{L}\right)^4 \left[1 + \left(\frac{t}{r}\right)^2\right] \tag{4}$$

$$r = \frac{2HS}{2H} + S \tag{5}$$

Based on fig. 3, it is clear that, the aluminum produces 5.4% higher heat transfer rate than copper test piece. With increase in fin spacing the radiation heat transfer in aluminum test piece is more when compared to the convective heat transfer. In free convection, the fluid motion takes place due to natural means of buoyancy effect. When the surface is heated the air present in the surface will get heated due to this the density of air decreases and it moves upward. The high density cooler air moves downwards and it replaces the hot air. In addition, the viscosity of the air increases with rise in temperature resulting in fast upward movement of air. This rapid upward movement of fluid layer tries to drag the adjacent slower layer and exert a frictional force. So shear stress will be high.

Shear stress is defined as frictional force per unit area and is denoted by ζ_s. The shear stress for the most fluid is proportional to the velocity gradient and the shear stress at the wall surface, which shown below in eqs. (6)-(8), is expressed as [11]:

$$\zeta_S = \mu\frac{\partial u}{\partial y} \tag{6}$$

The determination of shear stress is done by:

$$\zeta_S = c_f \rho \frac{v^2}{2} \tag{7}$$

When shear stress is high, frictional force is also high. The frictional force is calculated:

$$F_f = c_f A_s \rho \frac{v^2}{2} \tag{8}$$

If the frictional force is high, the air in contact with the surface is also high. Hence the heat transfer rate is high. This mechanism occurs in micro-fin with more spacing [15].

Figure 4 shows that, the numbered regions of radiation heat transfer. In rectangular micro-fin structure, the radiation heat transfer occurs on the top surface (5), bottom surface (2) and other four sides of the fin surface indicated as (1), (3), (4), and (6). The following eqs. (9) and (10) shows the shape factor relation between the fin surfaces and radiation in fin surface is calculated by considering the emissivity of copper and aluminum as 0.035 and 0.039, respectively [17]:

$$X = L/D \tag{9}$$

$$Y = B/D \tag{10}$$

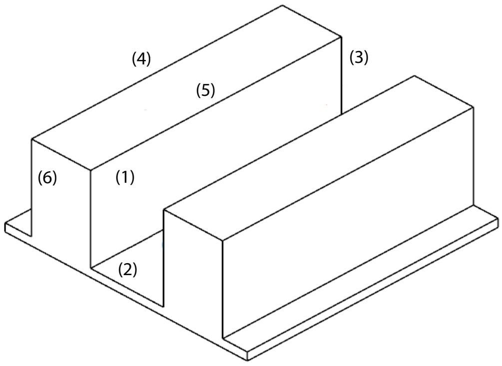

Figure 4. Sketch of the micro-fin

Radiation in fin surface is calculated by eq. (11):

$$Q_r = \varepsilon \sigma A(T^4_{\text{fin}} - T^4_{\text{a}})\, F_{i,K} \tag{11}$$

$$F_{i,k} = \text{Shape factor}$$

It is evident from the figs. 5 and 6 that coated aluminum test piece with 3.75 mm and 5 mm spacing shows higher radiation heat transfer when compared to other micro-fin structures. The radiative transfer is determined by the emissivity of the exposed surfaces, their geometry, and by base plate temperature and ambient temperature [18]. With the use of aluminum paint coating the fin surface will become smoother, resulting in increase of heat transfer through radiation. The coated aluminum test piece is highly reflective compared to copper material and it increases the radiative heat transfer. Moreover, the paint coating fills the rough surface. Which, serves as a reservoir for the air. Hence, the absence of non-participating medium such as air improves the radiation heat transfer in coated surface. The heat transfer coefficient is analyzed through commercially available ANSYS software and the output result is shown in the fig. 7. The micro-fin is modeled in PRO-E 2.0 and imported the diagram to the ANSYS in the file format IGES. The analysis was made for temperature difference of 60 K and convective heat transfer coefficient of 23.2 and 24.5 W/m^{2}K, respectively, for painted aluminum and copper test pieces. It is apparent from the figs.7(a) and 7(b) that highest heat transfer is observed in painted

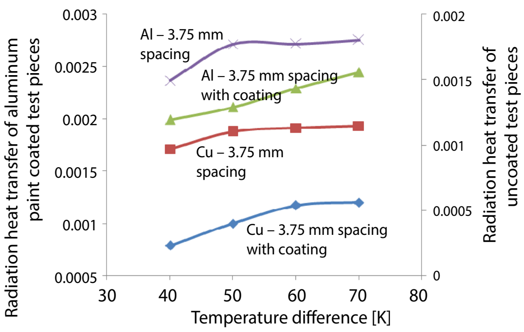

Figure 5. Radiation heat transfer plotted against the temperature difference at 3.75 mm spacing

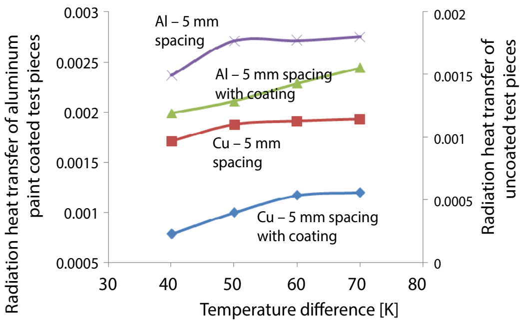

Figure 6. Radiation heat transfer plotted against the temperature difference at 5 mm spacing

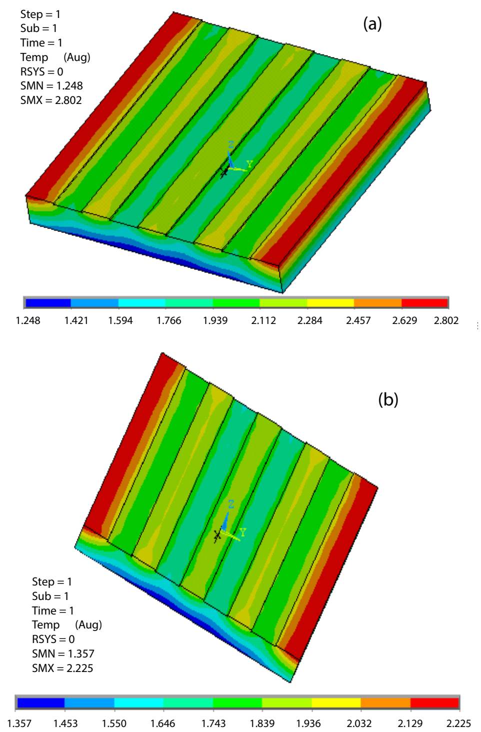

Figure 7. Convective heat transfer coefficient distribution on the painted test pieces in ANSYS (a) Al, (b) Cu

aluminum test piece compared to painted copper test piece. Moreover, heat transfer was adequately noticed on the either ends of the micro-fin.

Conclusions

The heat transfer by natural convection plays a very important role in micro-electronic components. The convective heat transfer coefficient of copper, and aluminum coated test pieces were calculated. The convective heat transfer coefficient of paint coated copper and paint coated aluminum is found to be 21.29 W/m^{2}K and 16.90 W/mK, respectively, for fin spacing of 3.75 mm. The highest value for convective heat transfer coefficient was found to be 24.54 W/m^{2}K for the paint coated aluminum test pieces of fin spacing 5 mm. The highest value for convective heat transfer coefficient was found to be 24.54 W/m^{2}K for the paint coated aluminum test pieces of fin spacing 5 mm. On comparing the aluminum with aluminum paint coating, the convective heat transfer rate increases by 49% and this shows that the coating enhances the heat transfer rate. Coated aluminum test piece with 3.75 mm and 5 mm spacing shows higher radiation heat transfer when compared to non-coated micro-fin structures. Among these test pieces, aluminum shows a greater response before and after coating. So, aluminum can be used in micro-electronic components with higher fin spacing. Aluminum test pieces are found to be suitable for enhancing the convective heat transfer with and without coating upto 10 W power. In future the novel engineered materials with different geometry and coating materials can be tried to enhance the natural heat transfer in microfin.

Nomenclature

A – area of the un-finned surface
A_S – fin surface area
B – width of the fin
c_f – coefficient of friction
D – distance between the fin
$F_{i,K}$ – shape factor ($F_{1,2}$ and $F_{1,3}$)
g – gravitational force
H – fin height
h_{fin} – convective heat transfer coefficient of fin, [Wm^{-2}K^{-1}]
K – thermal conductivity of the material
L – length of the fin
r – hydraulics radiu
Nu – Nusselt number (= hL/k)
Q_r – radiation heat transfer
Ra_r – Rayleigh number
S – fin spacing
T_a – air temperature, [K]
T_{fin} – fin surface temperature, [K]
t – fin thickness
X_μ – micro fin global shape parameter

Greek symbols

α – thermal diffusivity of air, [m^{2}s^{-1}]
β – 1/T$_f$, [K]
ε – emissivity of the surface
μ – dynamic viscosity
ν – kinematic viscosity, [m^{2}s^{-1}]
ρ – density of air
σ – Stefan-Boltzmann constant

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