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Fabrication and Thermal Analysis of Composite Pin-Fin

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Abstract:

The extended surfaces called fins are mostly used in the fields of automobiles, electronic components, electrical motors etc., to increase heat transfer rate, to increase the life and efficiency of the device. The heat transfer from one place to another place occurs by three mechanisms, namely Conduction, Convection and Radiation.

There are various shapes of fins generally used in practical applications. Aluminium is the basic metal preferred to make fins due to their less weight and cost. In general the heat transfer from fins depends upon different factors, like the material used to make the fin, thermal conductivity of the material, its shape, surface area, mode of heat transfer allowed, size of fin, etc,,

In the present work, an attempt is made to fabricate circular pin fin made of different metals, Aluminium ,Copper, combination of Aluminium and Copper and combination of Brass and Copper as composite bars and analyzed their performance in terms of fin efficiency , heat transfer rate and temperature distribution along the fin. A constant power is supplied to the heater and the fin is placed horizontally along the x-axis.

Results infer that the highest heat transfer rate is observed for the composite pin fin made of Brass-Aluminium (32.224 Watts) and highest efficiency is observed for the composite pin fin made of Copper-Aluminium (94.76%).

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***Keywords**: Composite Pin fin, thermal conductivity, conduction, convection, heat transfer rate, fin efficiency, temperature distribution.*

1. Introduction

In the Universe, each and every system or substance undergoes the process of heat transfer to make the system equilibrium. It occurs due to difference in temperatures in the substance. This temperature difference acts as a potential force to transfer heat from one place to another. But the rate of heat transfer depends on various factors like media surrounded by the substance, the material used to make the substance, temperature difference in the substance, force applied (if any) to occur heat transfer in the substance….etc.,

Thermal analysis is the process of finding the values of temperature at different points when the material is in steady state condition. A steady state is the material condition where there is input heat energy equal to output heat energy. The important factors which mainly affect the heat transfer rate are the thermal conductivity of material, size of material etc., Different materials have different thermal conductivity and it affects the rate of heat transfer. By increasing the length and diameter of the pin fin, the heat transfer rate can be improved but the fin faces the difficulty of increased self weight and size.

Dr. Raj Bahdur (1) has analyzed the optimization of orthotropic pin fin made of polymers in his Doctoral thesis work. It is concluded that coefficient of thermal performance for polymer fins is higher compared to aluminum heat sinks at lower pumping power.

F.M.Arif et al.(2) had conducted thermal analysis and optimization of orthotropic pin fins in a closed-form with convective insulated tip boundary conditions and the results are discussed in terms of Radial and Axial Biot numbers, fin aspect ratio as (L/R), and radial-to-axial conductivity ratio etc.,

Masoud Asadi et al. (3) investigated numerically on the interaction of thermal radiation with convection and an exact solution is presented for temperature distribution of fin of constant cross - sectional area. The results showed the temperature profile is uniform and rate of heat transfer by Convection-Radiation increases along the fin.

U S Gawai et al.(4) performed a test on pin fin with brass and Aluminium metals in terms of their dimensionless numbers of heat transfer like Nusselt number (Nu) and Reynolds number (Re) and the experimental results gives heat transfer co-efficient & efficiency of aluminum fin is greater than that of brass fin.

Naoko Matsumot et al. (5) had made a conclusion that the heat sinks with the same heat transfer area, it has been confirmed that the heat sink performance changes depending on the population density of pin and the pin size and from calculated results, the heat sink temperature has been shown to rise with increase in the number of pins. Especially, the heat sink with miniaturized pins has almost no effect on the heat transfer enhancement.

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1.1 Fins:

Extended surfaces called Fins are basically used for improving the heat transfer rate from the source to the atmosphere by conduction and convection modes of heat transfer. An extended surface configuration is generally classified for straight fin, an annular fin or spine. The term straight fin is applied to the extended surface attached to a plane wall where as annular fin are provided circumferentially to a cylindrical surface.

1.2 Types of Fins:

1. Rectangular fin
2. Triangular fin
3. Pin fin
4. Circumferential fin

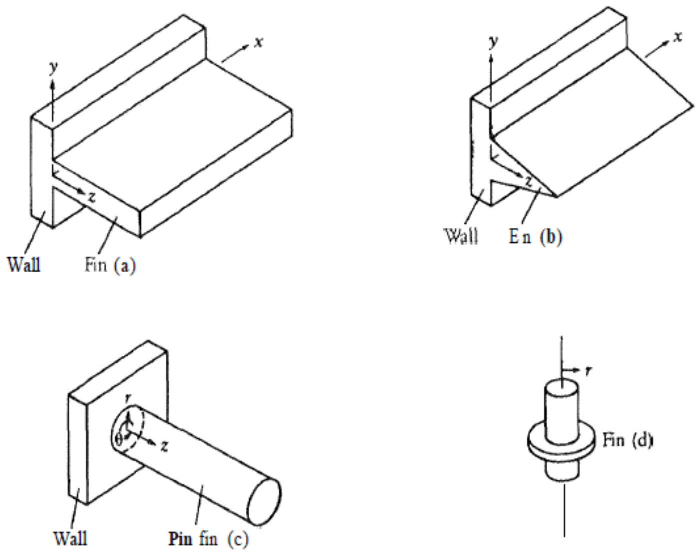

Fig:1 Types of Fins

1.3 Composite Metals:

These are metals made from two or more constituent metals with significantly different properties. That when combined, produce a metal with characteristics different from the individual components. The individual components remain separate and distinct within the finished structure. The new metal may be preferred for many reasons: common examples include metals which are stronger, lighter or less expensive when compared to traditional metals.

One can choose or prefer composite metals due to their enhanced properties like reduction in its wear and tear of metal, improvement in its strength, reduction in its weight, and improvement in its thermal properties etc.,

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2. Nomenclature

A	=	Cross sectional area of the fin (m^2)
d	=	Diameter of the fin (m)
D	=	Diameter of the duct (m)
h	=	Heat transfer coefficient (W/m^2-K)
k	=	Thermal conductivity (W/m-K)
k_f	=	Fin material thermal conductivity (W/m-K)
k_a	=	Thermal conductivity of air (W/m-K)
L	=	Length of the fin (m)
m	=	Fin parameter (m^{-1})
P	=	Perimeter of the fin (m)
Q	=	Heat transfer rate (W)
T	=	Temperature (^{0}C)
T_f	=	Film temperature (^{0}C)
T_{avg}	=	Average surface temperature (^{0}C)
T_a	=	Air inlet temperature (^{0}C)
U	=	Air velocity (m/s)
ΔT	=	Temperature difference (^{0}C)
Re	=	Reynolds number
Nu	=	Nusselt number
Pr	=	Prandtl number
η_f	=	Efficiency of the fin (%)
υ	=	Kinematic viscosity of air (m^2/s)
ρ	=	Density of air (kg/m^3)

3. Materials of Fins

Aluminum, Brass, Copper and their composites

3.1 Aluminum:

Aluminum is a chemical element in the group with symbol Al and its atomic number is 13.It is a silvery white, soft, nonmagnetic, ductile metal. Aluminum is the third most abundant element (after oxygen and silicon).The chief ore of Aluminum is Bauxite.

Its low density, excellent corrosion resistance, good thermal and electrical conductivity etc are the other good properties. Its other properties are Phase (solid), Melting point (933.47K/ 660.32^{0}C), density(2.70g/cm^3)

In the present work an Aluminium pin fin (fig 3.1) of diameter 19 mm (length of 140 mm between thermocouples) ane presentd a total length of fin as 175 mm is used.

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Fig 3.1 Aluminium pin fin

Fig 3.2 Copper Pin Fin

3.2 Copper:

Copper and copper alloys are widely used in a variety of products that enable and enhance our daily life. Copper, atomic number 29 with an atomic weight of 63.54, exhibits a face-centred cubic crystal structure.

Its excellent conductivity, malleability, corrosion resistance makes this metal is used vastly. Here in this paper, a copper pin fin (fig 3.2 shown above) of diameter 19mm and a length of 140 mm between thermocouples and a total length of fin as 175mm is taken.

3.3 Composite pin fin:

A composite pin fin is made with two selected metals like brass and aluminium, where aluminium pin is fitted in a hollow brass cylindrical fin whose inner diameter is equal to the outer diameter of the solid pin fin .(fig 3.3 , a & b).

Similarly another composite pin fin is made by selecting the materials like aluminium and copper.(fig 3.4, a &b). Aluminium pin fin is placed inside the brass hollow fin where the inner diameter of brass pin is equal to outer diameter aluminium fin.

Fig3.3(a) Compositepinfin
(brass+Aluminium)

(b)CrossSectional(SideView)
View Of Composite Pin Fin
(Brass+Aluminium)

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Fig 3.4(a) Composite pin fin (copper + Aluminium)

(b)Cross Sectional (SideView) View Of Composite Pin Fin (copper +Aluminium)

TABLE I: Properties & Specifications of Metals

S. No.	Fin Material	Diameter	Fin Length	Thermal Conductivity of fin material
		mm	mm	W/m-k
1	Aluminium	19	175	232.56
2	Copper	19	175	401
3	Brass +Aluminium	38	175	375.65
4	Copper +Aluminium	38	175	837.28

4. General Equation for a Pin Fin:

The methodology to find the fin efficiency, heat transfer rate, Heat transfer coefficient is considered from basics of Heat Transfer. (Ref No :6,7,8 and 9)

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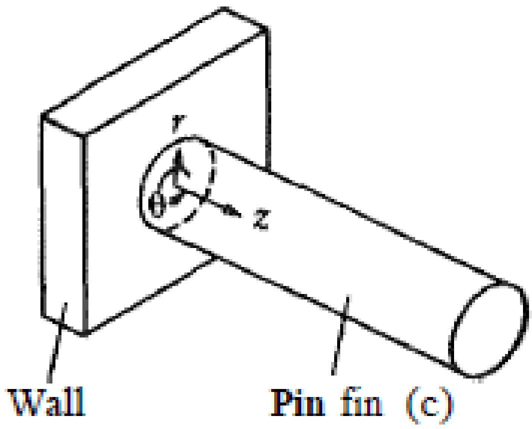

Fig :2 Circular pin fin

Consider a circular pin fin (fig :2) of length (L), diameter (d),of cylindrical shaped which is attached to a base plate at a temperature(t_b) and the whole fin is exposed to the environment which is at (t_∞) and a heat transfer coefficient (h).Consider a strip at distance of (x) from the base plate having the length (dx) then the heat entering into the strip by conduction is given by the equation

$$Q_x = -k*A_C*\frac{dt}{dx} \qquad \text{------ equation 1 (from Ref : 8)}$$

Heat leaving from the strip by conduction

$$Q_{(x+dx)} = Qx + \frac{\partial}{\partial x}(Qx)dx \qquad \text{(from ref :8)}$$

$$= -k*A_c*\frac{dt}{dx} + \frac{\partial}{\partial x}\left(-k*A_C*\frac{dt}{dx} \right)dx \quad \text{------- equation 2}$$

Heat leaving from the strip by convection

$$Q_{Conv} = h*(pdx)*(t-t_\infty) \quad \text{------- equation 3}$$

For steady state condition heat entering into the strip must be equal to the heat leaving from the strip

$$-k*A_C*\frac{dt}{dx} = -k*A_C*\frac{dt}{dx} - \frac{\partial}{\partial x}\left(k*A_C*\frac{dt}{dx}\right) dx + h*(pdx)*(t-t_\infty)$$

$$\frac{\partial}{\partial x}\left(K*A_C*\frac{dt}{dx}\right) dx = hpdx*(t-t_\infty)$$

$$K*A_c*\frac{d^2t}{dx^2} = h*p*(t-t_\infty)$$

$$\frac{d^2t}{dx^2} = \frac{hp}{kA_c}*(t-t_\infty)$$

$$\frac{d^2t}{dx^2}-m^2*(t-t_\infty) = 0 \qquad [\text{since } m^2=\frac{hp}{kA_c}]$$

Let $(t-t_\infty)=\theta$

$$\frac{dt}{dx}=\frac{d\theta}{dx}$$

$$\frac{d^2t}{dx^2}=\frac{d^2\theta}{dx^2}$$

$$\frac{d^2\theta}{dx^2}-m^2\theta=0$$

$$D^2\theta - m^2\theta=0$$

$$= (D^2-m^2)\theta=0$$

$$= D^2 = m^2$$

Therefore $D=\pm m$

$$\theta=C_1e^{mx}+C_2e^{-mx}$$

$$\frac{d\theta}{dx}=C_1me^{mx}-C_2me^{-mx}$$

(θ Having two real roots)

Therefore, the solution for differential equations is given by

$$\theta=C_1e^{mx}+C_2e^{-mx}$$

4.1 Heat transfer coefficient :(h)

$h = (Nu*k_a) / d$ W/m^2-K

4 .2 Properties of air at film temperature (T_f)

(from the data book --- **Ref No:10)**

Average surface temperature of fin

$T_{avg} = (T_2+T_3+T_4)/3$		ºC
Ambient temperature	$T_a=T_1$	ºC
Film temperature $T_f = (T_{avg}+T_a) / 2$		ºC

At T_f

ρ	= Density of air	kg/m^3
ϑ	= Kinematic viscosity of air	m^2/s
k_a	= thermal conductivity of air	W/m-k
Pr	= Prandtle number	

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4.3 Temperature distribution along the fin:

$$\frac{\theta}{\theta_b} = \frac{\cosh m(L-x)}{\cosh mL}$$ Where

$\theta = T-T_1$ K

θ_b = temperature difference between the base of the fin and air inlet temperature $=T_2-T_1$

L = Fin length m

M =fin parameter=$\sqrt{h * p/k_f * A}$ m^{-1}

k_f = fin material thermal conductivity W/m-k

P = Perimeter of the fin = $\pi * d$ m

A = Cross sectional area of the fin = $\frac{\pi d^2}{4}$ m^2

4.4 Fin Efficiency: η_f = $\frac{\tanh mL}{mL}$ **%**

4.5 Heat transfer rate (Q):

Q = $\sqrt{h * p * k * A}(T_2-T_a)$Tanh (mL) W

5. Pin Fin Performance

The performance of a fin is judged by its efficiency. The efficiency of a fin is defined as the ratio of actual heat transfer from a fin to that of heat transfer from the fin if its entire length is maintained at its base temperature. In ideal case we assume that the entire fin is its base temperature T_b since T_b is constant all along the length and h, A are al so constant the ideal rate of heat transfer can be calculated as

$$Q_{ideal} = h*A_S*(T_b-T_\infty)$$

(where A_s =surface area = perimeter*length)

$$= h*p*L*(T_b-T_\infty)$$

Therefore (η_f) : $\frac{\tanh mL}{mL}$ %

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Table: 2 Experimental Readings:

S. No.	Fin Material	Air Velocity (m/s)	Fin Surface Temp. (^{0}C)			Air Temperature (^{0}C)		Reynolds number
		U	T_2	T_3	T_4	T_1	T_5	---------------
1	Aluminium	6	91.6	76.4	72.6	27.3	28.3	6218.46
2	Copper	6	79.6	73.2	62.1	27.1	28.3	6373.7
3	Brass + Aluminium	6	75.8	69.3	66.5	27.3	28.4	12778.77
4	Copper +Aluminium	6	63.9	61.6	58.6	27.4	28.5	13108.25

6. Results and Discussions

Table-3 : Experimental Results:

S. No.	Fin material	Heat transfer coefficient w/m^2-k	Heat transfer rate (w)	Efficiency %	Temperatures along the at x in mm			
		h	Q	T	X=0	X=35	X=70	X=105
1	Al	56.77	21.19	67.7	91.6	79.78	71.28	65.57
2	Cu	57.05	20.56	77.64	79.6	73.05	68.19	64.85
3	Brass + Al	43.5	35.22	89.12	75.8	72.9	70.7	69.15
4	Cu + Al	44	29.51	94.76	63.9	62.87	62.06	61.49

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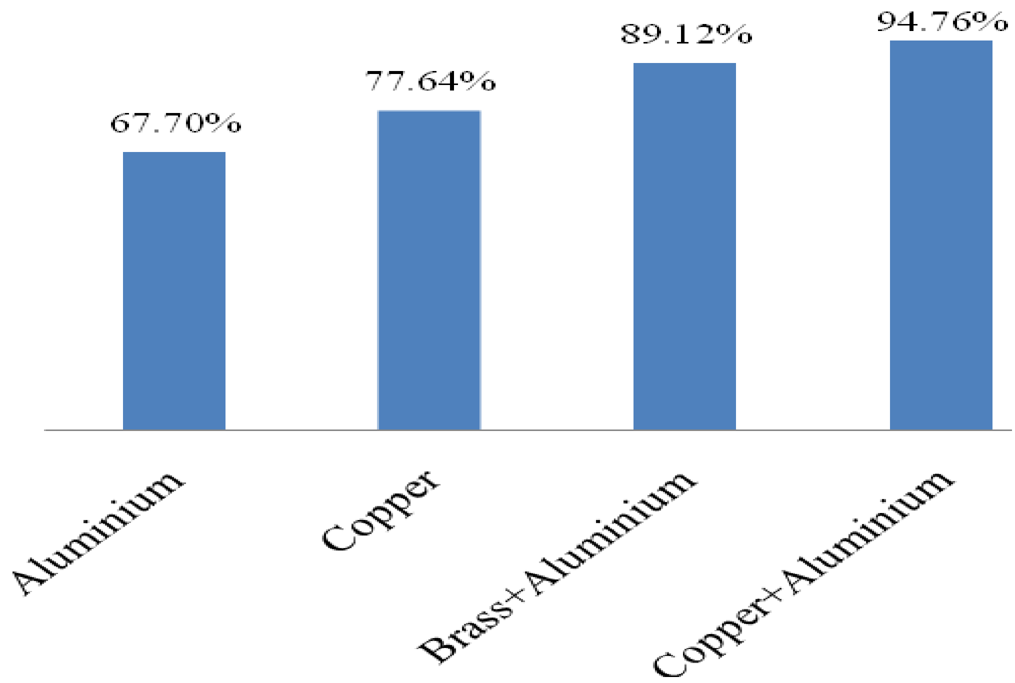
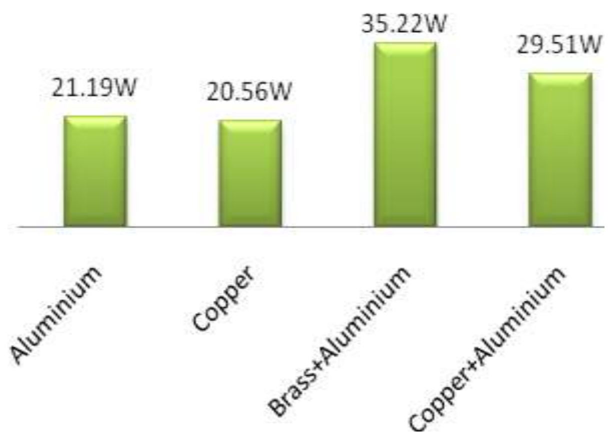
6.1. GRAPHS:

6.1.1. Fin Efficiency (η_f):



6.1.2 Heat Transfer Rate (Q):



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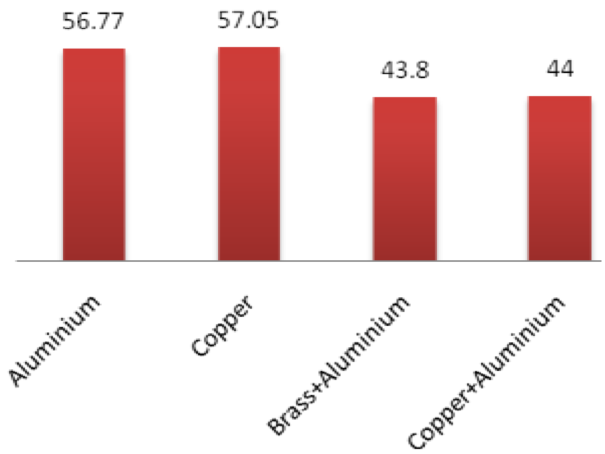
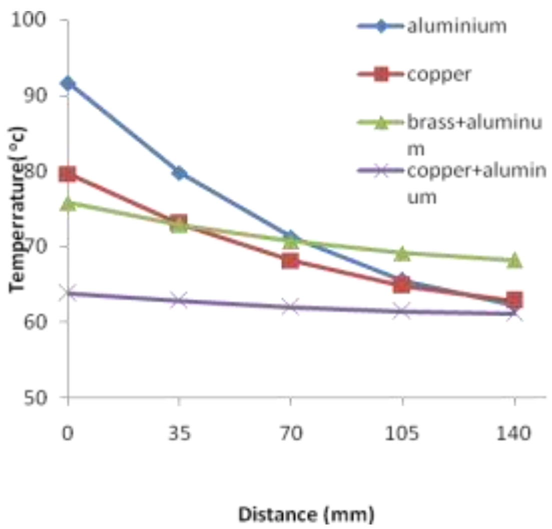
6.1.3 Heat transfer Co-efficient (h):



6.1.4. Temperature Distribution:



In the present work, a fin with constant cross sectional area and a finite length of 175mm is considered. From the results

- The efficiency of the composite material (copper+ aluminium pin fin) shows the high value of 94.76%.
- The composite fin (brass + aluminium) shows high heat transfer rate of 35.22 Watts.
- The temperature gradient of an Aluminium material is high along its length as it varies from 91.6 to 65.77^{0}C but it attains high temperature at the starting stage due to its less thermal conductivity.
- In Composite material (copper+ aluminium) the initial temperature is low and temperature gradient is less along the length of the Fin due to its high thermal conductivity.

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7. Conclusions

In the present work, an attempt is made to find the fin efficiency, heat transfer rate, temperature distribution and heat transfer coefficient for a solid and composite pin fin.

From the results it is concluded that, the efficiency , heat transfer rate are higher for composite pin fin than that of solid pin fin.

- The efficiency for composite fin is improved by 22.05% and heat transfer rate improved by 66.21%. when compared to solid pin fin.

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