DEVELOPMENT OF EXTENDED SURFACE HEAT TRANSFER EQUIPMENT AS LABORATORIES TEACHING AIDS

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ABSTRACT

One of the effective ways of enhancing the heat transfer rate between a solid and an adjoining fluid is through the use of an extended surface called fin. Extended surface enhances the heat transfer rate by increasing the area of the surface through which heat is transferred. This paper presents the design, construction and testing of an extended surface heat transfer teaching equipment. Extended heat transfer equipment is made of metal rod of 10 mm diameter and length 350 mm, heater of 60 W capacity, Plaster of Paris (P.O.P) insulator, stands-support for heater, insulator and the metal rod and base flat bed of 500 mm × 200 mm × 80 mm. Experimental studies were carried out on three materials (brass, mild steel and aluminum) to determine their respective temperature distribution along an extended surface over a length of 28 cm for 2700 seconds interval at different voltage of 50, 100 and 150 volts. The theoretical analysis results were compared with the experimental results and the temperature distribution in the three materials were compared. The results revealed that, Aluminium has the highest temperature value, followed by Brass and Mild Steel at different voltages considered. The temperature increases as voltage increases, at 50, 100 and 150 volts, temperature values are 70, 113 and 157 ^oC for Aluminum, 65, 111 and 141 ^oC for Brass and 60, 87 and 100 ^oC for Mild Steel respectively for 2700 seconds. This explains the reason why Aluminium has the highest heat transfer characteristics followed by Brass and Mild steel. Statistical t-test analysis at 95% confidence limit confirmed that there is no significant difference between the theoretical results and experimental results. Analysis of variance, ANOVA at 95% confidence limit confirmed that, there is significant difference between the temperature gradient of the three selected material. Finally, the extended surface heat transfer equipment is affordable as produced with locally available materials; It has enhance easy maintenance, reliability and accuracy of results. It can be used as teaching aids in laboratories and research institutes.

Keywords - Extended surface, fin, heat transfer, conduction and convection

1 INTRODUCTION

An extended surface is used specially to enhance the heat transfer rate between a solid and an adjoining fluid, such an extended surface is termed a fin (Esmail, 2003). A fin is a surface that extends from an object to increase the rate of heat transfer to or from the environment by increasing convection heat transfer, The term (extended surface) is commonly used to depict an important special case involving heat transfer by conduction within a solid and heat transfer by convection (and/or radiation) from the boundaries of the solid. The temperature distribution along the fin or pin must be known to determine the heat transfer from the surface to its surroundings. The temperature difference with surrounding fluid steadily diminishes as one moves out along the fin. The design of the fins therefore required knowledge of the temperature distribution in the fin. (Gawai *et al*, 2013).

Thermal performance of extended surfaces has been subjected to numerous investigations for natural convection. Plate-fin heat sinks were evaluated by Yüncü and Anbar (1998) who found that for a given heat rate, optimal fin spacing decreases as fin height increases. Razelos and Georgiou (1992) developed a guideline for longitudinal, annular, and pin fins. A fin effectiveness value of 10 was found to be the minimum value that justified the addition of fins. Bar-Cohen *et al*. (2003) developed optimal fin spacing and fin aspect ratios for a plate-fin heat sink for both constant mass and constant volume. Mahmoud *et al*. (2011) compared optimal fin dimensions for micro-scale heat sinks and macro-scale heat sinks to assess the validity of using the same model for both scales. It was concluded that micro-scale heat sink behavior cannot be accurately predicted using macro-scale models and analysis. Fujii and Imura (1972) investigated the fin inclination angle and its effect on the performance in a heat sink. A Nusselt number correlation was developed and it was shown that boundary layer separation increased with higher inclination angle.

The shape of a fin has also proved to be critical to the heat transfer performance. Sikka *et al*. (2002) investigated the comparative performance of heat sinks in which longitudinal fins were replaced by fluted and wavy fins. Fluted fin heat sinks were found to increase heat transfer by up to 9% while wavy fins were found to increase heat transfer by up to 6%. Lin and Jang (2002) investigated the effects of an elliptical annular fin in place of a circular fin. When an ellipse was compared to a circle with the same perimeter, the elliptical efficiency was higher and increased with increasing elliptical aspect ratio. Another investigation in the comparison of elliptical and circular fins was performed by Li *et al*. (1998). This study however examined the geometric effect on the performance of a pin fin. Elliptical pin fins were able to result in higher heat transfer coefficients while reducing the pressure drop across the array of fins. Razelos and Satyaprakash (1996) investigated a trapezoidal shaped pin fin for optimization based on heat rate or volume and found an optimal shape aspect number of 1.5. Kang (2007) investigated adding a rectangular base to a triangular profile fin and found that for a minimized volume optimization, the simple triangular profile achieves greater heat transfer than the modified design.

Sasikumar and Balaji (2002) studied the contributions of both radiation and natural convection in a plate fin heat sink and found that radiation could contribute up to 55% of the heat transfer for heat sinks with short fins. It was noted that the contributions of radiation was reduced with increasing fin height. Rao and Venkateshan (1996) also showed that the interaction between radiation and natural convection must be accounted for as radiation can account for 25-40% of the heat dissipation in the array. In a study of a strip fin heat sink, Guglielmini *et al*. (1987) noted that radiation could contribute up to 40% of the heat dissipation. It was also shown that a staggered fin arrangement resulted in increased heat transfer for a vertical arrangement. For pin fins, with the mutual interaction of radiation between fins, Gerencser and Razani (1995) found that the optimal shape resembled a parabolic spine, with a triangular cone providing comparable effectiveness.

Another problem studied in heat transfer is the attempt to maximize the performance of a heat sink by modifying existing conditions. Yu *et al*. (2012) developed a plate fin heat sink that placed pin fins in between the longitudinal fins for increased heat transfer per pumping power of up to 20%. This method was presented as a technique for modifications of existing plate fin heat sinks. Sparrow *et al*. (1982) investigated the enhancement of cooling in electronic equipment by placing barriers to alter the flow before reaching the desired cooling device. While this was found to greatly increase the heat transfer, it required additional fan power. In a comparison study, Jonsson and Moshfegh (2001) evaluated the thermal performance and pressure drop of strip fin heat sinks versus pin fin heat sinks. While the thermal resistances of strip fin heat sinks were comparable to pin fin heat sinks, the pressure drop across pin fin arrays were larger than strip fins.

The importance of radiation heat transfer can be easily seen in space related applications as it is the only means of rejecting waste heat to the surroundings. Krikkis and Razelos (2002) optimized rectangular and triangular plate fins for radiation temperature subject to opening angles between fins less than 180°. The fin height and fin thickness required to optimize heat transfer were found to be a function of the fin surface emissivity. The optimal ratio of the dimensionless radiation to conduction parameter was found to be 0.8464. Kumar *et al*. (1993) performed an optimization based on weight to use the optimal number of fins for a plate fin heat sink. As the number of fins was increased, heat transfer increased greatly with low number of fins. A sharp initial increase in heat transfer was found until the optimal number of fins was reached with little increases in heat transfer for a number of fins greater than the optimal amount.

The equipment comprises of a rod mounted horizontally. Thermocouples are located at intervals along the rod to record the surface temperature (Guillermo, 2004). The use of extended surface heat transfer equipment for experimental purposes in the laboratories and research institutes is a necessity. However, the equipment is not readily available in the laboratory due to number of limitations, some of which are not being produced locally and in the event of damage, parts are not easily available. This paper seeks to solve these problems by designing, fabricating and testing extended surface heat transfer equipment using locally available materials.

2 Material and Method

Mathematical Model of Heat Transfer in Fins

Consider the area *A* on the surface shown in Figure 1 where heat is being transfer from the surface at a fixed temperature T_s to the surrounding fluid at a temperature T_∞ with a heat transfer coefficient *h*. The heat transfer rate may be increased by increasing the convection coefficient *h*, reducing the fluid temperature T_∞, or adding materials to the area *A*.

Analysis - Consider the cylindrical extended surface with diameter *D as* shown in Figure 1.0

The following assumptions are made: steady state, constant thermal conductivity, no internal heat generation, one-dimensional conduction, uniform cross-sectional area, uniform convection across the surface area, no radiation, constant heat transfer coefficient, and constant physical properties were assumed. The mathematical model for a fin with uniform cross-sectional area was developed.

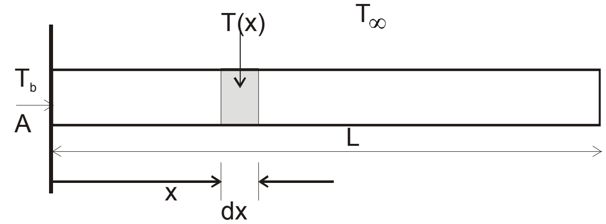

Fig. 1: A cylindrical fin with convective end

An energy balance is applied to a differential control volume, ΔxA, as shown in Figure 1. Since temperature is dependent on x, a differential distance along x was chosen. The surface area of the control volume is given in eqn. (1)

$$\Delta A_s = \Delta xP = \Delta x\pi D \quad (1)$$

The energy balance applied to the control volume ΔxA is given in eqn. (2)

$$q_x - (q_{x+\Delta x} + \Delta q_c) = 0 \quad (2)$$

The energy equation becomes eqn. (3)

$$-\frac{dq_x}{dx} - h\frac{dA_s}{dx}(T(x) - T_\infty) = 0 \quad (3)$$

Using Fourier's law, $q_x = -kA\frac{dT}{dx}$ where A is the cross-sectional area normal to the x direction, the energy equation becomes eqn. (4)

$$\frac{d}{dx}\left[kA\frac{dT}{dx}\right] - h\frac{dA_s}{dx}(T(x) - T_\infty) = 0 \quad (4)$$

The energy equation becomes a second order ordinary differential equation (ODE) with constant coefficients, k and A is given in eqn. (5)

$$\frac{d^2T}{dx^2} - \frac{hP}{kA}(T(x) - T_\infty) = 0 \quad (5)$$

Homogenizing by introducing a new variable $\theta = T(x) - T_\infty$ to get eqn. (6)

$$\frac{d^2\theta}{dx^2} - \frac{hP}{kA}\theta = 0 \quad \text{and} \quad m^2 = \frac{hP}{kA}, \quad (6)$$

The temperature distribution along the pin fin is given in eqn (7)

$$\frac{\theta}{\theta_b} = \frac{T_x - T_a}{T_1 - T_a} = \frac{\cosh m(L-x)}{\cosh mL} \quad (7)$$

Where; T_x is temperature at point x, T_a is ambient temperature,. T_1 is temperature at x = 0 cm

L is length of metal rod, and m is a constant as given in eqn. (6)

The heat transfer coefficient for a long, horizontal cylinder can be estimated from appropriate empirical correlations for free and forced convection flow. This equation is valid for cross flow and $Re_DPr > 0.2$. The physical properties are evaluated at the film temperature is as given in eqn. (8)

$$T_f = (T_s + T_\infty)/2 \quad (8)$$

For free convection, Nusselt number is as given in eqn. (9)

$$\overline{Nu_D} = \left\{0.60 + \frac{0.387Ra_D^{1/6}}{[1 + (0.559/\Pr)^{9/16}]^{8/27}}\right\}^2 \text{ and Nu } = \frac{h_cD}{K} \quad (9)$$

The total heat loss from the rod, Q_{total} is given as in eqn (10);

$$Q_{total} = hA_s(T_s - T_a) \quad \text{(Watts)} \quad (10)$$

Where the heat transfer coefficient, h is the combined coefficient due to natural convection and radiation, it is given in equation (11)

$$h = h_c + h_r \ (Wm^{-2}K^{-1}), \quad (11)$$

where T_s is average surface temperature of the rod (averaged from temperature T_1 to T_5) and T_a is ambient air temperature (T_6)

Coefficient due to natural radiation is as given in eqn. (12)

$$h_r = \sigma\varepsilon F\frac{(T_s^4 - T_a^4)}{(T_s - T_a)} \quad (12)$$

Where σ = Stefan Boltzmann constant = 5.67×10^{-8} ($Wm^{-2}K^{-4}$), ε = Emissivity of the surface ≡ 0.85, F = View factor = 1

The thermal conductivity of the material is given as:

$$K_{material} = \frac{hP}{m^2A} \quad (8)$$

Where P = Perimeter of the pin = πD (12)

A = Cross sectional area of the pin = $\frac{\pi D^2}{4}$ (13)

This equation is valid for *Rayleigh* number $Ra_D < 10^{12}$, RaD is calculated using eqn. (14)

$$Ra_D = \frac{\beta g(T_s - T_a)D^3P_r}{\nu^2} \quad (14)$$

β is the expansion coefficient that depends on the fluid. For an ideal gas, $\rho = p/RT$, the expansion coefficient are determined using equation (115), Pr is Prandtl number and v is the kinematic viscosity

$$\beta = -\frac{1}{\rho}\left(\frac{\partial\rho}{\partial T}\right)_p = \frac{1}{\rho}\frac{p}{RT^2} = \frac{1}{T} \quad (15)$$

Parts of Extended Surface Heat Transfer Equipment

1. **Metal rod -** This is a rod of 10mm diameter and length 350mm.
2. **Heater -** This is the source through which heat is supplied to the equipment. The heater has 60 W capacity.

3. **Insulator –** It is used to prevent heat loss from the heater. The insulator used is Plaster of Paris (P.O.P).
4. **Stands -** They support the heater, insulator and the metal rod.
5. **Base-** This is the flat bed upon which the entire device is mounted of 500 mm × 200 mm × 80 mm as shown in Figure 2.0.

Determination of Heater Capacity

The power of heater was calculated for expected surface temperature (T_s) is 120°C and ambient temperature (T_a) is 35°C. The calculated parameters are Ra_D = 3967.7, Nu = 3.53, hc = 10.36 W^2/mK, hr = 8.84 W^2/mK, h = 18.78 W^2/mK, $A_s = 8.796 \times 10^{-2}$ m^2

The power rating of the heater was calculated using eqn. (10) is 14 W

Therefore, the power rating of the heater is the addition of the calculated value of power and 10% factor of safety

Heater capacity = 14 + 1.4 = 15.4 W

Hence, the heater to be used must have a minimum power rating of 15.4W. However, the heater rating capacity of 60 watts was selected (standard rating in the market).

Determination of Temperature at Different Points along a Fin

The temperature distribution at different points along the metal rods were calculated using temperature distribution equation along the pin fin is as given in eqn. (7)

Material Selection

The materials required for heat transfer equipment are materials were based on the availability, good mechanical properties and cost of cylindrical fins: mild steel, aluminum and brass. The bill of engineering measurements and evaluation of the developed extended surface heat transfer teaching equipment is as presented in Table 1.0 with the production cost of ₦45,000.00. The developed extended surface heat transfer teaching equipment is as shown in Figure 2

Table 1.0: BILL OF ENGINEERING MEASUREMENTS AND EVALUATION

S/N	DESCRIPTION	QUANTITY	MATERIAL	SPECIFICATIONS	COST (#)
1	Base	1	Cast iron	500mm × 200mm × 80mm	2500
2	Voltmeter	1	---------	------------	1000
3	Heating element	1	---------	60W	800
4	Thermocouples	6	---------	Temperature probe Thermocouple sensor (Type K) -40°C to 250°C	21000
5	Metal rod	1	Aluminium	Ø10mm × 350mm	2500
6	Metal rod	1	Mild Steel	Ø10mm × 350mm	1000
7	Metal rod	1	Brass	Ø10mm × 350mm	4000
8	Bolt and Nut	6	Cast iron	12mm bolt	60
9	Overhauling	-----	-------	--------	3290
10	Contingency	------	-------	--------	3950
11	Workmanship	------	-------	--------	4930
	TOTAL				**45,030.00**

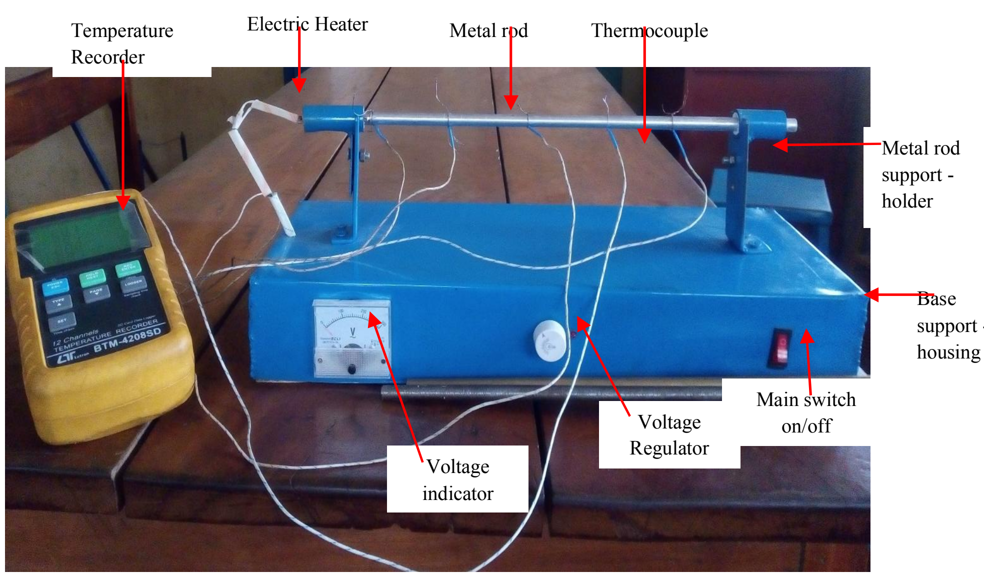

Fig. 2: Developed Extended Surface Heat transfer Teaching Equipment

Experimental Procedure

The extended surface heat transfer teaching equipment which was designed and fabricated was used to perform some experiments. From the experiments, the temperature distributions for each of the cylindrical metal rod were determined. The time duration for each voltage; 50V, 100V and 150V for each material (Mild Steel, Brass and Aluminium) was 45 minutes to ensure that the temperature reach a steady state.

The experiment was carried out with the following procedures;

1. The Mild Steel cylindrical rod was mounted on the equipment,
2. Five thermocouples were attached to different points, T1, T2, T3, T4 and T5 along the cylindrical rod to measure the temperatures at the points. The thermocouples distance were 0 cm, 7 cm, 14 cm, 21 cm and 28 cm. Another thermocouple was used to measure the ambient temperature as T6
3. The six thermocouples were connected to the temperature data logger.
4. The main switch was switched on.
5. The voltage was set to 50 volts with the help of the adjusting knob and left at this voltage for a period of 45 minutes so as to ensure that steady state is reached.
6. The data logger was switched on to record the temperature readings at different points along the rod and the ambient temperature.
7. The voltage was set to 100 volts after 45 minutes.
8. The voltage was set to 150 volts after 45 minutes.
9. After taking the reading at 150 volts, the temperature data logger was switched off.
10. The voltage was set to 0 volts and the equipment switched off.
11. The above 10 steps were repeated for the other two materials (Brass and Aluminium).

3 RESULTS AND DISCUSSIONS

The temperature distributions for the three materials (Mild Steel, Brass and Aluminium rod) at three different voltages are presented graphically in Figures. Experimental temperature distributions along the Mild Steel, Brass and Aluminium rods at 50, 100 and 100 Volts are presented in Figure 3, 4 and 5 respectively.

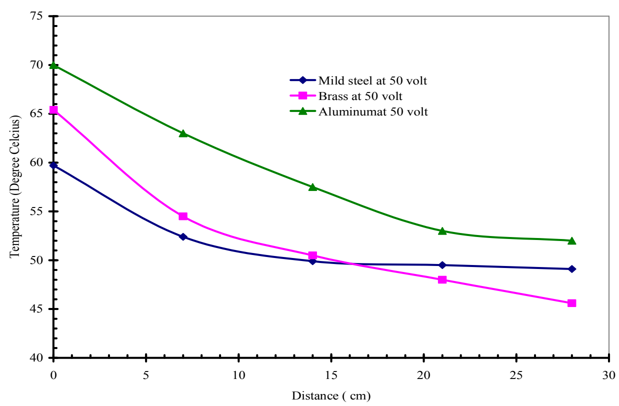

Fig. 3.0: Variation of temperature with distance at 50 volt for the three materials

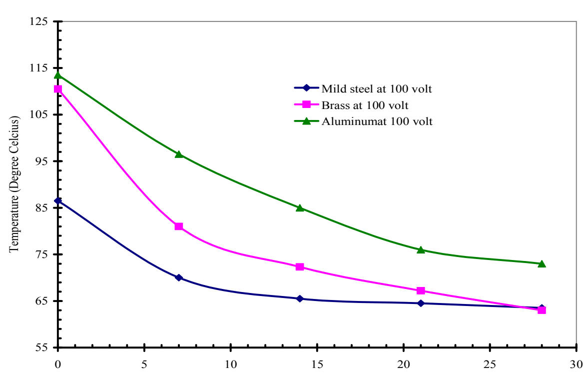

Fig. 4.0: Variation of temperature with distance at 100 volt for the three materials

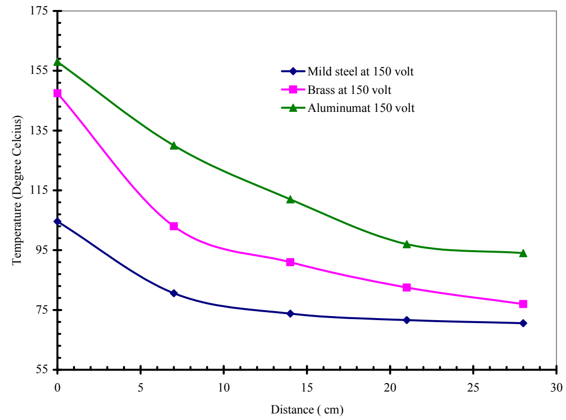

Fig. 5.0: Variation of temperature with distance at 150 volt for the three materials

From figure 3, 4 and 5, it is observed that temperature distribution graph patterns are similar; it follows negative temperature gradient as proposed by Fourier law of conduction. It can be deduced from Figures 3 – 5 that, there is difference among temperature distribution of Aluminum, Brass and Mild Steel. Rate of heat transfer is dependent on the temperature gradient of a material. The results revealed that, Aluminium has the highest temperature value, followed by Brass and Mild Steel at different voltages considered. The temperature increases as voltage increases, at 50, 100 and 150 volts, temperature values are 70, 113 and 157 ^{o}C for Aluminum, 65, 111 and 141 ^{o}C for Brass and 60, 87 and 100 ^{o}C for Mild Steel respectively for 2700 seconds. This explains the reason why Aluminium has the highest heat transfer characteristics followed by Brass and Mild steel respectively. This was due to the different thermal conductivity of the materials. Aluminium has the highest thermal conductivity (237 W/m.K), followed by Brass (110 W/m.K) and Mild Steel (42.3 W/m.K) (Yunus, 2002).

These differences are further investigated by using statistical analysis known as ANOVA. Summary of ANOVA result, two-factor without replication for comparing temperature distribution in the three metal rods at 50, 100 and 150 volt are presented in Table 1

Table 1: Summary of ANOVA result: Two-factor without replication for temperature distribution for 50, 100 and 150 volt

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Metals at 50 volt	148.1213	2	74.06067	15.78053	0.001672	4.45897
Metals at 100 volt	884.8	2	442.4	14.78033	0.002058	4.45897
Metals at 150 volt	3605.605	2	1802.803	25.38646	0.000343	4.45897

ANOVA analysis in Table 1 shows analytical comparison of temperature gradient of the three metal rods. In Table 1, Fcal = 15.78053 is greater than F-critical = 4.45897 and *P-value* of 0.001672 is less than 0.05 which implies, that there is a significant difference in heat conduction and loses with distance at 50 volt. Fcal = 14.78033 is greater than F-critical = 4.45897 and *P-value* of 0.002058 is less than 0.05 at 100 volt which implies, that there is a significant difference in heat conduction and loses with distance. Fcal = 25.38646 is greater than F-critical = 4.45897 and *P-value* 0.000343 is less than 0.05 at 150 volt which implies that there is a significant difference in heat conduction and loses with distance. It implies that the difference in the three metal rods conduction of heat and losses of heat is significant along the metal rod length.

The Theoretical Analysis of Temperature Distribution

The theoretical analysis of temperature distributions at different distance along the rods (0 cm, 7 cm, 14 cm, 21 cm and 28 cm) at 50, 100 and 100 volts for the three materials are calculated using eqn. (7)

Comparison between Experimental and Theoretical Values of Temperature

The graphical comparisons of experimental and theoretical values of temperature at different distance for Mild Steel, Brass and Aluminium at 50V are as presented in Figure 6, 7 and 8 respectively

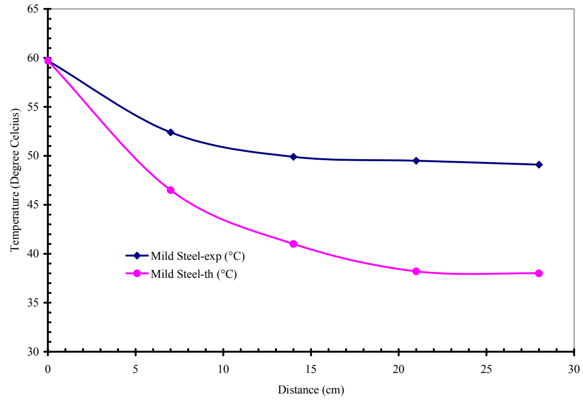

Fig. 6: Experimental and theoretical values of temperature for Mild Steel at 50V

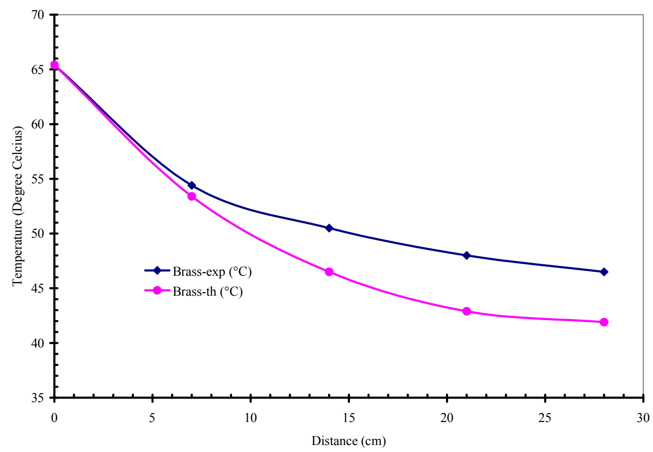

Fig. 7.0: Experimental and theoretical values of temperature for Brass at 50V

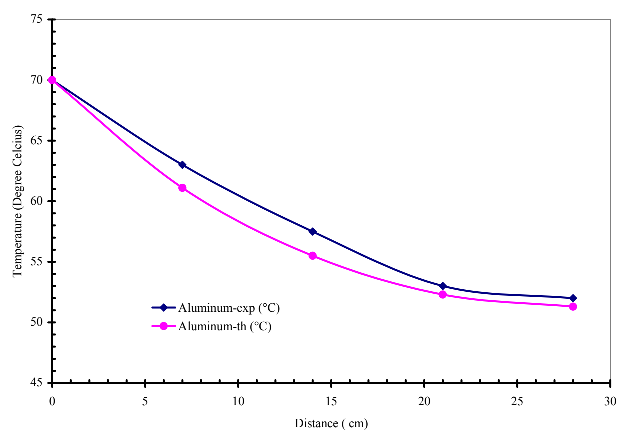

Fig. 8.0: Experimental and theoretical values of temperature for Aluminium at 50V

From Figure 6, 7 and 8, it is observed that the theoretical values are less than their correspondent experimental values. It was also observed that the experimental values and theoretical temperature distribution graph patterns are similar; it follows negative temperature gradient as proposed by

Fourier law of conduction. It can be deduced from Figures 6 – 8 that, there is negligible difference between experimental and theoretical temperature distribution of aluminum, brass and mild steel. These differences are further investigated by using statistical test known as t-test. Summary of t-test results are presented in Table 2 for comparing the theoretical and experimental temperature distribution in the three metal rods

Table 2: Summary of t-test: two-sample assuming unequal variances

Materials	t-stat	t-critical one tail	t-critical two tail
Aluminium	0.220682049	1.859548033	2.306004133
Brass	0.534016114	1.859548033	2.306004133
Mild Steel	1.648221599	1.943180274	2.446911846

Table 2 revealed that there is no significant difference between the theoretical results and experimental results for the three metals because t-stat values for Aluminum is 0.220682049, Brass is 0.534016114 and Mild steel is 1.648221599 are less than t-critical values at 95% confidence limit, and 6 degree of freedom for both t-critical one-tail is 1.859548033 and t-critical two-tail is 2.306004133. Hence the developed extended surface heat transfer equipment results are reliable with good accuracy of results for the three metal rods

The comparison of the temperature gradient of the three materials at the end of Rods, 28 cm at different voltage of 50, 100 and 150 volts with time are as presented in Figures 9, 10 and 11 respectively.

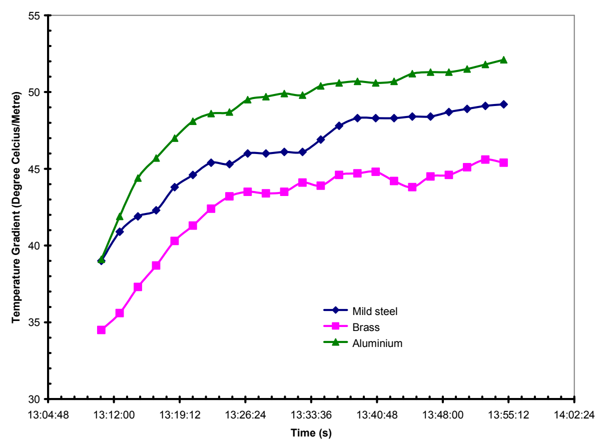

Fig. 9: Comparison of the temperature gradient at the end of rod, for 50 volts

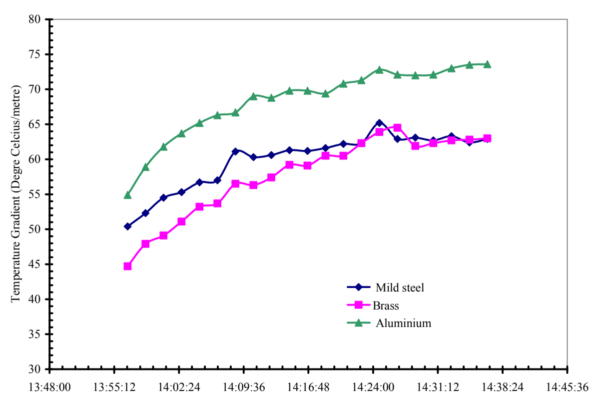

Fig. 10: Comparison of the Temperature Gradient at the end of Rod, for 100 volt

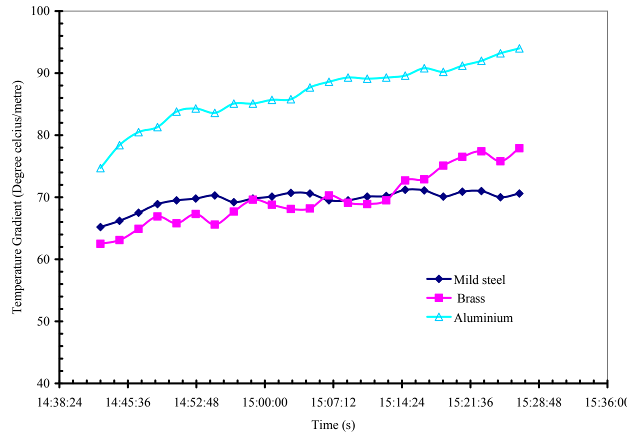

Fig. 11: Comparison of the Temperature Gradient at the end of Rod, for 150 volt

It was observed that, at 50, 100 and 150 volts as presented in Figures 9, 10 and 11, Aluminium has the highest temperature gradient, hence the highest heat transfer characteristics. Mild Steel has the lowest temperature gradient at the end of the rod. It shows that Aluminum has highest heat transfer characteristics and retention but Brass has lowest heat transfer characteristics and heat retention capacity.

Conclusions

Extended heat transfer equipment was designed, fabricated and tested. The device measures temperature distribution along an extended surface for three different cylindrical rods. Experimental studies were carried out on three materials (brass, mild steel and aluminum rod) to determine their respective temperature distribution along an extended surface over a distance of 28 cm for 2700 seconds interval at different voltage of 50, 100 and 150 volts. Statistical t-test analysis at 95% confidence limit confirmed that there is no significant difference between the theoretical results and experimental results and Analysis of variance, ANOVA at 95% confidence limit confirmed that, there is significant difference between the temperature gradient of the three selected material. As it was observed, at different points, Aluminium has the highest temperature gradient, followed by Brass and Mild Steel respectively. This explains the reason why Aluminium has the highest heat transfer characteristics followed by Brass and Mild steel respectively. Finally, the extended surface heat transfer equipment is affordable as produced with locally available materials. It is simple with easy maintenance, reliability and accuracy of results. It can be used as teaching aids in laboratories and research institutes.

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