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Research Article

Comparative Studies on Micro-Fins Geometry for Fin Efficiency and Effectiveness

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Abstract

The emergence of high-speed internet connectivity has enabled the development of very large-scale, integrated semiconductor chips and processors. High-speed data processors emit heat energy proportional to their operation speeds. Micro-fins have broad applications in medical devices and for cooling solar and fuel cells. Herein, natural convective heat transfer studies were conducted on copper- and aluminium-coated micro-fins. Rectangular, triangular, and parabolic specimens were fabricated (dimensions: 45×45×6mm^3, spacing: 5 mm). The rectangular copper-coated micro-fin exhibited better performance than triangular micro-fins. Among all specimens, the parabolic copper- and aluminium-coated ones exhibited the best fin efficiency and effectiveness. The parabolic aluminium-coated micro-fin showed fin efficiency and fin effectiveness of 98.80% and 2.0, respectively, after one hour of heating. For the same heating duration, the parabolic copper-coated micro-fin showed the highest fin efficiency of 99.02%; its fin effectiveness was 2.60. The copper-coated micro-fin with the same geometry showed fin efficiency and effectiveness of 99.02 and 2.493, respectively, for four hours of heating.

1. Introduction

The arrangement of micro-fins considerably influences the cooling of micro-electronic components because of the effect of their space optimisation and several modes of heat transfer. Understanding temperature distribution in a fin is essential for estimating the modes of heat transfer through it. When the fin transfers heat through conduction, it is a convectively heated metallic plate fastened to a wall at its base. The temperature distribution of the fin is influenced by the properties of the fluid surrounding it and fin material. Fin efficiency is defined as the ratio of maximum heat transfer to actual heat transfer of a micro-fin. When the temperature of the fin area is the same as the base temperature, the amount of heat transfer is the maximum. Fin effectiveness is the ratio of heat transfer with and without a fin. Several researchers have studied the natural convective heat transmission of micro-fins, and the inherent convective heat transfer characteristics of pin-fin heat sinks have been numerically analysed. Compared to a uniformly distributed fin-pin heat sink with 0.891µm porosity, fin-pins with changeable fin density show 11% less weight. Through natural convection and lower weight, the variable fin density resulted in improved thermal performance [1]. Another study on fins with different geometrical shapes and variable fin spacing determined that the natural convective heat transfer coefficient increases with increased heat input.

For a drop-shaped fin with fin spacing of 75 mm and heat input of 200 W, the maximum heat transfer coefficient of 11.97 $W/m^2 \cdot K$ was obtained [2]. Experiments were conducted using both uphill and downhill setups. In both configurations, when fin spacing of 20 mm was used, the thermal resistance decreased by 11% and 14%, respectively [3]. Deepa et al. investigated micro-fins with coatings of aluminium, paint-coated aluminium, copper, aluminium, and alumina-reinforcement (thickness = 5 mm, spacing = 5 mm, height = 0.25 mm, and length = 45 mm) [4]. Paint-coated aluminium exhibited good natural convective heat transmission and was deemed appropriate for electronic applications [4].

Experiments were conducted for various pipe inclination angles. Hot water was used as the heat source, and the highest Nusselt number of Nu≈408 was considered [5]. Testing was done on various orientations using 5–50 W heating outputs. When a 121 × 40mm pin fin was used, maximum natural convective heat transfer was observed [6]. Using the natural convention approach, a novel fin array with continuously changing heights and unequal sizes was proposed to remove heat from electrical equipment in confined spaces. These findings demonstrated that micro-fin arrays with greater height differences exhibited more concentrated heat transfer coefficients and less flow resistance. An optimisation technique was applied to maximise output performance, and it was determined that fin spacing and height variations influence output performance [7]. High-temperature ceramics have replaced low-temperature co-fired ceramics in power amplifier heat management, whereas silicon-based heat sinks are used. The resulting micro-pins made of silicon decrease the heat resistance considerably [8].

Another study on convective heat transfer suggested using a nanofluid-filled square chamber with an angular change. The titling fin significantly increased the heat transfer rate; maximum heat transfer for straight and curved fins was achieved at an inclination of 90° and 45°, respectively [9]. Rath et al. combined a radial heat sink with a longitudinal wavy heat sink for their experiments on natural convection. They considered the fin height, pitch-to-amplitude ratio, Rayleigh number, number of fins, and cycle of the wavy fin. The fin efficiency and Nusselt number were higher in wavy fins with higher surface roughness. The three cycles of wavy fins exhibited the highest fin efficiency and Nusselt number. Thus, fin effectiveness increased with surface roughness [10]. A plate and pin fin array was used in another study, resulting in pin micro-fins with enhanced thermal performance [11]. The impact of micro-fin height and spacing on the natural convective heat transfer coefficient was experimentally investigated by Mahmoud et al. [12]. They used microwave electric discharge machining to fabricate copper micro-fins. Fins of varied heights (0.25-1.00 mm) and spacing (0.5-1.00 mm) were used. The convective heat transfer coefficient decreased with the increasing fin height but increased with the increase in fin spacing. Therefore, contemporary research focuses on optimising natural convective heat transfer by altering fins' material, design, spacing, height, and orientation. Herein, to investigate the efficiency and usefulness of fins for natural convective heat transfer, three different geometrical shapes—rectangular, triangular, and parabolic—with dimensions of 45 × 45 × 6 mm^3 and 5 mm spacing were created.

2. Experimental Setup

A micro-fin profile was created using a wire electric discharge machine(EDM) on copper and aluminium materials, considering the type of heat transmission. Copper and aluminium materials were considered because of their innate characteristics, such as high thermal conductivity, corrosion resistance, lightweight, and compatibility. A total of six test pieces (dimensions: 45 × 45 mm^2, fin height = 6 mm, fin spacing = 5 mm) were prepared. The study aimed to increase the convective heat transfer coefficient using various micro-fin geometrical structures. The following metrics were used to gauge the performance of the as-fabricated fins [13].

Fin effectiveness represents the relationship between the rate of heat transfer with and without fins, and it is expressed as shown in Eq.1:

$$€ = Q_{\text{with fin}}/Q_{\text{without fin}} \tag{1}$$

Fin efficiency is the ratio of the maximum amount of heat transfer that can occur through a fin to the actual rate of heat transfer, and it is represented using Eq. (2):

$$\eta = Q_{\text{Actual heat Transfer}}/Q_{\text{Maximum possible heat transfer}} \tag{2}$$

Different heat transfer rates were obtained for different fin shapes. Copper and aluminum materials with various shapes—such as parabolic, triangular, and rectangular fins—were considered [14].

Table 1. Dimensions for fins

Parameters	Specification for Rectangular, Triangular, and Parabolic fin
Fin Length	4 mm
Fin Thickness	5 mm
Spacing between each fin	5 mm
Total size of Specimen	45 x 45 x 6 mm
No of Fins	5

2.1. Electric Discharge Machining of Micro-Fins

Wire EDM was used to create specimens with different geometries, as depicted in Figures 1-3; Figure 4 shows a photograph of a machined specimen.EDM is a machining technique used to create micro-fin alloys. In EDM, a strong electric spark discharge between the tool (cathode) and the specimen material (anode) removes metal. A direct current power source was linked to both the tool and the specimen. The tool was attached to the negative terminal of the electric source, and the specimen on which the micro-fin was to be created was connected to the positive terminal [15, 16]. Transformer oil was used as the dielectric fluid medium where the tool and specimens were immersed. The servo mechanism maintained the spark gap between the tool and the workpiece, ranging from 0.005 to 0.05 mm. Sparks appeared every 10–30 μs, and thousands melted and evaporated the workpiece in a second. The dielectric fluid pumped around it carried away the removed material particles, generating the necessary micro-fins.

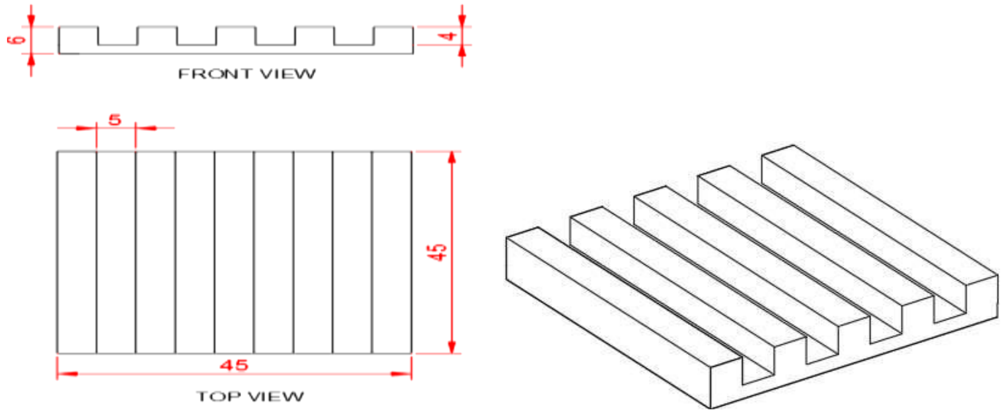


Figure 1. Two-dimensional view of a rectangular fin

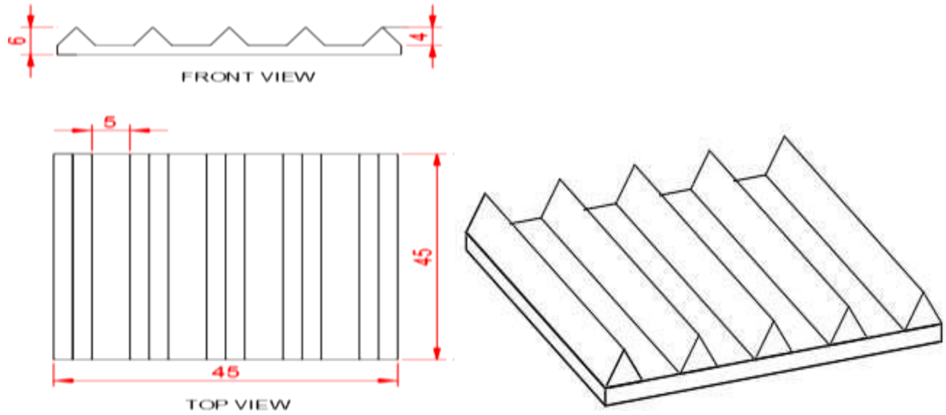


Figure 2. Two-dimensional view of a triangular fin

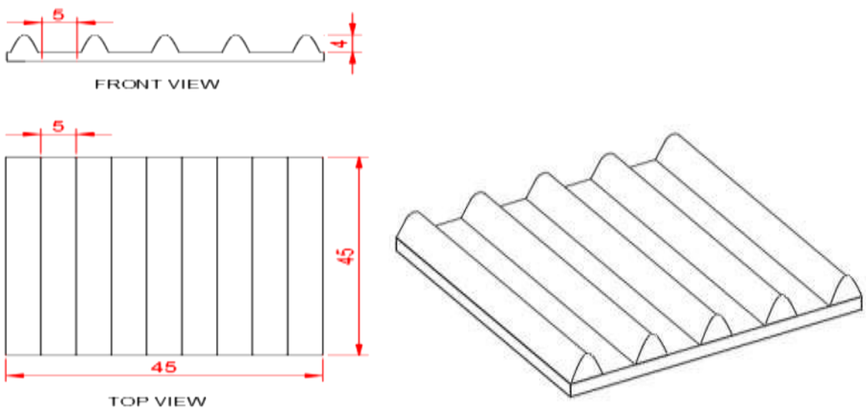
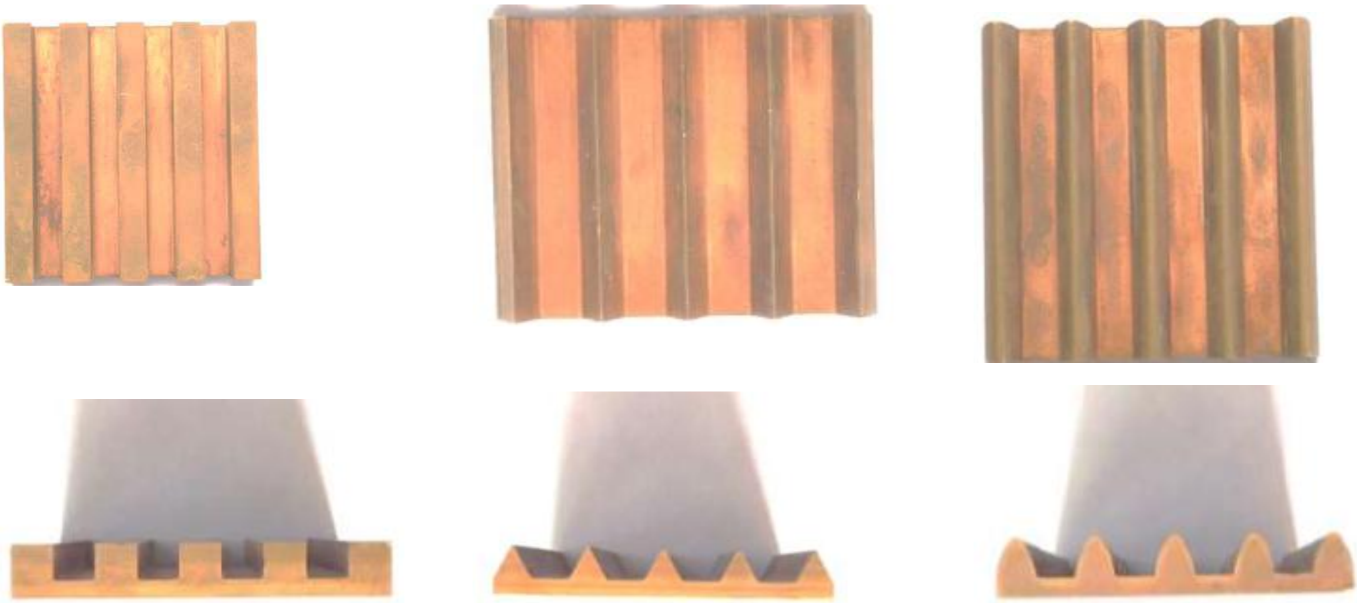


Figure 3. Two-dimensional view of a convex-parabolic fin



Figures 4. Micro-fins fabricated using EDM

Microfins with three types of geometries were created using aluminium and copper materials. An electric heater with a power supply of 8W was used to heat the test items. Figure 5 shows the experimental apparatus used in the study. The test piece was covered on three sides, and the top surface was left uncovered to allow unhindered convection heat movement. A transformer managed the current supply. Readings were taken every hour, and the experiment lasted four hours. The temperature of the air above the specimen and heat transfer on the top and bottom surfaces were measured using a thermocouple. Tables 2 and 3 display the experimental readings for the different micro-fin types. The efficiency and efficacy of the micro-fins were computed. There was a disparity between the parabolic, triangular, and rectangle profiles.

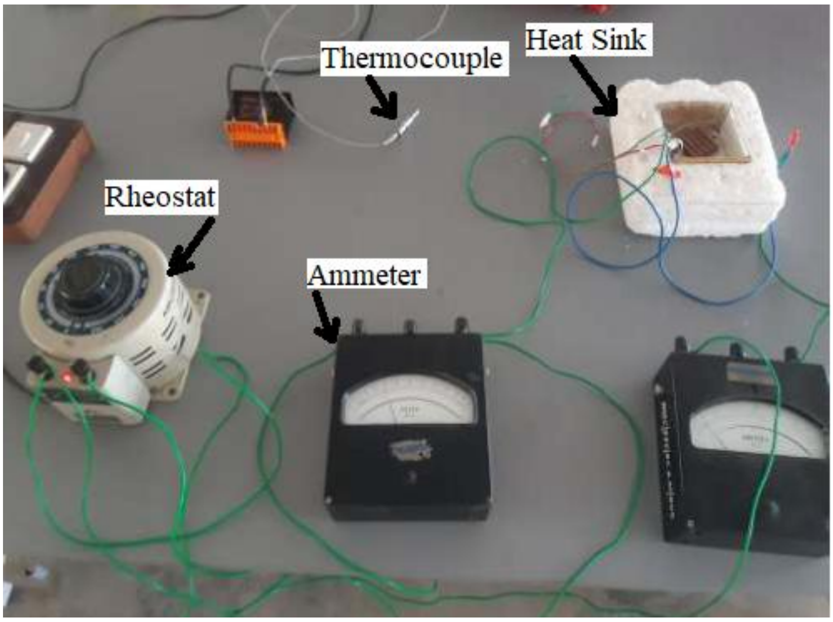


Figure 5. Micro-fin heating arrangements

Table 2. Experimental observations on rectangular micro-fin

No of hours	Copper			Aluminium		
	Top air Temp. ◦c	**Top surface Temp. ◦c**	**Bottom surface Temp. ◦c**	**Top air Temp. ◦c**	**To surface Temp. ◦c**	**Bottom surface Temp. ◦c**
1	34	76	77	33	75	76
2	36	84	87	35	76	78
3	38	88	90	37	78	79
4	39	89	93	38	80	81

Table 3. Experimental observations of triangular micro-fin

No of hours	Copper			Aluminium		
	Top air Temp. ◦c	**Top surface Temp. ◦c**	**Bottom surface Temp. ◦c**	**Top air Temp. ◦c**	**To surface Temp. ◦c**	**Bottom surface Temp. ◦c**
1	35	76	77	33	75	76
2	39	81	85	35	76	78
3	43	83	88	37	78	79
4	46	85	90	38	80	81

Table 4. Experimental observations of parabolic micro-fin

No of hours	Copper			Aluminium		
	Top air Temp. ◦c	**Top surface Temp. ◦c**	**Bottom surface Temp. ◦c**	**Top air Temp. ◦c**	**To surface Temp. ◦c**	**Bottom surface Temp. ◦c**
1	36	77	79	35	70	73
2	40	80	85	39	73	75
3	42	84	87	42	75	78
4	45	86	90	45	77	82

3. Results and Discussion

The rate of heat transfer from a surface at a temperature TS to the surrounding medium at T∞was given using Newton's law of cooling (3) [17-18].

$$Q_{con} = h\, A_s (T_s - T_\infty) \tag{3}$$

where, $Q_{con =}$ Convection heat transfer coefficient, A_s =Heat transfer surface area h = Convection heat transfer coefficient

The convective heat transfer coefficient can be increased by using highly conductive materials or installing pumps and fans. The convection heat transfer coefficient is lower near the base of the fin because of an excess of solid surface, which is in agreement with the bottom surface temperature of the fins presented in Tables 2–4. The convection heat transfer coefficient fluctuated along the fin and was considerably influenced by fluid velocity. There was minimal contact with the solid surface and minimal flow resistance at the fin side. Eqs.4–12 were utilised to determine the fin efficiency and effectiveness for all fins.

Rectangular fin:

$$\eta_{\mathrm{fin}} = \frac{\tanh(\mathrm{mL})}{\mathrm{mL}} \tag{4}$$

$$A_p = 2WL \tag{5}$$

$$mL = \sqrt{\frac{2\bar{h}}{k\ th}}\ L \tag{6}$$

Triangular fin:

$$\eta_{fin} = \frac{Bessell(1{,}2mL)}{mL\ Bessell(0{,}2mL)} \tag{7}$$

$$A_p = 2W\sqrt{L^2 + \frac{th^2}{2^2}} \tag{8}$$

$$mL = \sqrt{\frac{2\bar{h}}{k\ th}}\ L \tag{9}$$

Parabolic fin:

$$\eta_{fin} = \frac{2}{\left[\sqrt{4(mL)^2+1+1}\right]} \tag{10}$$

$$A_{p,fin} = W\left[C_1L + \frac{L^2}{th}ln(\frac{th}{L} + C_1)\right] \tag{11}$$

$$mL = \sqrt{\frac{2\bar{h}}{k\ th}}\ LC_1 = \sqrt{1 + \frac{th^2}{L^2}} \tag{12}$$

The fin efficiency and efficacy of rectangular copper and aluminium fins are displayed in Figure 6. The fin efficiency of a copper rectangular fin at a surface-to-air temperature differential of 42°C was 98.20%, as shown in Figure 6(a). The rectangular fin is most popular for natural, conventional heat transfer investigations. It has the highest heat transmission because the fin surface is the only part that breaks the heat. While convection loss occurs from the upper and lower surfaces of the fin, the main path of heat conduction is along the x-axis. This fin exhibits one-dimensional heat conduction; temperature distribution depends on the x-coordinate. At a surface-to-air temperature differential of 48°C, fin efficacy was 0.9142. Overall, the rectangular aluminium fin had low efficiency and effectiveness. The surface area of a rectangular fin does not increase or decrease; these results are consistent with those from a previous study [19].

In triangular micro-fins, equal heat transmission occurs in less space; thus, they are preferably used in air-cooled engines. Triangular and rectangular fins are typically used on the outer surfaces of air-cooled engine cylinders. The optimisation process involves adjusting the temperature of the base of the fin and measuring the fin's air and surface temperatures. Figure 7 illustrates aluminium and copper fins' high fin efficiency and effectiveness (86.37% and 2.37%, respectively). The air-cooled engine's cooling system mostly depends on the size of its fins. Heat is transferred through the surfaces of the fins and is contested by air passing through them.

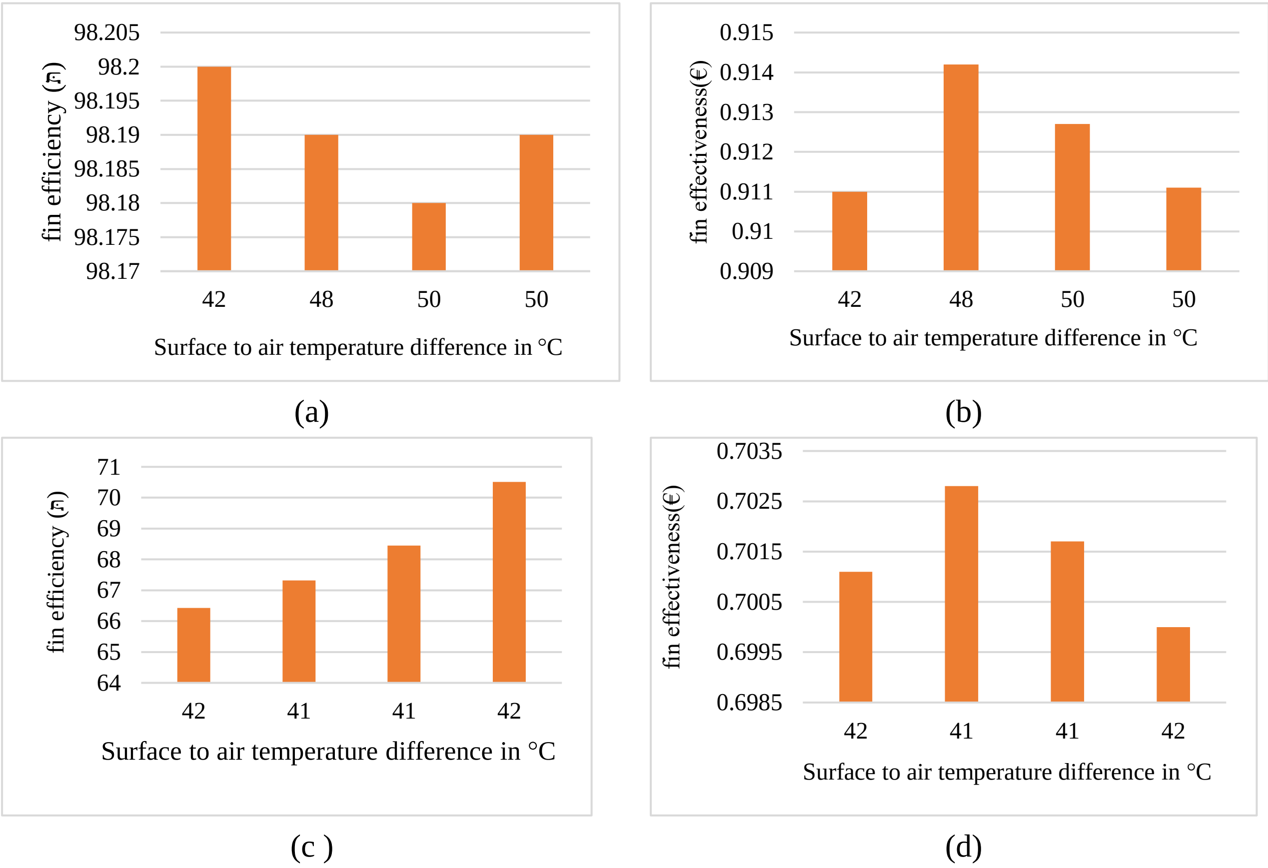


Figure 6. Fin efficiency and effectiveness of (a-b) copper and (c-d) aluminium rectangular fins

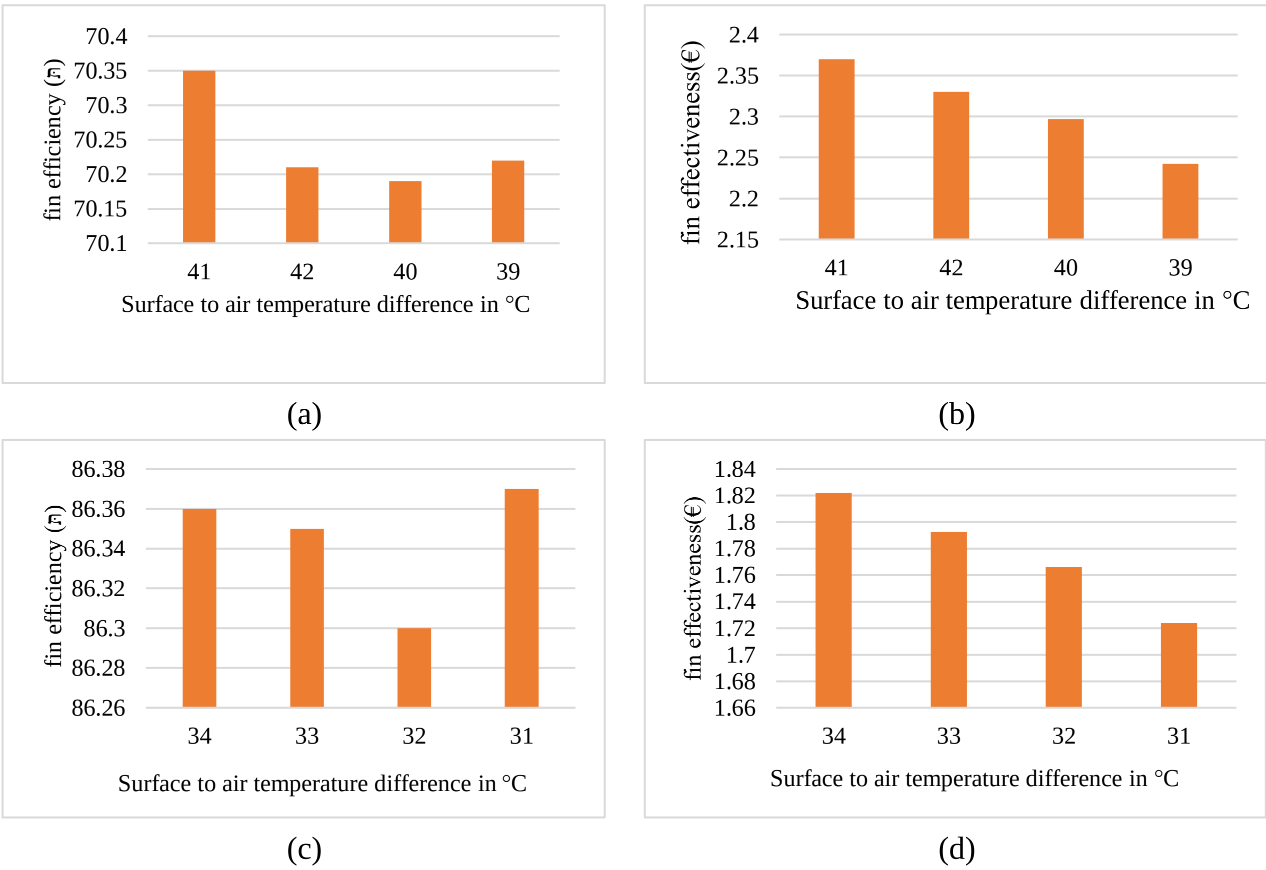


Figure 7. Fin efficiency and effectiveness of triangular (a-b) copper and (c-d) aluminium fins

The heat dissipation process of each fin segment with a uniform cross-sectional area was different. The parabolic profile fin was efficient because it distributed the most heat for the least material. The concave parabolic fin had the maximum efficiency and efficacy, remarkably higher than the triangular and rectangular fins. With parabolic fins, heat loss was maximised at the same fin length and base height for a fixed fin volume. The terms "optimum heat loss," "optimum fin length," and "optimum base height" refer to the maximum heat loss, the matching fin length, and the fin base height, respectively. The fin efficiency and efficacy of aluminium and copper micro-fins are displayed in Figure 8(a-d). For a temperature differential of 40°C and 41°C, the copper fin had efficiency and effectiveness of 99.04% and 2.6, respectively. The temperature and heat loss of the symmetrical triangular fin and parabolic fin were compared. Good results in terms of efficiency and efficacy were obtained for the parabolic copper micro-fin, demonstrating that the parabolic geometry had a high heat transmission rate.

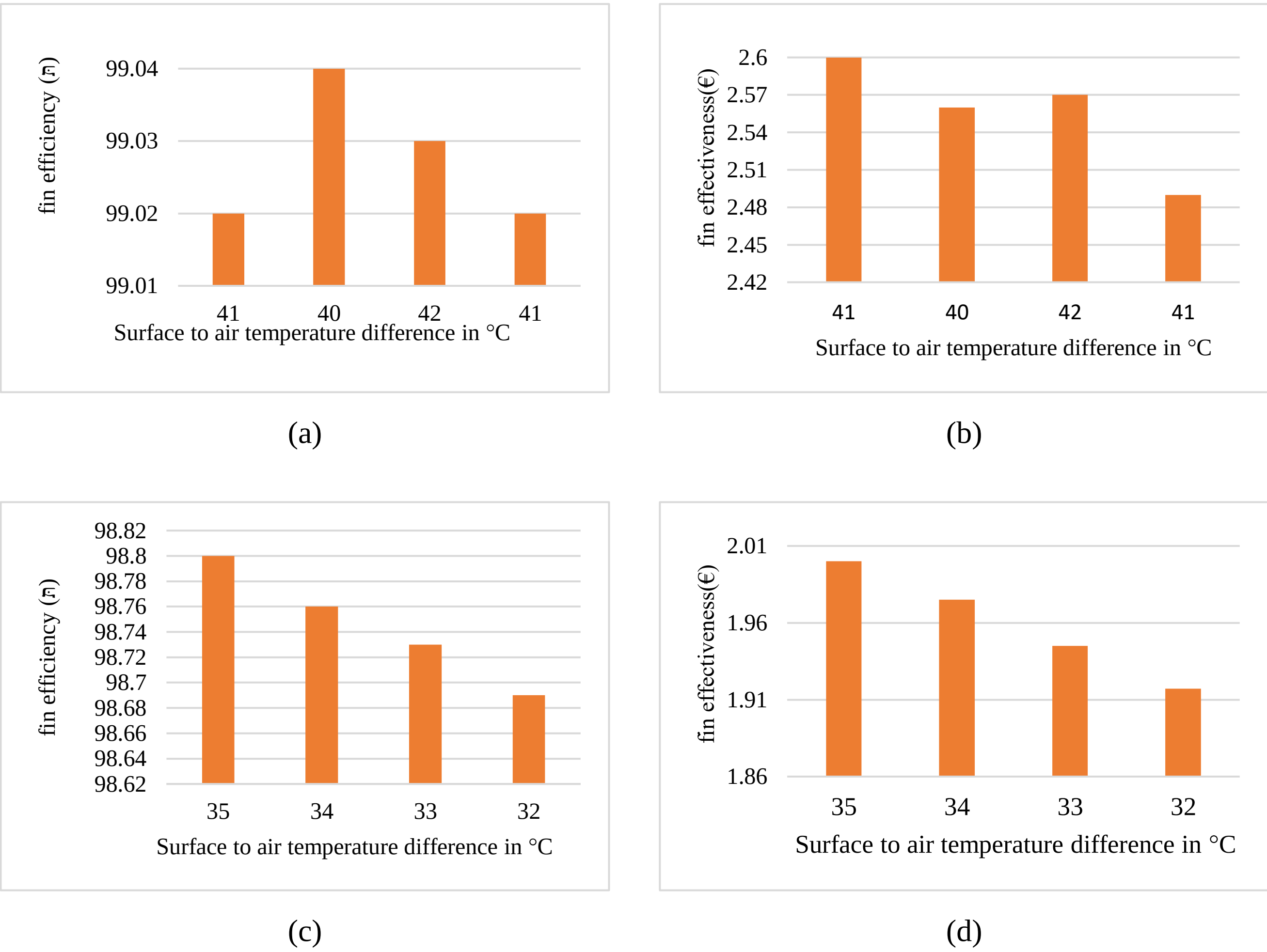


Figure 8. Fin efficiency and effectiveness of parabolic fin: (a-b) copper, (c-d) aluminium

As shown in Table 5, the best fin efficiency and effectiveness were observed for copper parabolic fins, followed by aluminium parabolic fins. Compared with the copper triangular micro-fin, better results were observed for the copper rectangular micro-fin.

Table 5. Comparing results of different geometries of micro-fins

Hours of heating	Rectangular fin(Copper)		Triangular fin(Copper)		Parabolic fin(Copper)	
	Fin efficiency (תּ)	**Fin effectiveness(€)**	**Fin efficiency (תּ)**	**Fin effectiveness(€)**	**Fin efficiency (תּ)**	**Fin effectiveness(€)**
1	98.20	0.911	70.35	2.370	99.02	2.60
2	98.19	0.914	70.21	2.33	99.04	2.56
3	98.18	0.913	70.19	2.297	99.03	2.569
4	98.19	0.911	70.22	2.242	99.02	2.493
	Rectangular fin(Aluminum)		**Triangular fin(Aluminum)**		**Parabolic fin(Aluminum)**	
	Fin efficiency (תּ)	**Fin effectiveness(€)**	**Fin efficiency (תּ)**	**Fin efficiency (תּ)**	**Fin effectiveness(€)**	**Fin efficiency (תּ)**
1	66.43	0.7011	86.36	1.822	98.80	2.00
2	67.32	0.7028	86.35	1.7926	98.76	1.975
3	68.45	0.7017	86.30	1.7659	98.73	1.945
4	70.51	0.700	86.37	1.7238	98.69	1.9171

4. Conclusion

In this study, an EDM was used to fabricate micro-fins with three distinct fin profiles—rectangular, triangular, and parabolic—using copper and aluminium materials. Fin efficacy and efficiency were assessed by analysing the performance of the micro-fins. The best fin efficiency and effectiveness were observed for the copper parabolic fins, followed by aluminium parabolic fins. Copper rectangular micro-fins produced better results than triangular micro-fins. With a temperature differential of 40°C between the surface and the air, the copper parabolic micro-fin exhibited the best fin efficiency and effectiveness of 99.04% and 2.56%, respectively. These values were 28.53% and 1.86% greater than the aluminium rectangular micro-fins. Thus, the copper parabolic micro-fin outperformed the rectangular and triangular copper micro-fins. The aluminium rectangular micro-fin exhibited the lowest fin efficiency and effectiveness of 70.51% and 0.7% at a surface-to-air temperature differential of 42°C. Thus, parabolic copper micro-fins are recommended for high natural convective heat transfer performance. In future studies, surface modification methods such as coating shot peening and laser scribing on the fins' surfaces can be considered for enhancing the surface area.

Declaration of Competing Interest: The authors declare they have no known competing interests.

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