THE 3-D COMPUTATIONAL INVESTIGATION OF THERMAL PERFORMANCE ON ENGINE CYLINDER
Effect of Different Geometry Fins

by

Ramesh Kumar AYYAKKANNU[a*], Sakthi Rajan CHANDRAMURTHY[b], Ramasamy VEERAMALAI[c], and Pradeep Kumar MADHESAN[a]

[a] Department of Mechanical Engineering, Sona College of Technology, Salem, Tamil Nadu, India
[b] Department of Mechanical Engineering, SBM College of Engineering and Technology, Dindigul, Tamil Nadu, India
[c] Department of Mechanical Engineering, Velammal Institute of Technology, Thiruvallur, Tamil Nadu, India

Original scientific paper
https://doi.org/10.2298/TSC220917026A

A fin is a surface that extends from an object to increase the rate of heat transfer to or from the environment for enhancing convection. The heat transfer performance of the engine cylinder fin is investigated in this study using fin geometries with various extensions, including rectangular, trapezium, and triangular segmental extensions. These are compared to fins without extension and showed a 5-13% increase in heat transfer rate. The primary idea behind adding extensions to finned surfaces is to increase the surface area of the fin in contact with the fluid/coolant flowing around it, resulting in a faster heat transfer rate.

Key words: *convection, heat transfer, fins, thermal analysis, engine cylinder*

Introduction

Extensions on engine finned surfaces are used to increase the surface area of the fin in contact with the fluid-flowing around it, resulting in a higher rate of heat transfer from the base surface with a fin than a fin without extensions. Surfaces that protrude from a base are called fins, and they improve convection speed up the rate at which heat transfer to or from the environment. Rectangular extensions, trapezium extensions, and triangular extensions are examples of fin extensions. A number of experiments were carried out to determine the impact of the pin-fin tube's structural parameters on heat transfer and resistance characteristics and found that the heat transfer and resistance performance of pin-fin tubes were greatly influenced by the longitudinal pitch and transverse fin spacing [1]. Free convection around a single vertically oriented square fin on a horizontal plate was numerically investigated, and it was predicted that heat flux at the fin base decreases almost linearly with increasing fin width [2].

A steady-state thermal analysis was used to observe the temperature distribution and heat dissipation along the fin surface of two shapes, and a better shape of the fin, as well as a suitable material, was selected based on the FEM results and a comparison the existing shape and material of the fin [3]. The influence of circular, pin, and rectangular fins on the efficiency of the Stirling engine was investigated, resulting in an increase in the heat transfer rate, effi-

* Corresponding author, e-mail: rameshkumara@sonatech.ac.in

ciency, and power output of the engine, with rectangular fins achieving the highest efficiency of 19.03% [4]. In the light of flow morphologies around micro pin-fins of various forms, a performance evaluation research is conducted using 3-D numerical models and found that the rectangular-shaped micro pin-fin design has the maximum Nusselt number and friction factor over the whole Reynolds number range [5]. Reported that the heat transfer from a cylinder with eccentric fins is slightly lower than that from a cylinder with concentric fins and the temperature plume and flow field over a horizontal cylinder with fins of different eccentricity [6].

The use of three slides with impinging flow results in an adequate reduction in thermal resistance while requiring little additional pumping power. When using parallel flow, the change in heat sink performance that occurs as the number of slides increases is not proportional to the substantial rise in pumping power [7]. When compared to the aluminum test piece, the paint coated copper test piece produces a 20.62% higher heat transfer and the convective heat transfer rate increased by 49% when comparing the aluminum with the aluminum paint coated test piece [8]. The heat transfer coefficients of different cross-sections were investigated using an experimental investigation with a helical coil heat exchanger and the combination of Ethylene glycol and water improves heat transfer efficiency by 10% to 15% and lowers heat loss from the pipe [9].

The amount of heat transferred by an object is determined by its conduction, convection, or radiation. Heat transfer rates can be enhanced by increasing the temperature gradient between the object and the environment, the object's surface area and the object's convection coefficient. The object's surface area is the most feasible and cost-effective technique to increase the heat transfer rate.

Mathematical modelling of fins

Laws of heat transfer

Heat transfer through fins with or without extensions in an engine cylinder is governed by the following laws: the Fourier Law of Heat Conduction and Newton's Law of cooling.

Fourier Law:

$$Q = -kA\frac{\mathrm{d}T}{\mathrm{d}x} \quad \text{or} \quad \frac{Q}{A} = q = -k\frac{\mathrm{d}T}{\mathrm{d}x} \tag{1}$$

where Q [W] is the heat transfer, k [Wm^{-1}K^{-1}] – the thermal conductivity of material, q [Wm^{-2}] – the heat flux, and A [m^2] – the area.

Newton's Law:

$$Q = hA\left(T_\mathrm{s} - T_\infty\right) \tag{2}$$

where A [m^2] is the area exposed to heat transfer, h [Wm^{-2}K^{-1}] – the heat transfer co-efficient, T_s [K] – the temperature of the fin surface, and T_∞ [K] – the temperature of the fluid.

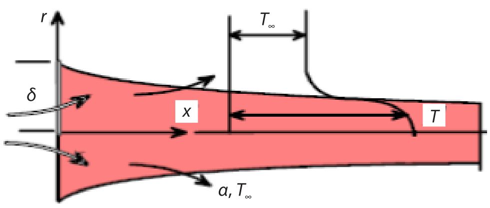

Figure 1. Heat flow and temperature distribution through a fin

Heat transfer and temperature distribution in fins

Conduction and heat loss through convection cause the temperature to drop down the fin. Along the length of the fin, the conduction is considered to be 1-D. Figure 1 depicts the temperature distribution and heat transfer through a fin as an axial and lateral, 2-D.

Fin heat equation

Considering a small element dx, per conservation of energy:

$$Q_x = Q_{x+\mathrm{d}x} + Q_{\mathrm{conv}} \tag{3}$$

where

$$Q_x = -kA\frac{\mathrm{d}T}{\mathrm{d}x}$$

is the heat conducted at x,

$$Q_{x+\mathrm{d}x} = -kA\frac{\mathrm{d}T}{\mathrm{d}x} - kA\frac{\mathrm{d}^2T}{\mathrm{d}x^2}\mathrm{d}x$$

is the heat conducted at x + dx, and

$$Q_{\mathrm{conv}} = h\left(P\,\mathrm{d}x\right)\left(T_\mathrm{s} - T_\infty\right)$$

is the heat convected through the length dx, where P [m] is the perimeter, Pdx [m^2] – the area for convection, and A [m^2] – the cross-sectional area of the fin.

Thus the energy balance gives:

$$kA\frac{\mathrm{d}^2T}{\mathrm{d}x^2} - hP\left(T_\mathrm{s} - T_\infty\right) = 0 \tag{4}$$

$$\frac{\mathrm{d}^2T}{\mathrm{d}x^2} - m^2\left(T_\mathrm{s} - T_\infty\right) = 0 \tag{5}$$

where $m^2 = hP/KA$.

If, $\theta = (T_\mathrm{s} - T_\infty)$, the previous equation takes the form:

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

This is the wave equation describing the temperature as function of x and m. It is a second order, linear ordinary differential equation with the general solution:

$$\theta = C_1\mathrm{e}^{-mx} + C_2\mathrm{e}^{+mx} \tag{6}$$

The temperature change along the fin is determine using eq. (6). Two boundary conditions are required to solve for the unknown C_1 and C_2. The first is that the temperature at the end of the fin that connects to the wall is the same as the temperature of the wall. The second boundary condition can be found at the other end of the fin and assume that the heat exchange from the end is moderate. Considering the three cases such as long fins, insulated end fins, and convection at the end fins, each yielding a set of two boundary conditions, the solution can be used to determine the temperature distribution and heat transfer as formulated.

Long fins

Boundary conditions

$$\frac{\mathrm{d}^2\theta}{\mathrm{d}x^2} - m^2\theta = 0 \ \text{ in } \ x \ge 0$$
$$\theta = T_0 - T_\infty \ \text{ at } \ x = 0 \ \text{ and } \ \theta \to 0 \ \text{ as } \ x \to \infty \tag{7}$$

Temperature distribution

$$\frac{T_s - T_\infty}{T_0 - T_\infty} = e^{-mx} \tag{8}$$

Heat transfer

$$Q = \sqrt{hPkA}\theta_0 \tag{9}$$

Fins with insulated end

Boundary conditions

$$\begin{gathered}\frac{d^2\theta}{dx^2} - m^2\theta = 0 \ \text{ in } \ 0 \le x \le L \\ \theta = T_0 - T_\infty \ \text{ at } \ x = 0 \ \text{ and } \ \frac{d\theta}{dx} = 0 \ \text{ at } \ x = L\end{gathered} \tag{10}$$

Temperature distribution

$$\frac{T_s - T_\infty}{T_0 - T_\infty} = \frac{\cos h\left[m\left(L - x\right)\right]}{\cos h\, mL} \tag{11}$$

Heat transfer

$$Q = \sqrt{hPkA}\theta_0 \tan h\left(mL\right) \tag{12}$$

Fins with convection at the end

Boundary conditions

$$\begin{gathered}\frac{d^2\theta}{dx^2} - m^2\theta = 0 \ \text{ in } \ 0 \le x \le L \\ \theta = T_0 - T_\infty = \theta_0 \ \text{ at } \ x = 0 \\ k\frac{d\theta}{dx} + h\theta = 0 \ \text{ at } \ x = L\end{gathered} \tag{13}$$

Temperature distribution

$$\theta = \theta_0 \frac{\cos h\, m\left(L - x\right) + \left(\frac{h}{mk}\right)\sin h\, m\left(L - x\right)}{\cos h\left(mL\right) + \left(\frac{h}{mL}\right)\sin h\left(mL\right)} \tag{14}$$

Heat transfer

$$Q = \sqrt{h\,PkA}\,\theta_0 \frac{\tan h\left(mL\right) + \left(\frac{h}{mL}\right)}{1 + \left(\frac{h}{mL}\right)\tan h\left(mL\right)} \tag{15}$$

Fin efficiency, η_{fin}

The efficiency of fin is defined as the ratio of actual heat transferred by fin to the maximum heat transferred by fin. The maximum heat transfer would occur if the temperature of extended surface was equal to the base temperature at all points:

$$\eta_{\text{fin}} = \frac{Q_{\text{fin}}}{Q_{\text{max}}} \tag{16}$$

Fin effectiveness, E

The ratio of the heat transfer rate from a surface with fin to heat transfer rate from without fin. The effectiveness of fins must be greater than unity to justify their addition surface dissipating heat to surroundings:

$$E = \frac{Q_{\text{with fin}}}{Q_{\text{without fin}}} \tag{17}$$

Overall surface efficiency

It is the ratio of total heat transfer from the finned surface to the heat transfer from the same surface if there were no fin:

$$\eta_{\text{fin overall}} = \frac{Q_{\text{total fin}}}{Q_{\text{total nofin}}} \tag{18}$$

Measurements

The motorbike TVS 50 engine cylinder block was chosen in order to determine the temperature distribution and the heat flux under various extension geometry. Over 44 million consumers have chosen a TVS product over the years. The TVS two-wheelers are affordable, and convenient to use. The engine block is made of aluminum alloy 6061. Table 1 lists the engine specifications with aluminum alloy 6061 material properties were used in this study.

Table 1. Engine specifications

Description	Specification
No of cylinder	1
Bore	40 mm
Stroke	80 mm
Piston displacement	50 cc
Engine position	Horizontal
Young's modulus	69 GPa
Density	2700 kg/m^3
Ultimate strength	310 MPa
Specific heat	0.896 KJ/kg°C
Thermal conductivity	167 W/mK

During the analysis, the same material properties of aluminum alloy 6061 were employed for all of the different extensions of engine cylinder. A vernier calliper was used to measure the engine block and fin dimensions. For further CAD modelling, the dimensions of an existing disassembled TVS engine block with a standard fin were measured. The measured dimension errors are insignificant, indicating that they have no impact on the outputs of the analysis. The dimensions of the results are examined in sections *Fin domensions* and *Dimension of Extensions*.

Modelling and meshing

Design of fin using solid works

The cylinder block and the fins along with the various extensions are designed using solid works. Solid works is a dassault systemes software programme for solid modelling in computer-aided design (CAD). It provides 3-D CAD software that enables designers to produce genuine design understandings. Figures 2(a)-2(c) represents the fins with various extensions of rectangular, triangular, and trapezium, respectively. The number of extensions used on the main fin is 10.

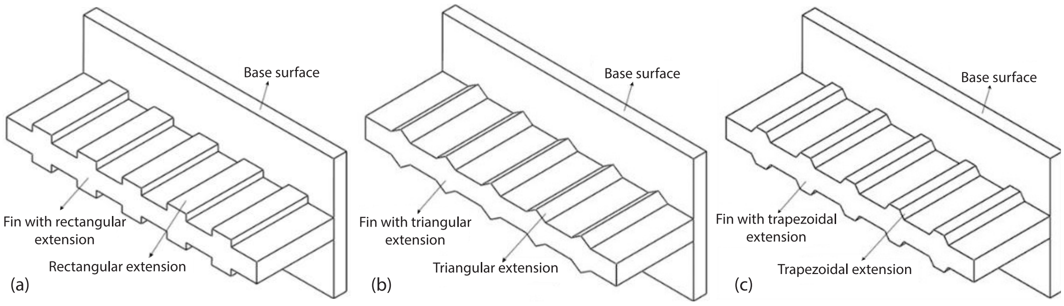

Figure 2. Fin with different extensions; (a) rectangular extension, (b) triangular extension, and (c) trapezoidal extension

Fin dimensions

The size of the rectangular fin was determined by measuring the current TVS engine fin physically. Other extensions dimensions were selected after comparison with earlier studies [3]. The fin dimensions are chosen to be: length, $l = 0.034$ m, width, $b = 0.06$ m, and thickness, $y = 0.015$ m

Dimension of extensions

The extensions such rectangular, triangular, and trapezium are drawn to the dimensions as shown in the figs. 3(a)-3(c).

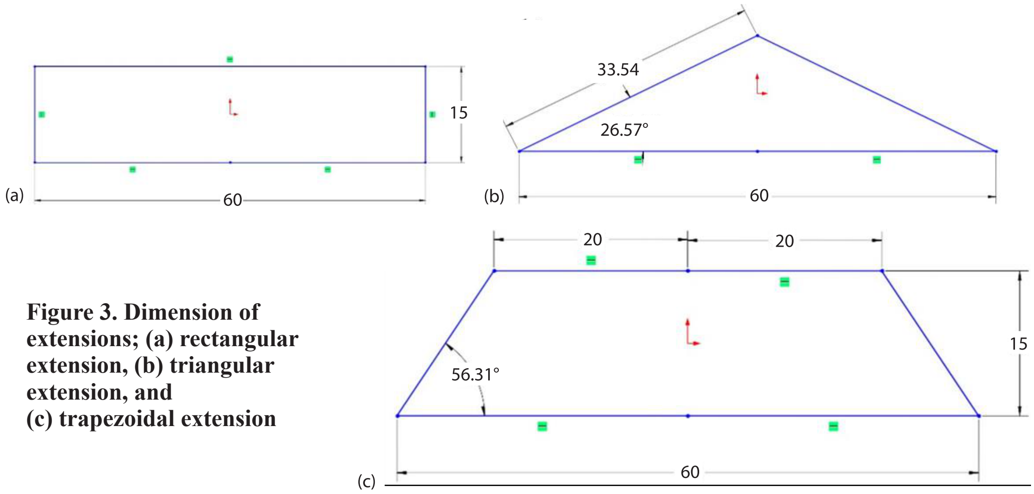

Figure 3. Dimension of extensions; (a) rectangular extension, (b) triangular extension, and (c) trapezoidal extension

Solid model of various extensions

Using the dimensions of the fins and the extensions as stated in the aforementioned sections, the solid models of the cylinder block with fins, with or without extensions are designed as represented in the fig. 4.

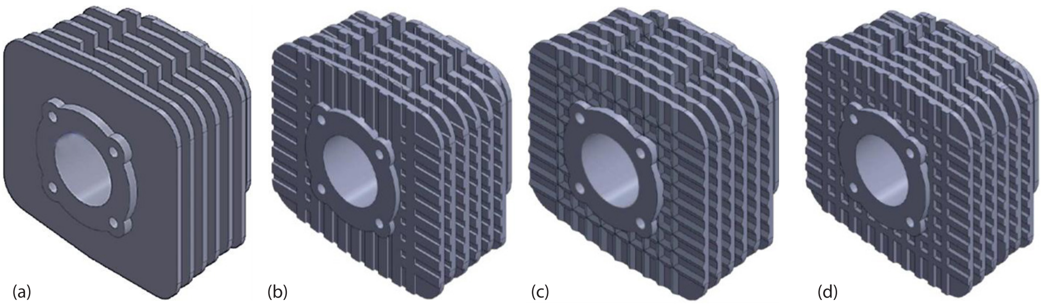

Figure 4. The 3-D CAD model of (a) ordinary fin without extension, (b) fin with rectangular extension, (c) fin with triangular extension, and (d) fin with trapezoidal extension

Meshing of solid model

Once the models are designed, they are imported into the ANSYS software to continue with meshing and analysis. For better analysis results, mesh the model with elements ~2mm in size. Tetrahedral meshing was preferred for mesh input in the solver and CFD was preferred in the physics. The average orthogonal quality attained after mesh generation was 76-81%, representing a very good mesh. A meshed model for ordinary fin is shown in the fig. 5.

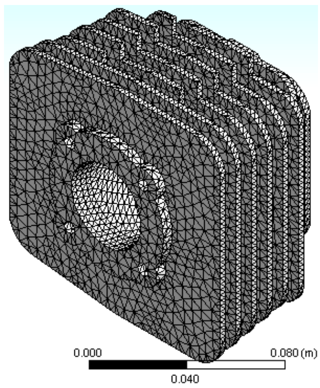

Figure 5. Meshing of ordinary fin solid model

Table 2. Meshing details of fins

Fin extension	Nodes	Elements	Average orthogonal quality
Ordinary	88440	46928	0.76
Rectangular	172551	95990	0.79
Triangular	175090	97818	0.78
Trapezium	178667	100852	0.81

Table 2 represents the resulted in meshing details of number of nodes, number of elements and average orthogonal quality for all the fin extensions.

Results and discussions

Geometric properties for various fins

The geometric properties of the various fins is given in the tab. 3. The mass of the fins is increased by a maximum of 15% in the rectangular extension compared to the fins without extension. The surface area also increased by a maximum of 10.2% with rectangular extension compared to the fins without extension.

Table 3. Geometric properties of fins

Fin extension	Area [m^2]	Mass [kg]
Ordinary	0.157	2.53
Rectangular	0.173	2.92
Triangular	0.160	2.75
Trapezium	0.166	2.89

Fin analysis

Analysis was carried out by using of ANSYS WORKBENCH 12 and the temperature distribution and heat flux is being determined for the fins with and without extensions. The typical properties of an aluminum alloy 6061 were input into ANSYS engineering data and incorporated therein for further thermal analysis. Utilized steady-state thermal analysis to determine the temperature distribution and heat flux of the different engine block extensions. Figures 6(a)-6(d) represents the temperature distribution for the fin without extension (ordinary), fin with extensions – rectangular, triangular, and trapezium, respectively. Figures 7(a)-7(d) represents the heat flux for the fin without extension (ordinary), fin with extensions – rectangular, triangular, and trapezium, respectively.

Temperature distribution

For all extension simulations, the inside cylinder surface's inlet boundary conditions are given a constant temperature of 200 °C. The minimum temperature distribution obtained for fin without extension (ordinary), rectangular extension, triangular extension, and trapezium extension were 185 °C, 106 °C, 155 °C, and 120 °C, respectively is shown in fig. 8.

Compared to ordinary without extension fin, the minimum temperature difference occurred as 79 °C, 30 °C, and 65 °C of rectangular extension, triangular extension, and trapezium extension, respectively. The rate of temperature distribution obtained in the rectangular

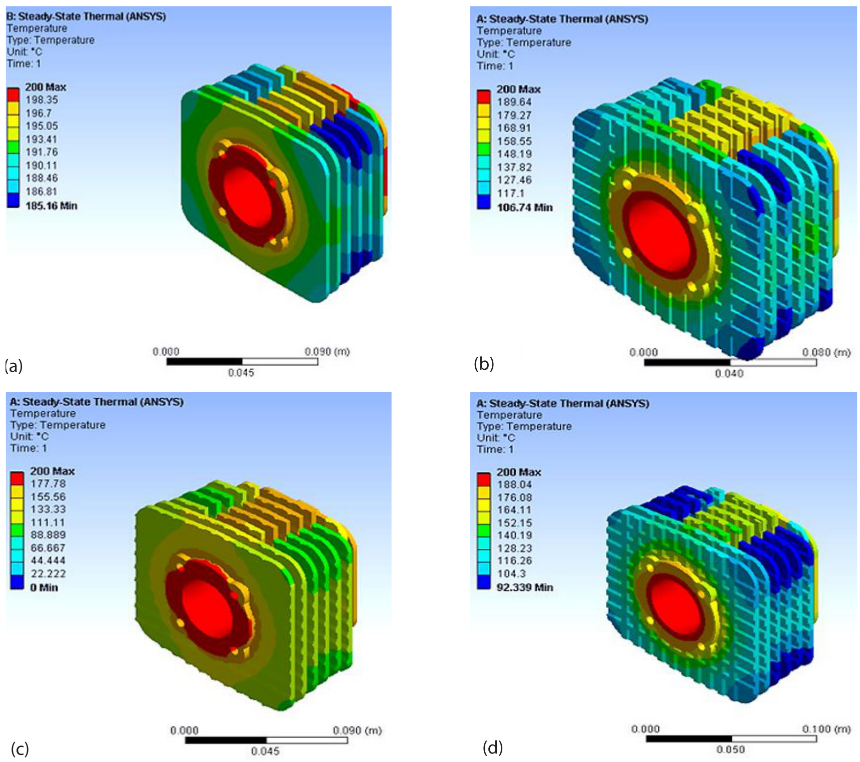

Figure 6. Temperature distribution of (a) ordinary fin without extension, (b) fin with rectangular extension, (c) fin with triangular extension, and (d) fin with trapezoidal extension

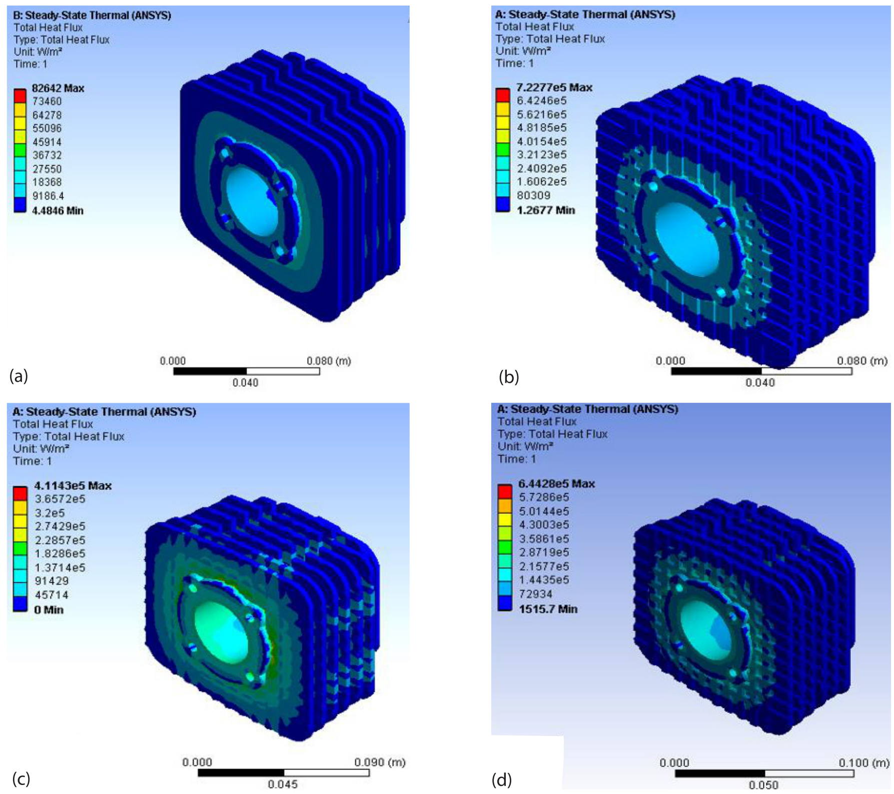

Figure 7. Heat flux of (a) ordinary fin without extension, (b) fin with rectangular extension, (c) fin with triangular extension, and (d) fin with trapezoidal extension

extension was higher and 5.2 times higher than the ordinary fin without extension. Previous research has also shown that rectangular fins perform more effectively in terms of temperature distribution than wavy and circular fins [10].

Heat flux

The amount of heat energy that a surface dissipates is heat flux. The numerical result of obtained heat flux for fin without extension (ordinary), rectangular extension, triangular extension, and trapezium extension were 82642 W/m^2, 722770 W/m^2, 411430 W/m^2, and 644280 W/m^2, is shown in fig. 9. The maximum heat transfer obtained in the rectangular extension (722770 W/m^2), which is 8.74 times higher than the ordinary fin without extension. Additionally, earlier research shows that com-

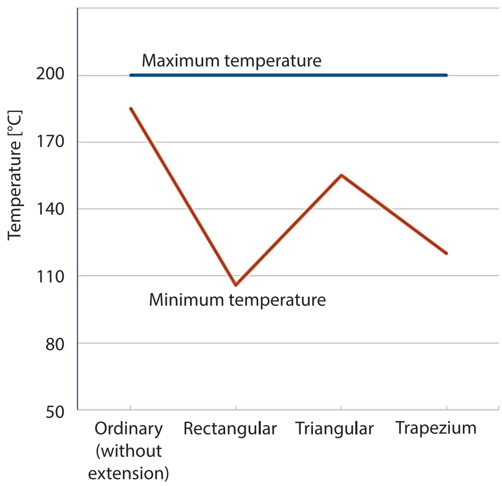

Figure 8. Temperature distribution of various extensions

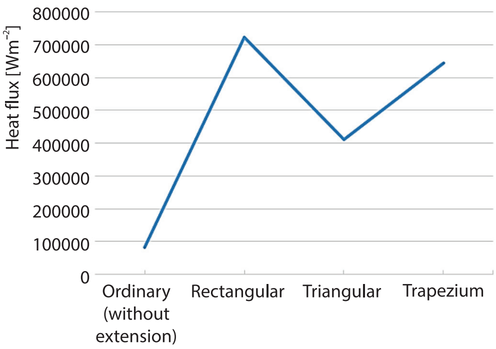

Figure 9. Heat flux of various extensions

pared to wavy and circular fins, rectangular fin give better heat flux [10].

Conclusion

From the results it is very clear that the use of fin with extensions, provides both effective and efficient heat transfer. The lowest temperature differences for rectangle extension, triangular extension, and trapezium extension, respectively, were 79 °C, 30 °C, and 65 °C when compared to ordinary without extension fin. The obtained maximum heat transfer (722770 W/m^2) in the rectangular extension was 8.74 times higher than the conventional fin without the extension. Fin with extensions provide near about 5-13% more in enhancement of heat transfer as compared to fin without extensions. Heat transfer through fin with rectangular extensions higher than that of fin with other type of extensions. Temperature at end of fin with rectangular extensions is minimum as compared to fin with other types of extensions. The effectiveness of fin with rectangular extensions greater than other extensions.

References

[1] Wang, Y., *et al*., Experimental Study on the Heat Transfer and Resistance Characteristics of Pin-Fin Tube, *Thermal Science*, *25* (2021), 1A, pp. 59-72
[2] Haldar, S. C., Manna, S., Free Convection Limit to Heat Transfer from Heat sinks with Square Fins on a Horizontal Base: Comparison with Cylindrical Fins, *Thermal Science*, *19* (2015), 5, pp. 1565-1574
[3] Rupesh, P. L., *et al*., Computational Investigation of Heat Transfer on the Surface of Engine Cylinder with Fins of Different Shapes and Materials, *Materials Today: Proceedings*, *46* (2021), Part. 9, pp. 3320-3326
[4] Kumaravelu, T., *et al*., Heat Transfer Enhancement of a Stirling Engine by Using Fins Attachment in an Energy Recovery System, *Energy*, *239* (2022), ID121881
[5] Izci, T., *et al*., The Effect of Micro Pin-Fin Shape on Thermal and Hydraulic Performance of Micro Pin-Fin Heat Sinks, *Heat Transfer Engineering*, *36* (2015), 17, pp. 1447-1457
[6] Senapati, J. R., *et al*., The 3-D Numerical Study of the Effect of Eccentricity on Heat Transfer Characteristics over Horizontal Cylinder Fitted with Annular Fins, *International Journal of Thermal Sciences*, 108 (2016), Oct., pp. 28-39
[7] Abdelmohimen Mostafa, A.H., *et a*l., Numerical Investigation of using different Arrangement of Fin Slides on the Plate-Fin Heat Sink Performance, *Thermal Science*, *25* (2021), 6B, pp. 4683-4693
[8] Thanigaivelan, R., Deepa, D., Heat Transfer Enhancement by Coated Fins in the Microscale Domain, *Thermal Science*, *22* (2018), 6B, pp. 2783-2789
[9] Sadhasivam, C., *et al*., Computational Investigations on Helical Heat Flow Exchanger in Automotive Radiator Tubes with Computational Fluid Dynamics, *Materials Today: Proceedings*, *37* (2021), Part 2, pp. 2352-2355
[10] Rishi, R., *et al.*, Optimization of Cooling Fin Efficiency in IC Engine Using Heat Transfer Analysis, *IJRESM*, *4* (2021), 8, pp. 259-262

Paper submitted: September 17, 2022
Paper revised: November 26, 2022
Paper accepted: December 2, 2022