Thermal analysis and experimental validation of pin fins with peripheral protrusions

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Abstract. With the growing pace of technological advancement, electronic and thermal components play a crucial role in every domain. These components are however challenged by continuous heat generation which is required to be dissipated for their efficient working. This gives rise to the need of heat dissipating measures and hence, an extensive research is being done in this field. Extended surfaces, known as fins provide an efficient way of cooling components and their utility ranges from medical, power, thermal to microelectronic components. The present work is aimed to augment the thermal performance of pin fins by the introduction of protrusions on the surface of the fin along the length, in two rows, each row having three protrusions. Different geometrical configurations viz. cuboidal, cylindrical, triangular and hemispherical for the protrusion were analysed using Computational Fluid Dynamics. From the results, it is evident that the maximum increase of approximately 7% of the total heat flux is obtained from the surface of the fin with cylindrical protrusions and considerable increase in the total heat flux is obtained in other configurations. It was also concluded that cuboidal and cylindrical protrusions have lowest temperature profiles indicating better heat transfer behaviour. The temperature profile for the fin without protrusions was experimentally validated. The results of the fins with protrusions are in agreement with the existing research papers.

Keywords: Pin fin, peripheral protrusion, thermal analysis, total heat flux, temperature variation.

| Nomenclature | \( Y \) | \( Z \) |
|--------------|--------|--------|
| \( Cp \) | specific heat capacity (J/kg·K) | Cartesian y-coordinate |
| \( H \) | the heat transfer coefficient (W/m²·K) | Cartesian Z-coordinate |
| \( K \) | thermal conductivity (W/m·K) | \( \rho \) | Density |
| \( Nu \) | Nusselt no.(h · De/K) | \( \tau \) | shear stress |
| \( Q \) | total rate of heat exchange (W) | \( \nabla \cdot V \) | Derivative of volume of any fluid element with respect to time |
| \( Re \) | Reynolds no. | \( \frac{D}{\Delta t} \) | Derivative of a moving fluid element with respect to time |
| \( T_{\text{out}} \) | Outlet temperature (K) | \( e \) | Internal energy |
| \( T_{\text{in}} \) | Inlet temperature (K) | \( f \) | body force per unit volume |
| \( T \) | temperature of the working fluid (K) | \( S \) | Subscripts |
| \( U \) | velocity in x-direction of air (m/s) | \( a \) | Air |
| \( V \) | velocity in y-direction of air (m/s) | \( Al \) | Aluminium |
| \( W \) | velocity in z-direction of air (m/s) | \( in \) | Inlet |
| \( X \) | Cartesian x-coordinate | \( out \) | Outlet |
1. Introduction
Heat dissipation plays a vital role in the performance of thermal and electronic systems. Its key importance in varied engineering applications has led to the development of numerous design innovations which enhance the heat transfer rate [1]. Heat dissipation is necessary for the effective working of thermal components, electronic systems and medical applications such as PCM capsule [2] for latent thermal energy storage, hybrid PV/T systems [3], heat exchangers [4, 5], gas turbines and power electronics for future aircrafts [6]. Increasing the surface area provides a reliable measure to dissipate heat, since it not always possible to circulate cooling medium around these components. Therefore, pin fins heat sink (PFHS) has been a remarkable solution to the prevailing heat transfer problem as compared to other conventional fins [7]. Reportedly, fins possess the capability to increase the heat transfer surface area by 5–30 times depending on the application [8].

Many researchers formerly focused on studying the effect of change in the shape of cross-section. A wide range of geometrical shapes have been studied and their advantages and disadvantages according to the applications have been extensively discussed. An experimental investigation was done by Huang et al. [1] on the varied cross sections of pin fins such as elliptical, drop-shaped and circular and it was concluded that circular shape has the most efficient thermal performance. However, the results of Yang et al. [9] for another set of different pin-fin configurations viz. hexagon, pentagon, square, circle and triangle, for heat exchanger application, showed that the highest pressure drop was obtained in triangle-shaped pin fins while it was lowest in circular pin fins. Also, with equal surface area for all morphologies, the cylindrical pins have the maximum weight whereas rectangular pins have the minimum weight [1]. In spite of these researches, the optimum geometry was still not affirmatively concluded, since the researches worked under varied test conditions and applications [10].

Considering the requirement of smaller volume, low cost and high efficiency in operation, various improvised fins including the offset strip fin [11, 12], helical fins [5], the louvered fins [13], slit fins [14], wavy fins [15-22] and corrugated vortex generator fins [23] were developed and have been experimentally investigated. The wavy surface of fins can increase the path which is covered by flowing air and thus results in better mixing of air flow. Therefore, superior heat transfer performance is obtained [24]. Interrupted surfaces are another popular design pattern which can supplement heat transfer by renewing the development of the boundary layer periodically. [12, 25-31], Zuoqin et al. [32] utilised this concept and manufactured slit fin, spiral crimped fin, louver fin, plain fin and others. These largely varied applications justify that even slightest positive modification in the design of heat exchanger can cause huge savings in overall energy utilisation.

Liu et al. [33] presented a similar numerical analysis on perforated fins. The contributing effect of perforations was that the heat transfer coefficient of the air dominated region increased and the temperature variation between fin tip and base decreased. Al Damook et al. [34-36] further investigated multiple circular, square and elliptical perforations and concluded that for an optimum design, a compromise has to be made between circular perforations, which provide the highest heat transfer and elliptical perforations, which minimize the power consumption and pressure drop. Bu, Yang et al. [37] proposed that the rate of heat transfer of latticework channels for turbine blades can be advanced by employing pin fins or by introducing slots on the sidewalls. The slots not only reduced the pressure drop, but also the cumulative heat transfer. Whereas, use of pin fin, increased the rate of pressure drop and heat transfer.

Yun et al. [14] realised the heat sink as an important component due to the fact that the maximum contribution to total thermal resistance is made by convective resistance. However, the rate of heat transfer depends on various other parameters such as the different fin surface patterns, shape of tube, spacing between fins, air velocity, thickness of fins, tube configuration (staggered /in-line), spacing of tubes, tube rows, etc. Investigation on pin fins and plate fins with elliptical, square as well as rounded geometry in in-line and staggered configuration has also been studied [38]. Results confirm that the staggered configuration provided higher rate of heat transfer and the round edge geometries are advantageous over similar sharp edge geometries [39-41]. The material of fin is another important consideration which has been extensively researched. There has to be a good compromise between the
thermal conductivity, weight, density, and cost while selecting fin material for a particular application. The experimental data demonstrated that tube of copper pin-fin show high heat-transfer enhancement ratios followed by brass and bronze tubes. The fin efficiency was affected more in the case of fins with low thermal conductivity viz. bronze and brass tubes. [42]

A O Elsayed [3] analysed the effect of making bulges on the surface of fins and concluded that cylindrical bulges provided maximum temperature drop of the absorber plate.

The present study provides another way of improving the heat transfer performance of the fins by making protrusions on the peripheral surface of fins. The protrusion on the surface of the fins does not affect the packing efficiency which may be compromised in case of bulges. A comparative study has been done of pin fin with protrusions to conventional pin fin. Four different shapes of protrusions viz. cylindrical, cuboidal, hemispherical and triangular as shown in figure 1 have been compared in this study. Computational fluid dynamics analysis has been performed for laminar flow under forced convection.

![Figure 1. Schematic view of fin with (a) no protrusions (b) cylindrical protrusions (c) triangular protrusions (d) cuboidal protrusions (e) hemispherical protrusions.](image)

2. Mathematical modelling

2.1 System description

The system investigated is a pin fin with 12mm diameter and 100mm length. The thermal characteristics of a simple pin fin were compared with pin fins having protrusions of different geometries viz. cylindrical, cubical, hemispherical and triangular on its periphery. The thickness of the protrusion in each case is 6mm and it projects out to a length of 5mm.

The material chosen for the fin is Aluminium. The thermo physical properties of aluminium taken for analysis are $\rho_{Al} = 2719 \text{ kg/m}^3$, $C_p_{Al} = 871 \text{ J/kg-K}$, $K_{Al} = 202.4 \text{ W/m-K}$ and of air are $\rho_{Air} = 1.225 \text{ kg/m}^3$, $C_p_{Air} = 1006.43 \text{ J/kg-K}$, $K_{Air} = 0.0242 \text{ W/m-K}$.

2.2 Governing equations

The computational domain is modelled similar to the experimental setup. The flow is considered as steady, incompressible and laminar. The heat generation is confined to the heater which is set to a constant value. The material and fluid properties are taken to be constant throughout. Based on finite volume method, the Ansys Fluent CFD solver divides the model into finite number of control volumes and solves the following equations [43].

2.2.1 Continuity equation

$$\frac{\partial \rho}{\partial t} + \rho \nabla . \vec{V} = 0$$ (1)
For incompressible fluid, \( \rho = \) constant i.e. independent of time and space. Hence, \( \frac{D\rho}{Dt} = 0 \) and the equation can be simplified as:

\[
\nabla \cdot \vec{V} = 0
\]  

(2)

2.2.2 Momentum Equations

For x-component \( \frac{\partial (\rho u)}{\partial t} + \nabla \cdot (\rho u \vec{V}) = -\frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z} + \rho f_x \)  

(3)

For y-component \( \frac{\partial (\rho v)}{\partial t} + \nabla \cdot (\rho v \vec{V}) = -\frac{\partial p}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{yz}}{\partial z} + \rho f_y \)  

(4)

For z-component \( \frac{\partial (\rho w)}{\partial t} + \nabla \cdot (\rho w \vec{V}) = -\frac{\partial p}{\partial z} + \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} + \rho f_z \)  

(5)

2.2.3 Energy Equation

\[
\rho \frac{D}{Dt} \left( e + \frac{V^2}{2} \right) = \rho q + \frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( k \frac{\partial T}{\partial z} \right) - \frac{\partial (up)}{\partial x} - \frac{\partial (vp)}{\partial y} - \frac{\partial (wp)}{\partial z} - \frac{\partial (wtr_{yx})}{\partial y} - \frac{\partial (wtr_{xz})}{\partial z} + \rho f^2 \vec{V} \]

(6)

The above equations are solved for particular boundary conditions of inlet velocity and ambient temperature conditions.

3. Experimental Setup

An experiment was carried out to validate the results using the setup as shown in figure 2 and figure 3. The setup consists of a rectangular metal duct with cross-section 189.5 X 200 mm\(^2\) to which the airflow is confined. A heater is provided as a constant source of heat input. The pin fin under observation is mounted vertically to the heater and is thus, subjected to cross flow motion of air. Three thermocouples are attached on the pin fin to measure the surface temperature and one thermocouple measures ambient temperature.

**Figure 2.** Schematic view of computational domain.  
**Figure 3.** Actual experimental setup.
4. Results and discussion

4.1 Total surface heat flux

The thermal performance of a fin can be measured in terms of the integral of the total heat flux which is dissipated from its surface. The heat is extracted by the fin from the base surface to which it is attached by conduction and then released into the ambient atmosphere by convection. This helps in lowering the temperature of the base surface. Figure 4 illustrates the comparative analysis of the surface integral of heat flux from the fin for different shapes of protrusions on its surface when varying heat input is given to the heater. The results clearly indicate that making protrusions on the surface of the fins considerably increase the total heat flux. The maximum increase in the value of heat flux is achieved for cylindrical protrusions with a percentage increase of 6.57% and minimum increase is achieved for hemispherical protrusions with a percentage increase of approximately 1%.

In Figure 5, the contours of heat flux depict that the heat flux has increased for the protruded surface. The shape of the protrusions has considerable effect on the heat flux dissipated from the surface. For rectangular protrusions the surface area is 26.3% more than in the case of cylindrical protrusions; however, the total heat transfer from the surface is more in the case of cylindrical protrusions. This result is in coherence with the results obtained by A.O. Elsayed [3] wherein the maximum efficiency was obtained in cylindrical bulges.

![Diagram of heat flux comparison](image)

**Figure 4.** Total heat flux variation at different heat input to heater.
4.2 Variation of temperature

The distribution of temperature along the length of the fin was plotted for constant value of heat input to the heater. It is clearly inferable from figure 6 and figure 7 that cuboidal and cylindrical protrusions have lower temperature profiles which indicate optimistic insight for the heat transfer behaviour. The results obtained are in agreement with the results obtained by A.O. Elsayed [3] for the similar analysis done on fins with multiple bulges.

The bottom peaks in the temperature profile are obtained at the location of protrusions indicating better heat transfer rate from these locations. The hemispherical bulges do not show any considerable variation in temperature profile and exempted from depiction.

The contours of temperature variation along the length of the fin as shown in Figure 8 indicate that lower temperature value is obtained on the inlet side; hence more heat transfer rate is achieved on the
surface which is directly exposed to the incoming air. The temperature is observed to be lesser on the protruded surface, again indicating better heat transfer rate from that surface.

**Figure 6.** Temperature variation along the length of fin with no protrusions.

**Figure 7.** Contours of temperature variation on the surface of fin with (a) no protrusions (b) cylindrical protrusions (c) triangular protrusions (d) cuboidal protrusions (e) hemispherical protrusions.
5. Experimental Validation
The validation of the analysis performed for the fin with no protrusion was done experimentally by obtaining the value of surface temperature with similar surrounding conditions as given in the analysis.

The temperature of the surface was noted at three locations with the help of thermocouples. These experimental values of temperature were then compared with the values obtained from analysis and were found in good agreement with percentage error of less than 4%.

The value of temperature obtained at the first location of thermocouple was in complete agreement of the temperature value obtained at that location from analysis. This indicates that the simulation results lie within acceptable range of the experimental values. The analysis of the fins with protrusions was done with similar boundary conditions of heat input, ambient temperature and inlet velocity.

Table 1. Experimental and simulation data for fin without protrusions.

| Distance along the fin (m) | Simulation (Temp. K) | Experimental (Temp. K) | Percentage error |
|----------------------------|----------------------|------------------------|------------------|
| 0.1                        | 371.87               | 371.15                 | 0.19%            |
| 0.5                        | 367.65               | 360.15                 | 2.08%            |
| 0.9                        | 365.76               | 352.15                 | 3.86%            |

Figure 8 Simulation and experimental results comparison for fin with no protrusions.
6. Conclusion
The present study proposes the idea of making protrusions on the surface of fins. The computational fluid analysis has been performed for analysing the thermal behaviour of fins. The increase in the surface heat flux from the surface of fins by making protrusions on its surface increase the thermal performance of fins and thus, enhance its heat dissipating characteristics. The following inferences could be drawn from the analysis performed:

- Cylindrical protrusions on a single fin show the maximum increase in the total surface heat flux which is more than 7% of its initial value.
- Cuboidal protrusions on a single fin have the lowest temperature profile but the increase in total heat flux is around 5.9% which is less than the cylindrical protrusions.
- The protrusions on the surface of fin may have good packing efficiency both in standard and staggered configurations since; alternate protrusions could be easily stacked together.

The analysis is performed on a single fin and shows considerable increase in heat dissipation characteristics by the introduction of protrusions on its surface. In practical applications, when array of fins is used, the heat dissipation could be further enhanced and thus, it provides a good insight for improving the thermal performance of fins.

![Figure 9. Percentage increase in heat flux with varied heat input.](image)

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