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Heat Transfer Characteristics of a Plate Fin Heat Sink with Pin Fins of Various Profile using CFD

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ABSTRACT

In recent decades, attempts have been made to create more advanced effective cooling technology for electronic and microelectronic devices, but heat dissipation is still a major challenge for increasing the cooling performance of heat sinks in a highly competitive electronics market. In the present analysis, the research is designing a new thermal design for plate-fin heat sinks with hexagonal pin fin connected to the plate-fins. A theoretical analysis focused on publicly usable computational fluid dynamics (CFD) codes has been performed to test the thermal efficiency of the proposed designs. Modelling done using ANSYS 14.5 and meshing has done using ICEM CFD software, simulations has done by using CFD-FLUENT software. In specific, in terms of their thermal performance, hexagonal pin fin connected to the plate-fins subject to flow have been contrasted. The plate-fin heat sink was made of Aluminium and an electrical heaters provide a heat of 10W constantly to warm up a plate-plate-fin heat sink with hexagonal pin fin subject to flow of air at variable values (i.e. 6.5, 9.5, and 2.5 m/s).Based on the results, the analysis has shown that the plate-fin heat sinks demonstrate superior thermal performance with hexagonal 3-pin fin subject to flow. The Nusselt number is approximately 1.32 times higher than the conventional plate-fin heat sink without pin fin and 1.13 times higher than plate-fin heat sink with elliptical 3-pin fin.

KEYWORDS: *Heat sink; Pin fin; Hexagonal Pin fin; Nusselt number; Pressure drop; Base Temperature and Computational fluid dynamics*

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I. INTRODUCTION

Modern appliances and computers are now always in our everyday lives, with the increasing growth of electronic technology. With the size of the components decreasing, however, the heat flux per unit area increases significantly. The electronic components work temperature which exceed the desired temperature level. The promotion of the heat transfer rate and the maintenance of the die at the optimal operating temperature thus played an important role in ensuring reliable operation of electronic components.

In electronics cooling there are a variety of methods, such as jet impingement cooling [1, 2] and heat pipe [3–5]. Usually used forced air cooling with heat sink, traditional electronics cooling showing dominance in terms of unit price, weight and reliability. Some requirements such as a high heat transfer rate, a low pressure drop and a simplified structure should be considered for the design of a functional heat sink.

When surveying the literature a number of scholars have extensively studied the heat sinks in terms of thermal and hydraulic properties. **Maveety and Jung [1]**analyzed contrasting theoretical and experimental findings for a pin-fin heat sink cooling output with an impinging air flow. In addition, optimization experiments were also undertaken to measure the cooling efficiency results by modifying the fining geometry. The empirical findings revealed the dynamic pressure gradients within the fine range and better mixing / heat transfer with a higher pressure gradient. It also revealed that a complicated fluid motion caused vorticity, circulation and flux reversals in high pressure gradients. **Vivek Kumar et al. [6]** gives practical insight into the empirical properties of flow and heat transfer. The regulatory equations are solved with the use of an orthogonal, non-uniform, phased grid regulation volume-based finite differentiation strategy. Through computational fluid dynamics the velocity and the pressure constraints of the momentum equations are solved. A heat sink plate finished with several circular pins between the plate fins consists of the Heat Sink Elliptical Pin Fin. The findings demonstrate the unusual efficacy of Elliptical Pin Fin Heat Sink as opposed to the flat heat sink. **Yue-Tzu Yang et al. [4]** performs platform-circular pin-fin heat sink numerical measurements and offers practical insight into flow and transition functions. The governing equations are overcome using an orthogonally uniform phased grid control-volume-based finite-difference approach with a power-law system. The SIMPLEC algorithm addresses the relation of the speed and pressing conditions of the momentum equations. A plate fine heat sink and multiple circular pins between the plate fin fins is made of a plate fine heat sink. The findings demonstrate that there is greater efficiency than the heat sink of the plate-circular pin-fin.

From the Yu et al. [4] findings, we know that the heat transfer rate could be improved by the plate-pin-fin sink. There is therefore an inherent weakness in the plate-pin-fin heat sink system. The columnar obstacles make the plat-pin-fin heat sink pressure drop too high. This is undesired for the heat sink's hydraulic efficiency. This study wants to conduct the mixed height of the pins to enhance the efficiency of the hydraulic system.

In spite of the aforementioned advances, varying degrees of success have been reported in previous works. It has been found that from above literature review highlights that, several studies were done for analysing the effects of the configurations of the pin-fins design in plate fin heat sink(PFHS) the effect of velocity over various shapes of pin fins like circular, elliptical mounted with plate fin on a flat plate is recorded [4,6]. To demonstrate the feasibility of more enhancement in the cooling efficiency of the plate-fin heat sinks with different profiles like Circular Plate Fin Heat Sink (PFHS), Elliptical plate Fin Heat Sink (EPFHS), more effective designs are needed to be investigated.

Generally, in an attempt to attain the thermal and hydraulic efficiency of heat sinks several techniques must be employed. If we take advantage of the numerical simulations before running experiments to obtain some realistic design parameters, the cost and time of research can be reduced. In this paper, numerical simulations of thermal and hydraulic efficiency of the plate-hexagonal pin-fin heat sinks are investigated. The current study seeks to close this gap and explores a CFD analysis to implement new effective cooling systems using Hexagonal Plate Fin Heat Sink (HPFHS). Based on the proposed designs, it would be feasible to improve the cooling performance of the Hexagonal plate heat sink that is crucial to many engineering applications. The key objectives of this paper are:

- Build a CFD model for the study of convective heat transfer in plate-fin heat sinks.
- Examine the influence of the Hexagonal pin-fins on plate fin heat sink (HPFHS) design on the Base plate temperature, Nusselt number and the pressure drop of the heat sinks.
- Validation will be carried on CFD model with previous model i.e. different profiles like Plate Fin Heat Sink with without pin fin (PFHS) and Plate fin heat sink with Elliptical 3-pin fin (EPFHS).
- Comparing the Pressure drop, Nusselt number and Base plate temperature of proposed model with respect to conventional model.

II. Methodology and Calculations involved

2.1. Steps taken during the analysis

This chapter mentions the steps that have been taken place to achieve the objectives of the work.

- Firstly we design the CFD model of Plate Fin Heat Sink with different profile on ANSYS 14.5 for CFD analysis.
- Meshing of model is done on CFD pre-processor.
- The boundary conditions are applied on the model and numerical solutions are calculated by using solver.
- The finite volume method is used in solving the problem.
- The solution is calculated by giving iterations to the mathematical and energy equations applied on model.
- Validation will be carried on CFD model with previous model.
- Applying formulas for calculating Base temperature, Nusselt number and Thermal resistance.
- The results can be visualized in the form contours and graphs by CFD post processor.
- Result analysis.

2.2. Calculation procedure

The ***average Nusselt number*** (Nū), estimates the output of a heat sink in the plate-fin and can be determined on the basis of the following equation:

$$\overline{Nu} = \frac{\bar{h} D_h}{K_a}$$

Where D_h is the inlet's hydraulic diameter, h is the standard heat transfer coefficient and K_a is the coolant fluid (air) thermal conductivity.

The latter is tabulated based on the ***mean temperature, T_m,*** which is given by Equation:

$$T_m = \frac{T_{avg}+T_b}{2}$$

Where, T_b is base of fin temperature and T_{avg} represents average air temperature given by Equation:

$$T_{avg} = \left(\frac{T_{out}+T_{in}}{2}\right)_a$$

Where, T_{out} and T_{in} are outlet and inlet temperature of air respectively

The ***mean heat transfer coefficient, $\bar{h}$,*** is prescribed by:

$$\bar{h} = \frac{Q}{A_h(T_b - T_m)}$$

Where Q is the heat transfer rate per convection to the cold medium (air), A_h is the cumulative region subjected to the cooling fluid and T_m is the mean air temperature.

The ***heat transfer rate, Q,*** and ***total cooling area, A_T,*** can be expressed by Equations:

$$Q = \dot{m}_a c_{p,a}(T_{out} - T_{in})$$

Where, $\dot{m}_a$ and $c_{p,a}$ are the mass flow rate and the specific heat of air respectively

The ***pressure drop, ΔP***, between the inlet and outlet along with the ***thermal performance, R_{th}*** of plate-fin heat sinks is given by:

$$\Delta P = P_{in} - P_{out}$$

Where, P_{in} and P_{out} are inlet and outlet pressure respectively.

$$R_{th} = \frac{1}{\bar{h}.A_T}$$

III. GEOMETRY SETUP AND MODELLING

The research uses a CFD model in this segment to examine the convective heat transfer in plate-fin heat sinks. CFD analytics include 3 main steps: (a) pre-processing and (b) execution of the solver. The first step involves in the development of the geometry and mesh generation of the desired model while the effects are displayed in the last step as planned. In the solver execution (middle) level, boundary conditions are fed into the model.

3.1. Geometry Setup

The geometry of Heat sinks performing the simulation study is taken from the one of the research scholar's **Vivek Kumar et al. (2013)** with exact dimensions and after than in the proposed designs, the hexagonal pin fin is attached to the Heat sink. The part of the model designed in ANSYS (fluent) workbench 14.5 software.

Table 1. Geometric parameters of Plate fin heat sink

Fin length, L(mm)	Fin height, H(mm)	Fin number, N	Fin thickness, t (mm)	Fin to Fin distance (mm)
51	10	9	1.5	5

Table 2. Dimension of elliptical Pin fin heat sink

Model	Major axis (mm)	Minor axis(mm)	Height (mm)
Elliptical plate fin heat sink	5	2.0	10

Table 3. Dimension of Hexagonal Pin fin heat sink

Model	Edge (mm)	Height (mm)
Hexagonal plate fin heat sink	1.575	10

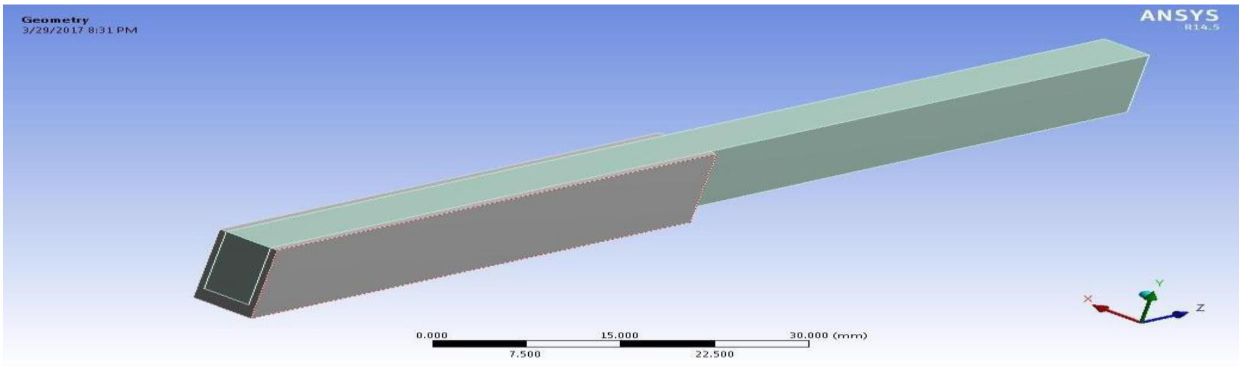

Figure 1. The geometry of Plate fin heat sink (without Pin fin).

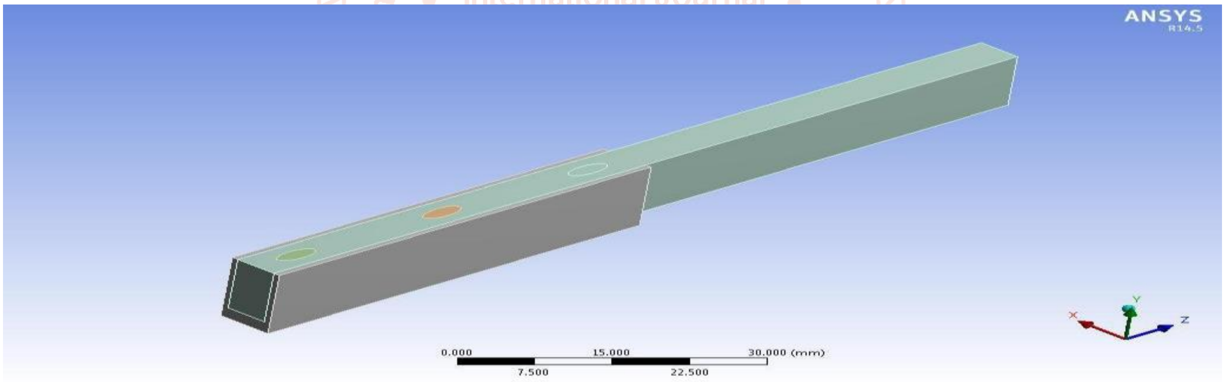

Figure 2. The geometry of Elliptical plate fin heat sink (3- Pin fin).

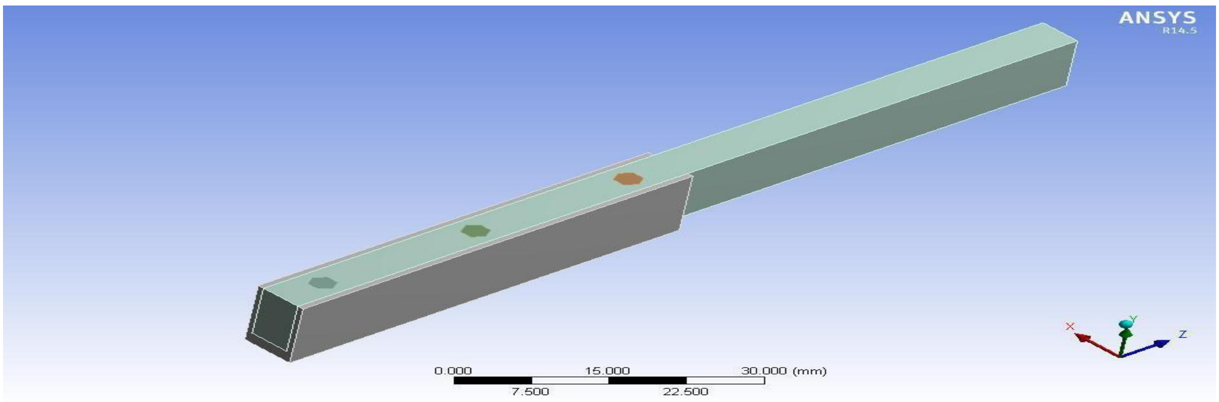

Figure 3. The geometry of Hexagonal plate fin heat sink (3- Pin fin).

3.2. Meshing

In the pre-processor step of ANSYS FLUENT R 14.5, a three-dimensional discretized model of heat sinks was developed. Although the styles of grids are connected to simulation performance, the entire structure is discretized in the finite volume of hexahedral grids in order to reliably calculate the thermal properties of heat sinks using correct grids.

Table 4. Mesh details

The applied design	Number of nodes	Number of elements
Plate-fin heat sinks (without pin fin)	70240	56928
Elliptical Plate-fin heat sinks (3- pin fin)	91871	74500
Hexagonal Plate-fin heat sinks (3- pin fin)	79040	63515

3.3. Model Selection and Solution Methods

The numerical method used in the present study is based on the semi-implicit method for pressure-linked equation consistent (SIMPLEC) algorithm. This is an iterative solution procedure, in which the measurement is started by measuring the pressure field.

Determining the velocity components is solved by the momentum equation. Since there is no pressure in the continuity equation, it can easily be converted into a Pressure Correction equation. Control-volume-based finite-difference system with power-law scheme discrete the conservation equations.

Pressure- velocity coupling
Scheme: SIMPLE
Pressure – Standard
Momentum – Second order
Turbulent Kinetic Energy (k) – First order
Turbulent Dissipation Rate (e) - First order

Solution Initialization: Initialized the solution to get the initial solution for the problem.

Run Solution: Run the solution by giving 500 no of iteration for solution to converge.

As the solution is converged the next phase to collect the observations also called as post processing.

3.4. Governing equations

By solving guided equations i.e. the convective thermal transfer features can be accomplished. Navier-Stokes, continuity and energy calculations for energy conservation, mass conservation and the continuous movement of heat respectively. The below are the following assumptions:

- It is assumed that the flow is steady, incompressible and tri-dimensional.
- The effects of heat transfer from the buoyancy and radiation are ignored.
- It is further assumed that the thermo physical properties of the fluid are unchanged.

The following are the three-dimensional governing equations of mass, momentum, turbulent kinetic energy, turbulent energy dissipation rate and energy in the steady turbulent main flow using the standard k-ϵ model are as follows:

The continuity equation is described by:

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0$$

The momentum equation is described by:

$$\rho \bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} = -\frac{\partial p_i}{\partial x_i} + \frac{\partial}{\partial x_j} \mu_t \left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right)$$

The Energy equation is described by:

$$\rho \bar{u}_j \frac{\partial \bar{T}}{\partial x_j} = \frac{\partial}{\partial x_j} \left[\left(\frac{\mu_1}{\sigma_1} + \frac{\mu_t}{\sigma_t} \right) \frac{\partial \bar{T}}{\partial x_j} \right]$$

The Transport equation for k is described by:

$$\rho \bar{u}_j \frac{\partial k}{\partial x_j} = \frac{\partial}{\partial x_j} \left[\left(\frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + \mu_t \left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) \frac{\partial \bar{u}_i}{\partial x_j} - \rho \varepsilon$$

The Transport equation for ε is described by:

$$\rho \bar{u}_j \frac{\partial \varepsilon}{\partial x_j} = \frac{\partial}{\partial x_j} \left[\left(\frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + C_1 \mu_t \frac{\varepsilon}{k} \left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) \frac{\partial \bar{u}_i}{\partial x_j} - C_2 \rho \frac{\varepsilon^2}{k}$$

The empirical constants appear in the above equations are given by the following values:
$C_1 = 1.44$, $C_2 = 1.92$, $C_\mu = 0.09$, $\sigma_k = 1.0$, $\sigma_\varepsilon = 1.3$, and $\sigma_t = 0.7$

The governing equation for the solid can be written as:

$$\frac{\partial}{\partial x_i} \left(k_s \frac{\partial T}{\partial x_i} \right) = 0$$

3.5. Material Property

For any kind of analysis material property are the main things which must be defined before moving further analysis .There are thousands of materials available in the ANSYS environment and if required library is not available in ANSYS directory the new material directory can be created as per requirement. For the present work aluminum used as a material of plate-fin heat sink. Due to light weight and high heat transfer rate. The manufacturing process is also simple for aluminum and cost wise it is economical.

Table 5. Thermo-physical Properties of Aluminium

	Density (Kg/m^3)	Specific Heat (J/Kg-K)	Thermal conductivity (W/m-K)	Dynamic Viscosity (N-s/m^2)
Aluminium	2689	951	237.5	0.012

3.6. Boundary Conditions

Research scientist ***Vivek Kumar et al. (2013)***in solver execution, based on the work reported in the existing CFD study, apply boundary conditions. The plate fin heat sink of different pin fin profile was constructed from aluminum as described in Ref. [6] In order to continuously heat up a plate-fin heat sink which is subject to variable flow of the air (i.e. 6.5,9.5 and 12.5 m /s), The bottom of the computational domain is heated at a constant heat transfer rate of 10W.

IV. RESULTS AND DISCUSSIONS

This segment aims to evaluate the thermal performance of proposed designs i.e. hexagonal pin fin which is attached to the Plate fin Heat sink. To study the performance of plate-fin heat sinks with various profile subject to flow, the variations in the temperature, pressure drop and the Base plate temperature are measured at different flow rates.

4.1. Validation of numerical computations

To validate the accuracy of developed numerical approach, comparison was made with the work reported in Ref. [4, 6]. The heat sink geometry that used for validation of numerical computations was considered to be as same as the geometry shown in Fig. 1 and Fig. 2.

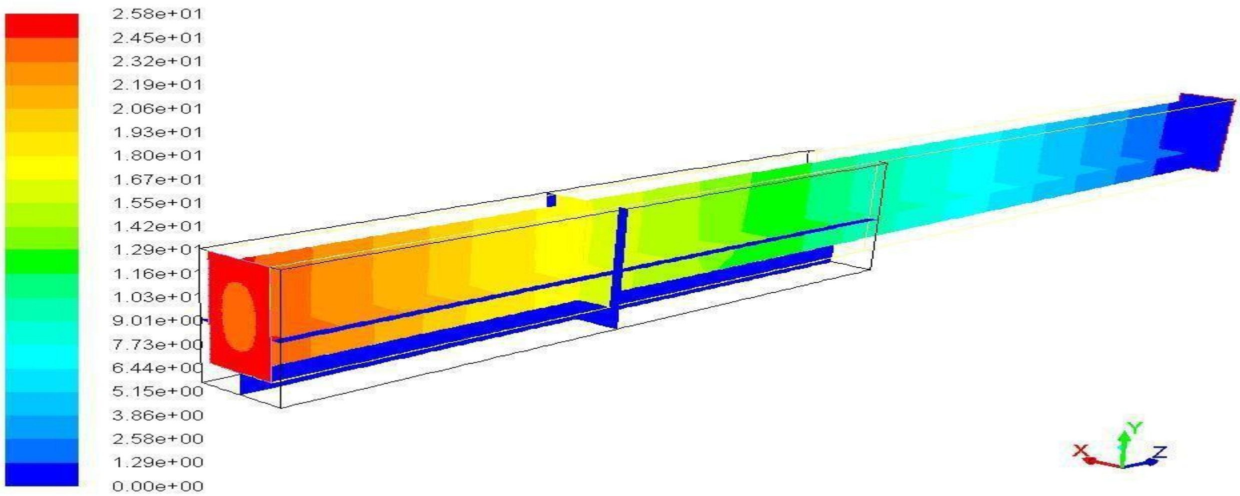

Figure 4. Pressure contour for PFHS (without Pin fin) at inlet velocity 6.5m/sec.

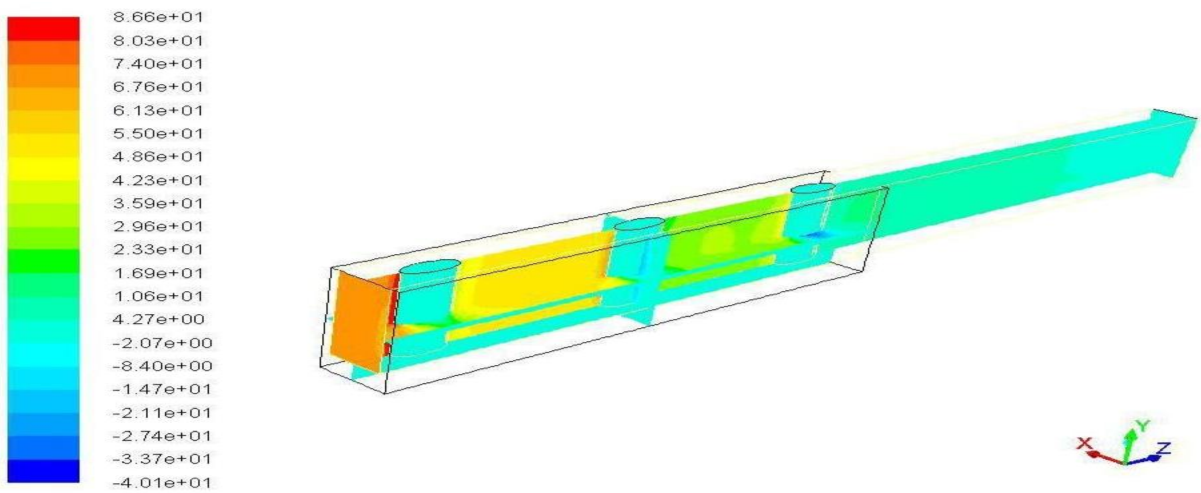

Figure 5. Pressure contour for EPFHS (3- Pin fin) at inlet velocity 6.5m/sec.

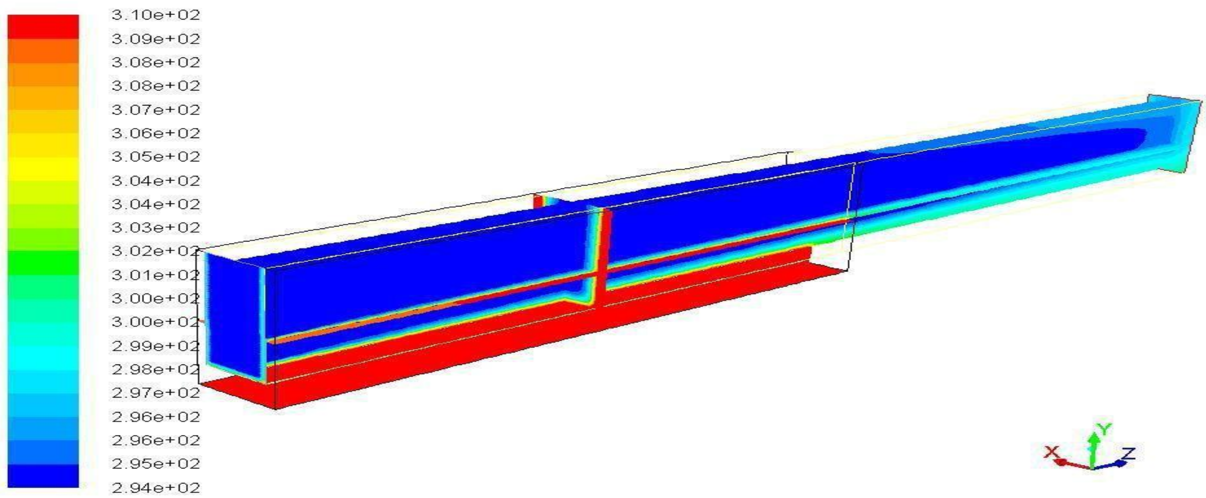

Figure 6. Temperature contour for PFHS (without Pin fin) at inlet velocity 6.5m/sec.

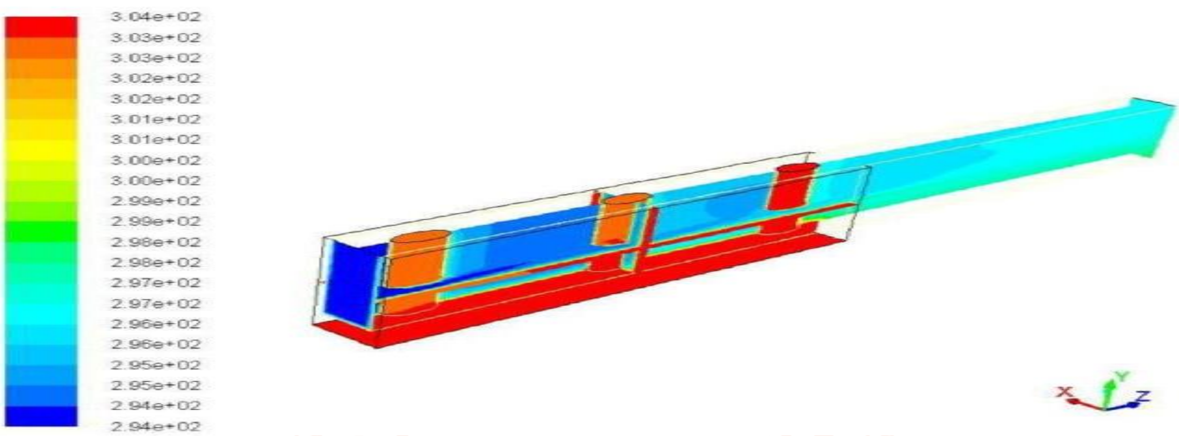

Figure 7. Temperature contour for EPFHS (3- Pin fin) at inlet velocity 6.5m/sec.

The values of Pressure drop and Base plate temperature calculated from the CFD modeling were compared with the values obtained from the analysis performed by **Ref. [4, 6].**

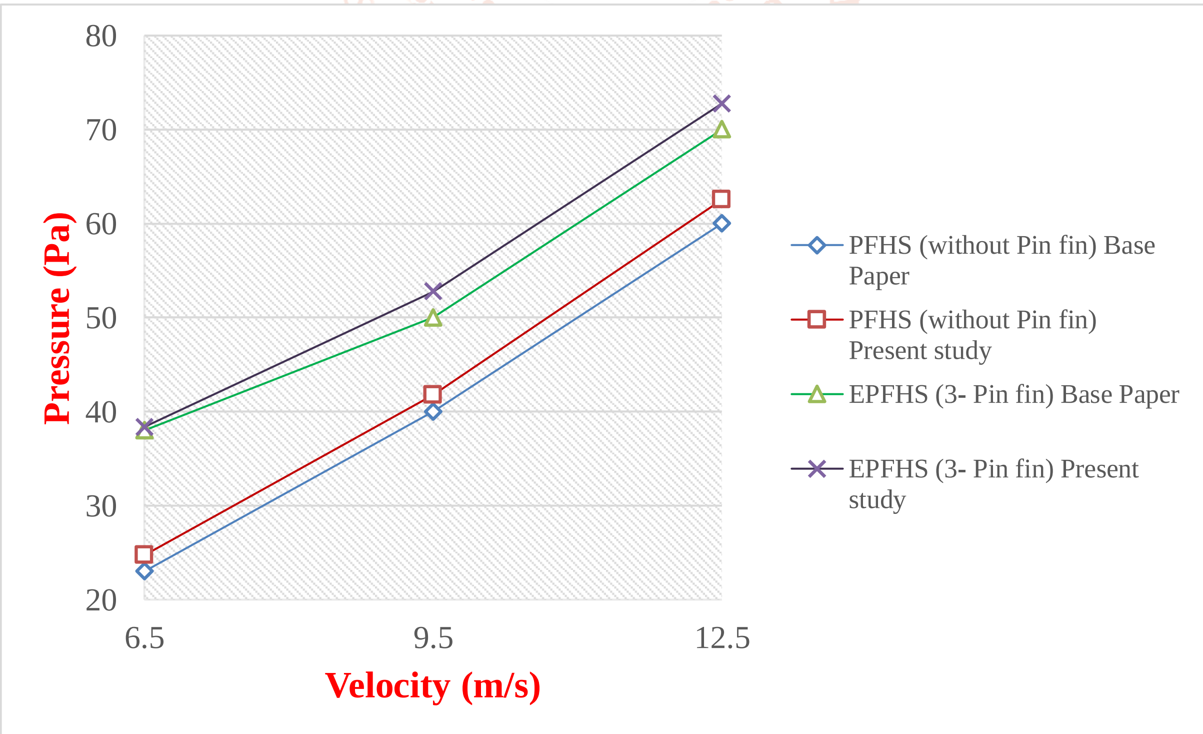

Figure 8. indicates the Pressure drop values determined from CFD models opposed to the values derived from Ref. [4, 6] study for Plate-fin heat sink with without pin fin and elliptical 3-pin fin..

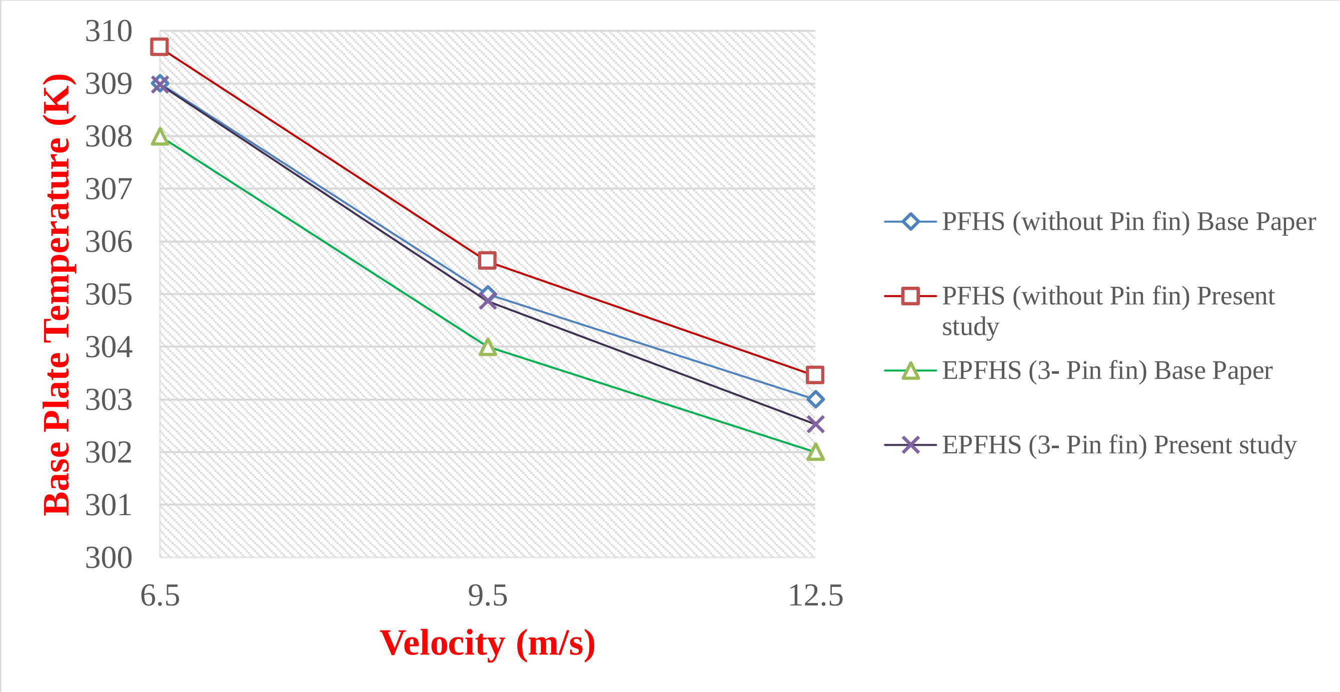

Figure 9. indicates the Base Temperature of the plate values determined from CFD models opposed to the values derived from Ref. [4, 6] study for Plate-fin heat sink with without pin fin and elliptical 3-pin fin.

From the aforementioned validation study it is observed that the values of the base temperature, and pressure drop measured from CFD study are similar to the values of the base temperature, and pressure drop obtained from the base journal. So here we can claim the heat sink model with without pin fin and elliptical 3-pin fin is right.

4.2. Effect of hexagonal 3-pin fin on plate fin heat sink

To investigate the thermal performance of proposed designs when subjected to flow, the temperature contours and pressure contours at a different flow rate are presented below:

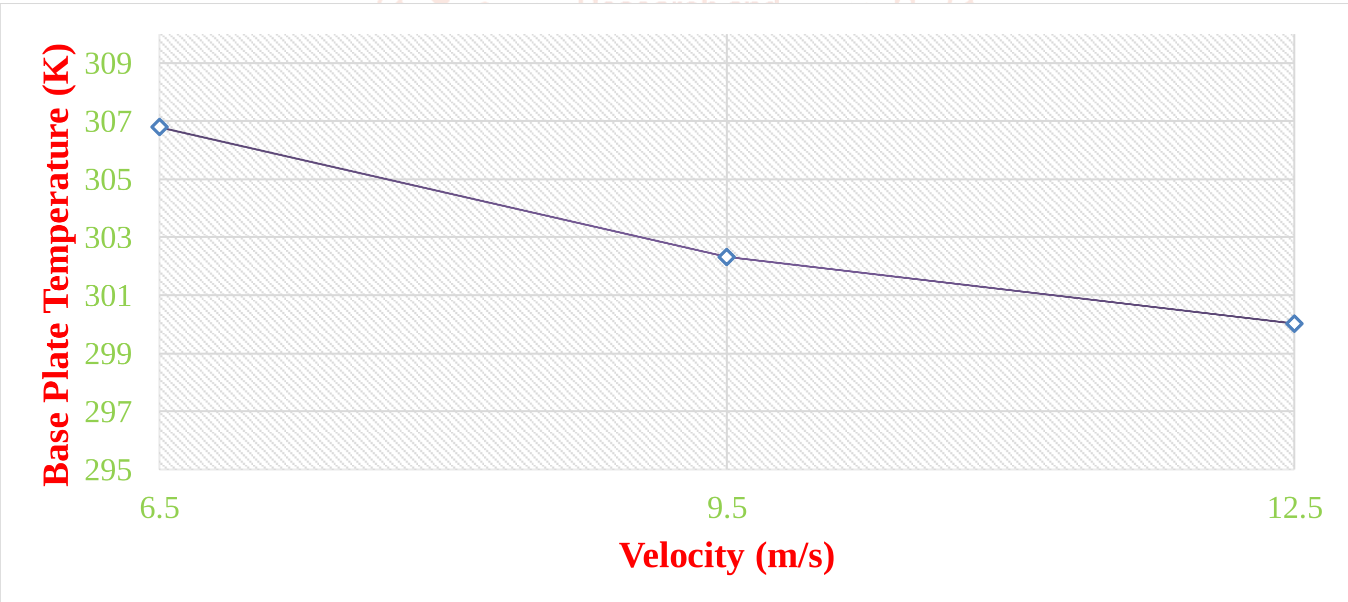

Figure 10. Indicates the Base Temperature of the plate values for Hexagonal 3-pin fin Plate-fin heat sink

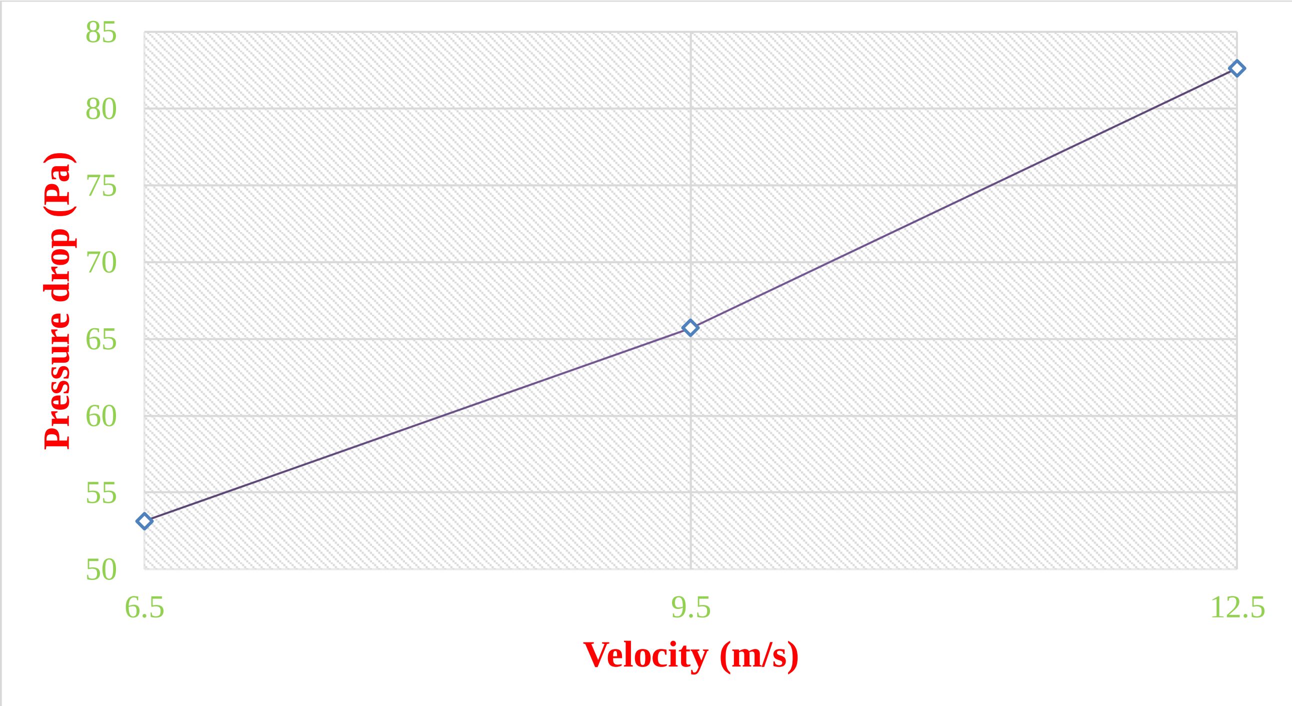

Figure 11. Indicates the Pressure drop values for Hexagonal 3-pin fin Plate-fin heat sink.

4.3. Comparison of different pin fin designs (3- pin fin) in on plate fin heat sink

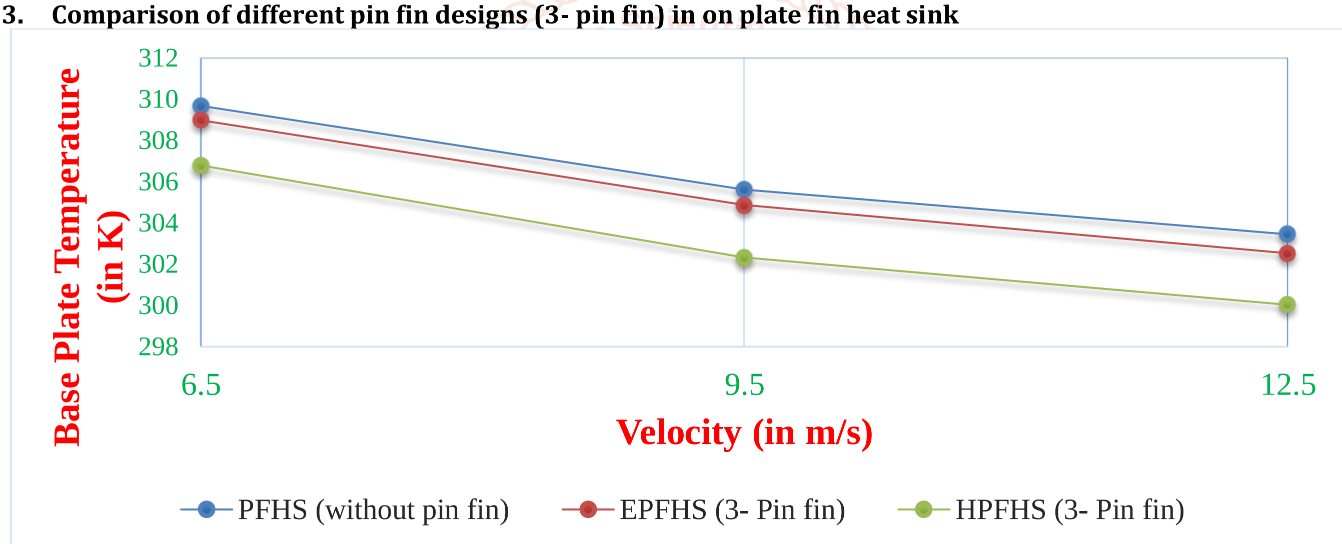

Figure 12. Indicates the Base Temperature of the plate values for Plate-fin heat sink with without pin fin, elliptical 3-pin fin, and hexagonal 3-pin fin.

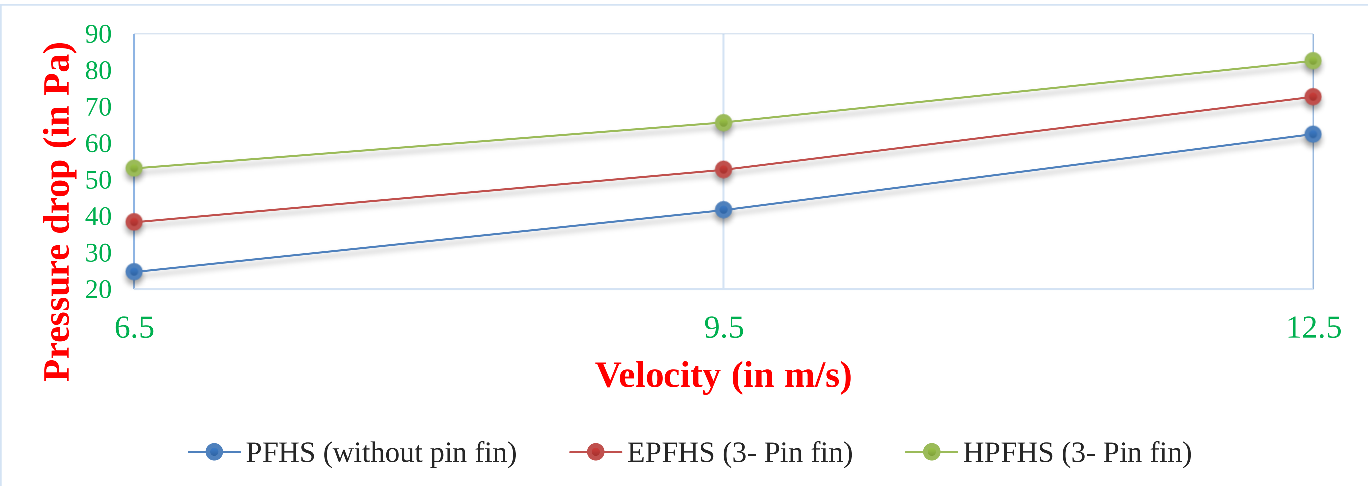

Figure 13. Indicates the Pressure drop values for Plate-fin heat sink with without pin fin, elliptical 3-pin fin, and hexagonal 3-pin fin.

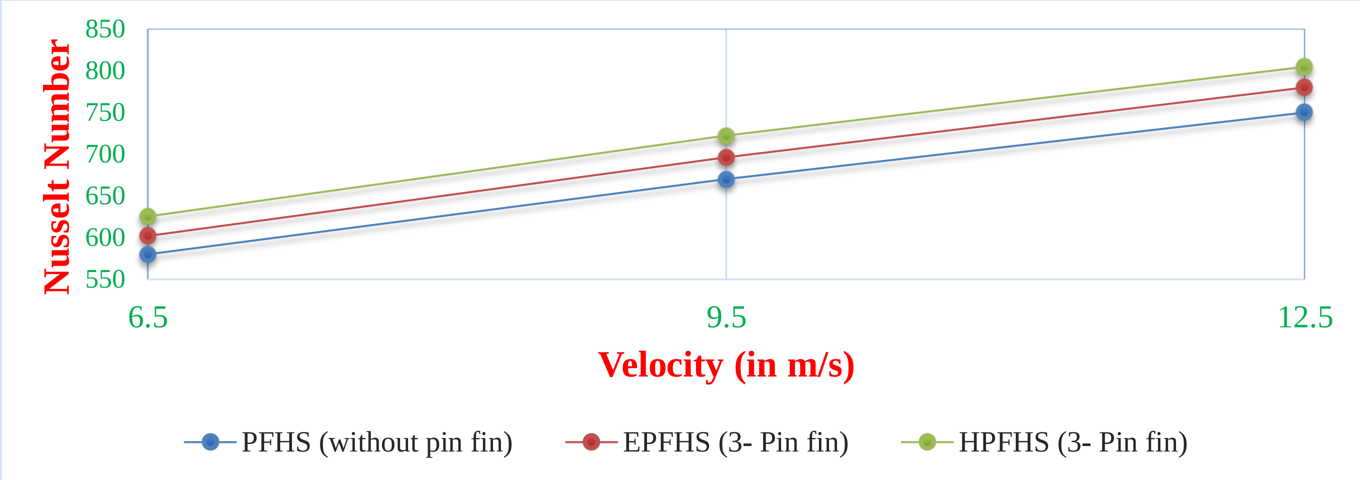

Figure 14.. Nusselt number values for Plate-fin heat sink with without pin fin, elliptical 3-pin fin, and hexagonal 3-pin fin.

V. CONCLUSIONS

New thermal designs have been developed for plate-fin heat sinks with hexagonal 3-pin fin which allow the thermal efficiency of system configurations to be investigated using CFD codes. Test analyses give primary points as follows:

- The analysis has shown that the plate-fin heat sinks demonstrate superior thermal performance with hexagonal 3-pin fin subject to flow.
- The former version, plate-fin heat sinks with hexagonal 3-pin fin subject to flow, proved to be the most effective configuration of all designs tested. In this configuration, the base temperature is approximately 22.15 % and 16.435 lower than the conventional plate-fin heat sink without pin fin and plate-fin heat sink with elliptical 3-pin fin.
- The Pressure drop is approximately 1.07 times higher than the conventional plate-fin heat sink without pin fin and 1.03 times higher than the plate-fin heat sink with elliptical 3-pin fin.
- The Nusselt number is approximately 1.32 times higher than the conventional plate-fin heat sink without pin fin and 1.13 times higher than plate-fin heat sink with elliptical 3-pin fin.

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