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Computational Model Analysis on Symmetrical Aerofoil Shaped Pin Fin Arrays

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Abstract
It is a computational model analysis on symmetrical aerofoil pin-fin arrays. The commercial ANSYS 2021 R2 computational tool has been utilized. There are four models prepared on symmetrical aerofoil pin-fin arrays. These four models are no perforated inline aerofoil pin-fin array, perforated inline aerofoil array, no perforated staggered aerofoil array and perforated staggered aerofoil array. The basic geometry, meshing and computational analysis has been created in the Workbench, ICEM and Fluent Discover tool, respectively. In the Fluent solver settings, the k-omega turbulent model has been selected. The Reynolds number implied from 5,000 to 50,000 with an incremental value of 5,000. Moreover, the temperature valve input from 27 to 350°C. The results show that at rising input airflow velocity increases Nusselt number. Out of all the four models the convective heat transfer rate in the perforated one is quite higher than no perforated one. In the staggered perforated aerofoil pin-fin obviously there is more material savings. Apart from that in the no perforated staggered aerofoil pin-fin the pressure drop is lesser and better streamline pressure drop maintained. As far as overall performance is concerning the perforated staggered aerofoil pin-fin arrangement gives very promising results.

Keywords: Symmetrical Aerofoil Pin Fin, CFD, Heat Dissipation, Friction Factor, Pressure Drop, Performance Effectiveness

Introduction
A pin-fin is a compact size extended surface. It plays a role to transfer heat from the hot surface to the surrounding air. They are mounted on the hot surface. It can be mounted internally as well as externally. Usually the pin-fin is made of highly conductive aluminum material. Because of cost effectiveness and light weight, the aluminum is popular in industrial and commercial applications. The pin-fins are constructed by using casting, forming, machining and fabrication. Their usage is expanded in the field of aerospace industry to cool the gas turbine blades, in power plant and refinery heat exchangers, cooling of electronic components etc. Moreover, the efficiency and effectiveness of each pin-fin is quite low. Therefore, to have better enhanced efficiency and effectiveness the pin-fins are implied in the form of arrays and the calculations are carried out accordingly.

On the contrast of pin-fins, a computational analysis on symmetrical aerofoil pin-fin arrays has been investigated. The computational study on micro pin-fins and circular pin-fins have been carried out by R.B. Gurav et al. and M.T.Malazi et al., respectively [1,2]. It is to be noted that the pin-fin geometry plays a key role to enhance effectiveness of pin-fins. So, it is found that a computation study has been carried out to know the influence of pin-fin patterns and geometry on the effectiveness by L. Ludick et al. [3].

The pin-fin optimization study and analysis also is advancement in research and analysis. W.H.Chen et al. performed varied numbers of square pin fins in a flow channel by computational fluid dynamics [4]. In the field of aerospace applications, pin-fin trial and analysis is a trending research. Computational analysis of rectangular, stepped and elliptical pin-fin profiles for space vehicle thermal control systems have been performed by M.P. Narayanasamy et al. and they obtained that in comparison with flat pin-fins, elliptical pin-fins increase heat transfer by an average of 20% [5]. The perforations in the pin-fin are one form of optimization and enhancement of heat transfer rate. A computational analysis of perforation effect on the micro pin-fin heatsink has been carried out by D. Gupta et al. and they achieved that one to two circular perforation improves performance by 30% followed by square and elliptical perforation [6].

It is to be noted that the pin-fin clearance plays a vital role in pressure drop analysis. In this regard C. Liang et al. carried out a detailed computational analysis on the heat transfer and pressure loss of a turbulent flow in detached pin fin arrays with various clearance values and obtained that compared with the pin fin arrays, the pressure loss is decreased by up to 30.5% with the increase of the clearance value for the detached pin fin arrays [7].

The pin-fin compatibility in central processing unit (CPU) cooling also is under investigation by the global eminent researchers because of enhancement in system speed. In this contrast, M. W. Alam et al. carried out the computational analysis, the finite volume method based general purpose computational fluid dynamics software ANSYS Fluent 15.0 on CPU heat sink cooling by introducing triangular shape micro-pin-fin and they observed that turbulence intensity 15 % and 20% at inlet produce very high efficiency, η of about 3.33 and 3.66 for micro-pin-fin diameter, d = 0.8 mm, respectively [8]. Furthermore, in the CPU and motherboard chip cooling, the cooling capability of the pin-fin plays a key role. S. Bhattacharyya et al. investigated by using computational shear stress transport (SST) model of micro-pin-fin heat sink cooling in the mainboard chip of a CPU and they have observed that the use of micro-pin-fin of diameter 0.8 mm and turbulence intensity (TI) of 15 – 20% at inlet is advantageous [9].

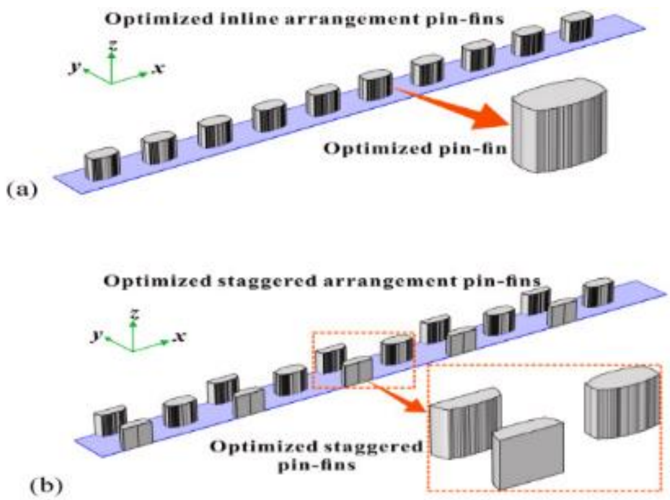


Figure : Optimized Design of Pin Fins a) Inline Arrangement and b) Staggered Arrangement [10]

As far as the phase change material (PCM) heat sink with pin-fin is concern, it is one of the cooling rates enhancing elements and is under investigation by the eminent researchers, worldwide. After conducting optimization research on triangular pin-fin arrangements, the full melt time was shortened by 14.3 % and the heat dissipation power was increased by up to 15.2 %, when compared with the PCM heat sink with triangular pin-fins, H. Pan et al. [11]. In the investigation of heat transfer performance for through-silicon via embedded in micro pin fins in 3D integrated chips, it is obtained by the W. He et al. that the best comprehensive heat transfer performance was achieved with an extended fin angle of 30 degrees for the micro pin fins [12].

The various trending research on pin-fin geometries are going on. A computational design and optimization of pin fin heat sinks with single, rectangular slotted or notched perforations were carried out by A. A. Damook et al. and their results show that the heat transfer increases monotonically while the pressure drop decreases monotonically as the size of the rectangular perforation increases [13]. In the gas turbine trailing edge cooling, the pin-fin investigation also plays a major role. The performance of pin-fin arrays installed in the trailing edge internal cooling channel of a turbine blade was investigated computationally using three-dimensional Reynolds-averaged Navier-Stokes equations, M. A. Moon and K. Y. Kim [14]. A numerical model for various pin-fin array heat sinks was developed and verified experimentally and from the analysis results, the staggered pin-fin radial heat sink was identified as the optimal configuration, demonstrating improved thermal performance by up to 10% while maintaining the same mass or reducing the mass by up to 12% for a given thermal resistance, S. J. Park et al. [15].

It is found that the researches performed investigation and analysis on pin-fin compatibility in the hydrothermal channel applications. In the CFD (Computational Fluid Dynamics) study on hydro thermal performance of heat sink using perforated twisted and grooved pin fins is conducted and the results showed an improvement of the average Nusselt number (Nu) by 32%, M. R. Haque et al. [16]. Further, it is to be noted that C. Balachandar et al. carried out computational heat transfer analysis and combined artificial neural network (ANN) – Genetic Algorithm (GA) of solid and optimized hollow cylindrical pin-fin on a vertical base plate and their analysis shows that the hollow fins provide an increased heat transfer and a weight reduction of about 90% when compared to solid cylindrical pin fins [17]. For instance, it is found that the computational modelling of hybrid nanofluid in micro pin fin heat sink for electronic cooling has been investigated by N. B. Sukhor et al. and they have observed that the Nusselt number increased from 14.00 at transverse pitch of 3.81 mm to 17.00 at a transverse pitch of 1.81 mm and this corresponds to 16.05% enhancement of Nusselt number [18]. Computation of natural convection in channels with pin fins have been analyzed by D. S. Boyalakuntla et al. and their results are useful in designing augmented cooling schemes in portable electronics [19].

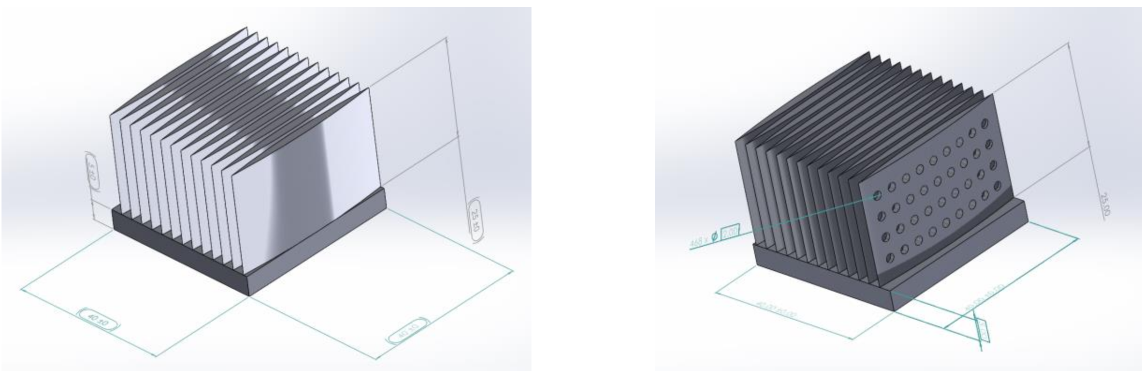
A part from core mechanical and electronic device cooling, the pin fin compatibility research has been implied by the researchers in the field of solar heater system. In this contrast, the M. S. Manjunath et al. performed computational fluid dynamics analysis of a flat plate solar air heater in the presence of a pin fin array and in their analysis the results show that the pin fin array exhibits a relatively superior effective efficiency to a maximum extent of about 73% for lower flow rate conditions [20]. It is noted that the experimental and computational analysis of transient, non-linear heat flux in circular pin fin of length =0.35 m, cross-section area = 7.85×10-5 m2 has been performed by M. Singhal et al. [21]. Further it is noted that a numerical simulation study of a pin–fin staggered manifold microchannel (PFSMMC) heat sink has been analyzed by Y. H. Pan et al. and their results show that the PFSMMC heat sink has better heat transfer capability and more uniform heating surface temperature [22].

Methodology

The three-dimensional base plate of size length, width and thickness, $40L_p$ x $40w_p$ x $5t_p$ mm and on top that the symmetrical aerofoil pin-fins of size chord length, nominal diameter and height, $40L_c$ x 3 D_n x 25 H mm has been constructed in ANSYS Workbench. In case of perforated aerofoil pin-fin array models, the diameter of the circular perforation, dc is 3 mm. An explicit image on the constructed geometries have been attached in the Figure 1.The uniform 3D structured meshing has been carried out to both the pin-fin array models as well as rectangular channel domain. An image on the meshed aerofoil pin-fin arrays have been illustrated in the Figure 2. It is to be noted that the inlet and outlet computational domain is in the form of rectangular channel has been constructed. The size of this rectangular channel domain is length, width and height, 220 x 70 x 60 mm. In this domain the computational fluid dynamics simulation has been carried out for all the four pin-fin array models. A sample set of mentioned domain with pin-fin array model under simulation has been illustrated in the Figure 3. To test the mesh quality, the grid independent test has been performed and is as attached in the Table 1. After this grid independent test, the mesh consists of 4, 94,039 node is used in the present computation. By using ANSYS Fluent discover tool the computational analysis has been performed on pressure and temperature. In the computational analysis turbulent k-omega SST (shear stress transport) model, the turbulent intensity factor taken as 5%. Accordingly, grid independent test has been carried out to find out the accuracy in computational analysis of all the four models.

Grid	Number of nodes	*Nu*	*F*
Grid 1	4, 49, 039	17.392	0.0768
Grid 2	4, 38, 732	16.123	0.0586
Grid 3	4, 28, 659	15.956	0.0473

Table 1: Grid independent test at Re = 5,000, Dn = 3 mm and TI = 5%



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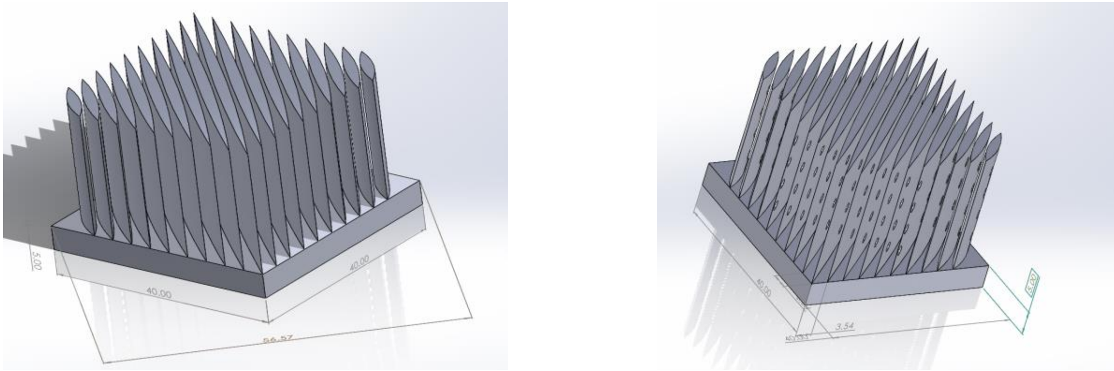

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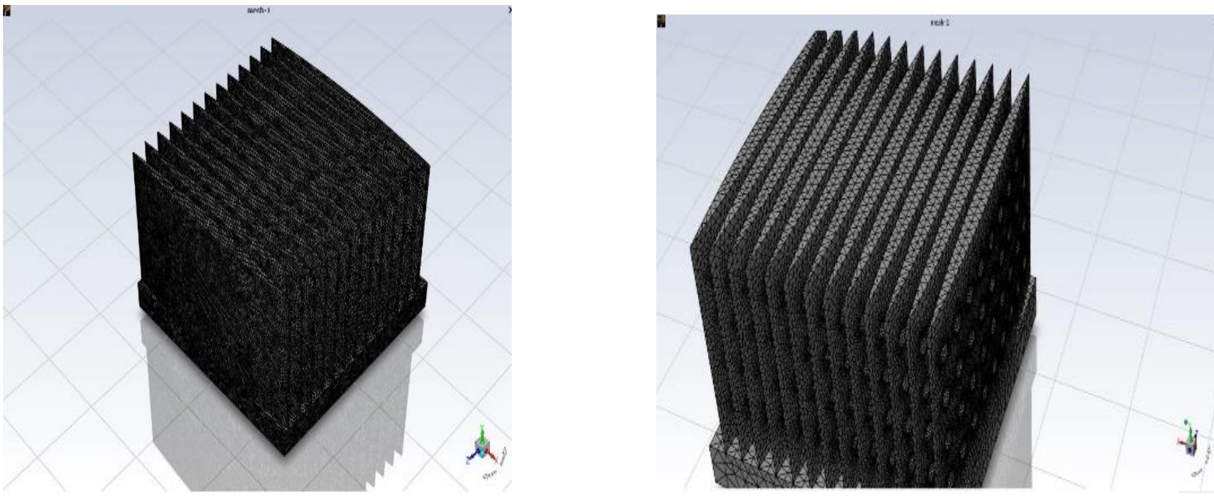
Figure 1: 3D Geometries of Test Plate Along With Symmetrical Airfoil Pin-Fin Array a) No Perforated Inline, b) Perforated Inline, c) No Perforated Staggered and d) Perforated Staggered Arrangement



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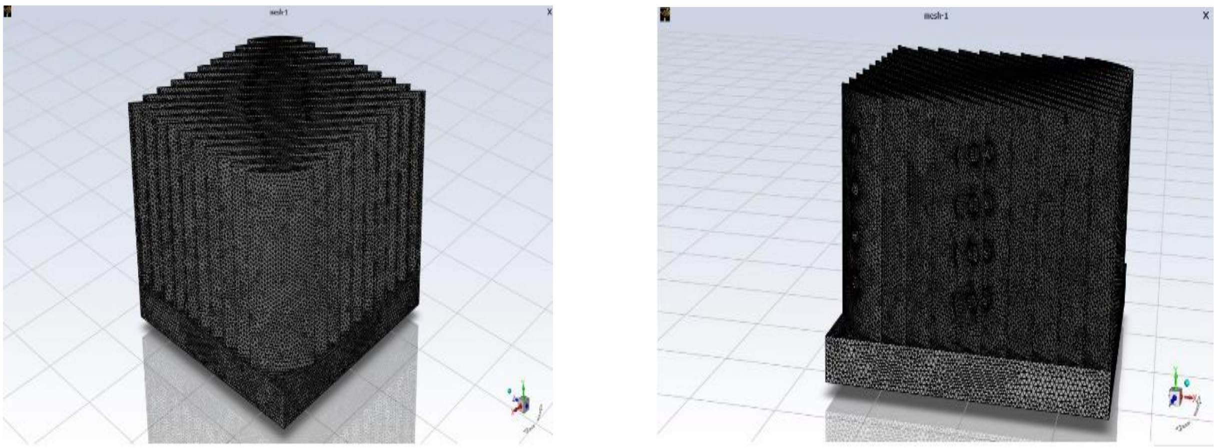

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Figure 2: 3D Uniform Meshing of Symmetrical Aerofoil Pin-Fin Array Models, a) No Perforated Inline, b) Perforated Inline, c) No Perforated Staggered, And d) Perforated Staggered Arrangement

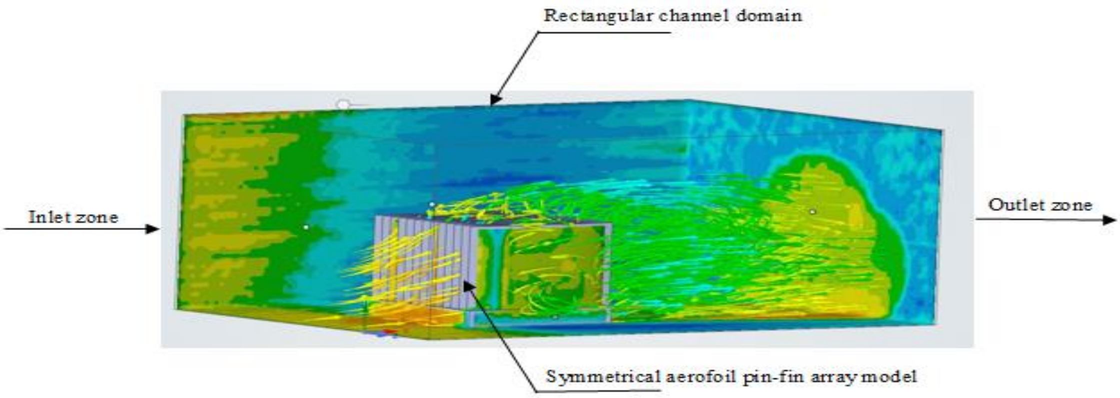


Figure 3: Rectangular Channel Domain with Symmetrical Aerofoil Pin-Fin Array Model is Under Simulation

Tools Utilized

As far as the computational tool is concern, the inherent ANSYS 2021 R2 software has been utilized starting from geometry and meshing creating to computational solving. In the simulation part the k-omega SST (shear stress transport) model has been activated. The high turbulence factor 5% has been implied in the simulation. Further in the tooling part the inherent Paint brush software has been utilized for marking and labeling.

Implied Boundary Conditions

The foremost prime boundary condition implied is the inlet working fluid as air mass flow rate supply from 1 kg/s to 100 kg/s at an ambient temperature of 27 °C. At the same time the inlet temperature supply at the bottom of the pin-fin model is from 27 to 350 °C. The other major boundary condition implied is turbulent intensity (TI). It is implied as 5%. While backflow turbulent intensity implied is also 5%.in similar fashion, the turbulent viscosity ratio and backflow turbulent viscosity ratio implied is 10 for both. The wall motion impinged as stationary wall and no slip shear boundary condition. In turbulent analysis, the Reynolds number (Re) implied from 5,000 to 50,000 with an increment value of 500.

Governing Equations

The governing equations in k-omega SST model involves, the Reynolds-averaged Navier Stokes (RANS) equation, turbulent kinetic energy (k), turbulent dissipation rate (ɷ), turbulence intensity (TI), and turbulent viscosity (μt).

The Reynolds-averaged Navier Stokes (RANS) equation in tensor form is stated as –

∂(ρUi)∂t+∂(ρUiUj)∂xj=-∂P∂xi+∂∂xj[μ(∂Ui∂xj+∂Uj∂xi)–ρui’uj’ (1)

Where, U = mean flow velocity, u’ = velocity fluctuations due to turbulence, μ = molecular viscosity and –ρui’uj’ = Reynolds Stress term.

Turbulent Kinetic Energy (k)

The turbulent kinetic energy (TKE) is the mean value of kinetic energy per unit mass according to eddy formation occurs in the turbulent flow. It is denoted by k and is mathematically determined from the transport turbulent kinetic energy equation. The transport turbulent kinetic energy is,

∂(ρk)∂t+∂(ρUik)∂xi=∂xj[(μ+μtσk)∂k∂xj]+Pk+Pb-ρϵ+Sk (2)

Where, Pk = production of turbulent kinetic energy (TKE) due to mean velocity shear, Pb = production of TKE due to buoyancy, Sk = user-defined source and σk = turbulent Prandtl number, Pr for k. From the transport turbulent kinetic energy equation (2), the turbulent kinetic energy has been expressed as –

k = 3/2 (U I)2 (3)

Where, U is the mean flow velocity and I is the turbulence intensity.

Turbulent Dissipation Rate (ɷ)

The turbulent dissipation rate is defined as the kinetic velocity per unit time. It is denoted by ɷ, unit is m3/s2 and is mathematically expressed as –

ɷ = (Cμ ¾ k1/2) / l (4)

Where, Cμ is the turbulence model constant, l is the turbulent length scale. The turbulence length scale is given by –

l = 0.07 Dh (5)

Where, Dh is the hydraulic diameter.

Turbulence Intensity (I)
The turbulence intensity gives the level of turbulence at the inlet fluid flow and it is mathematically defined as –

I = u′/ U (6)

Where u′ is the root-mean-square of the turbulent velocity fluctuations given as:

u′ = √ 1/3 (u′ x sq.+ u′ y sq. + u′ z sq.) = √ 2/3 k (7)

The mean velocity U is formed as –

U = √ Ux sq.+ Uy sq.+ Uz sq. (8)

Turbulent Viscosity (μ_t)

The turbulent viscosity is given by –

μt = ρk / ω (9)

Results and Discussions

The CFD simulation has been carried out to visualize velocity vectors and heat dissipation rate. In the k-omega SST model the inlet turbulence intensity factor is impinged as 5%. Accordingly, the iterations are performed. The unsteady, 1st. order implicit time domain simulation has been performed. It is to be noted that the air acts as the working fluid in this convection heat transfer dissipation analysis on the four aerofoil pin-fin array models. The maximum 300 iterations per second time step has been occurred. In all the four models, the iterations performed in terms of residuals have been illustrated in the Figure 4.

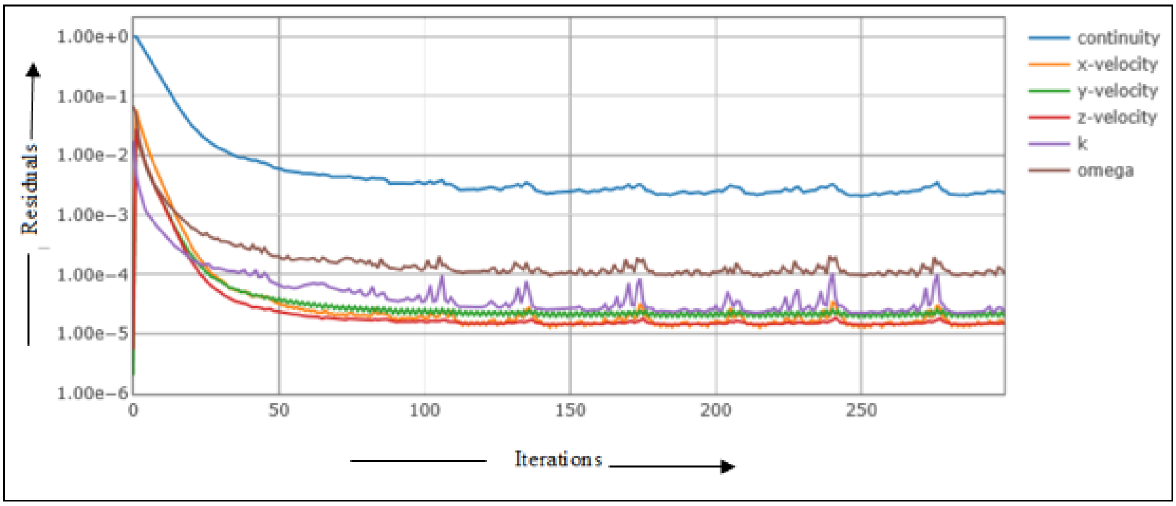


Figure 4: Aerofoil Pin-Fin Models Simulation Iterations V/S Residuals

Velocity Vectors

The velocity vector analysis has been performed to visualize the vortacity of convective air passing through the models under simulation. A sample of the velocity vector vortacity analysis in the rectangular channel domain has been illustrated in the Figure 5. The individual simulation results on velocity vector of all four models, viz. symmetrical inline without perforation, perforated symmetrical inline, symmetrical staggered without perforations and symmetrical perforated staggered aerofoil pin-fin array is attached in the Figure 6. It is found that in the symmetrical perforated aerofoil pin-fin array model, the velocity vector and vortacity is higher than other models. The vortacity in the perforated inline and staggered models are surrounded at the perforated zone. These perforations lead to velocity drop and increase in vortacity at the perforated zone. In the no perforated inline and staggered aerofoil pin-fin array models, the voracity occurred at the wall edge of the pin-fins. There is no as such limited vortacity has been observed at the central part of the arrays in case of no perforated inline and staggered aerofoil pin-fin arrays. Hence, there is lesser velocity drop in the no perforated aerofoil pin-fin array models, than the perforated aerofoil pin-fin array models.

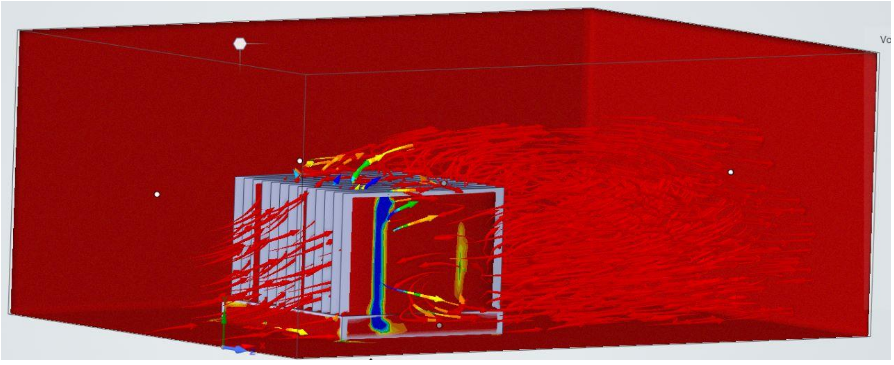
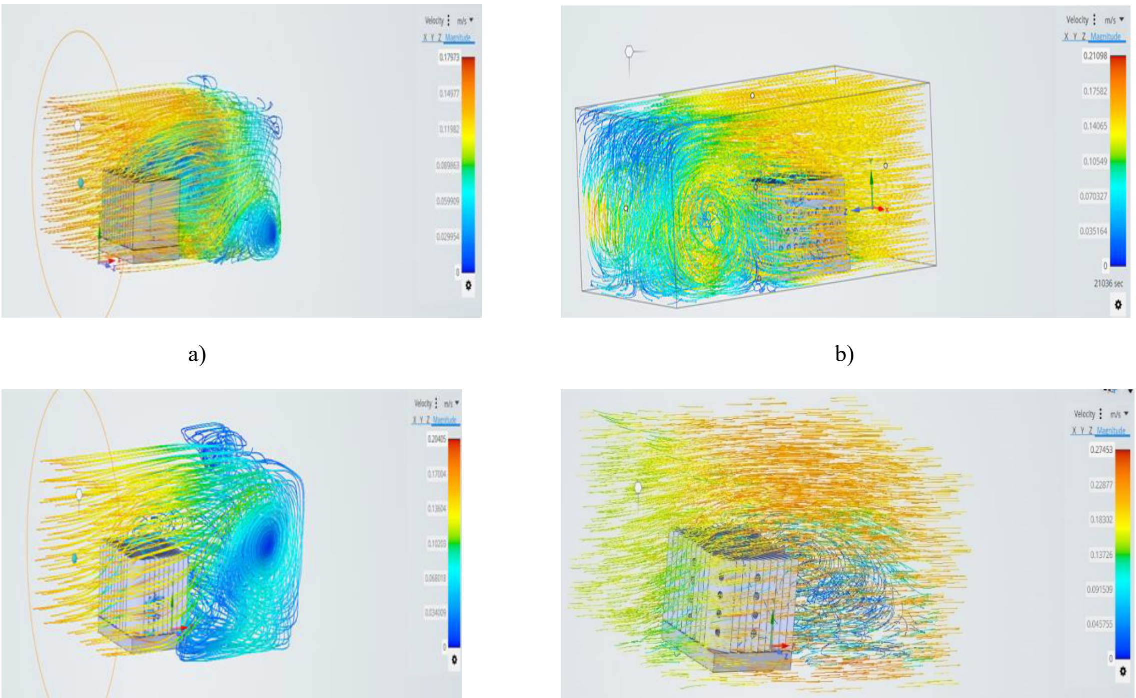


Figure 5: Velocity Vector Analysis of Aerofoil Pin-Fin Array Model in the Rectangular Channel Domain

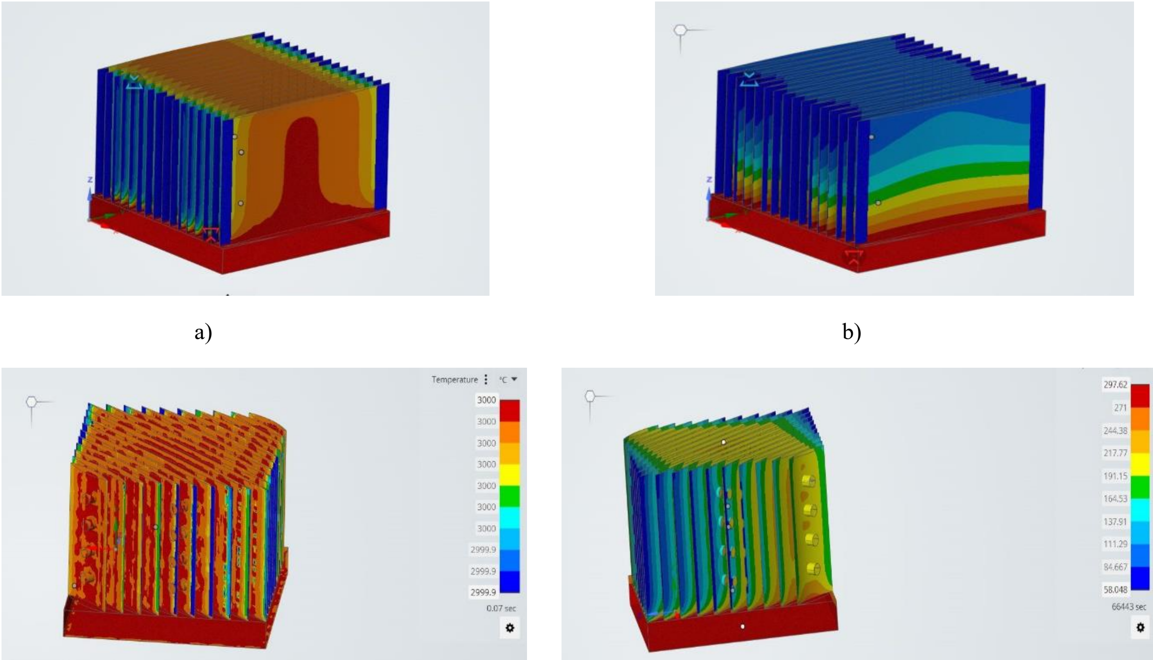


a) b) c) d)

Figure 6: Velocity Vector Analysis Results of a) Symmetrical Inline Without Perforations, b) Symmetrical Perforated Inline, c) Symmetrical Staggered Without Perforations, and d) Symmetrical Perforated Staggered Aerofoil Pin-Fin Array Models

Temperature Contour

In the temperature contour analysis, the growth in temperature profile of the aerofoil pin-fin array models have been visualized in the form of different colors. The Figure 7 illustrates the temperature contour profile of all the four models undergo CFD temperature contour analysis. It is observed that in the no perforated inline arrangement of aerofoil pin-fin array, the temperature contour is more progressive than perforated one. On the surface plate of the aerofoil pin-fin array model, the temperature growth has been developed. The highest temperature growth has been observed in the without perforated inline and staggered arrangements of symmetrical aerofoil pin-fin array models. While in case of the perforated inline and staggered symmetrical aerofoil pin-fin array models, the progressive and minimal temperature growth has been observed at the surface as well as at the tip of the pin-fins. Hence, from the temperature contours of all the four models, it is understood that the perforated inline and staggered aerofoil pin-fin array models dissipate more heat and in turn temperature to the surrounding. Therefore, the perforated inline and staggered aerofoil pin-fin array models are more suitable in heat dissipation rate.



c) d)

Figure 7: Temperature Contour, a) Symmetrical Inline without Perforations, b) Symmetrical Perforated Inline, c) Symmetrical Staggered without Perforations, and d) Symmetrical Staggered Perforated Aerofol Pin-Fin Array Models

Conclusion

The four aerofoil pin-fin array models have been studied using computational modelling, ANSYS 2021 R2 software. Air implied as cooling fluid. The three-dimensional computational domain has been created. In the analysis the Reynolds number varied from 5,000 to 50,000 with an increment of 5,000. The inlet air working fluid temperature value is 27 °C and the viscous model SST k-omega turbulence model has been selected. At the bottom of the aerofoil pin-fin array model, the temperature supplied from 50 to 350°C with an increment of 50°C. It is to be noted that the velocity vector and temperature contour simulations have been performed.in this CFD simulation, it is obtained that at the perforated inline and staggered arrangement of aerofoil pin-fin arrays more vortacity occurred at the perforated zone. In the temperature contour plot, it is observed that at the no perforated inline and staggered aerofoil pin-fin arrangement hot spot zone occurs. While at the perforated inline and staggered aerofoil pin-fin array models, no as such hot spot zone occurs. Hence, the heat transfer performance effectiveness of perforated inline and staggered aerofoil pin-fin array models are more active and better than no perforated models.

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