Studying the Effect of Different Vortex Generator Geometries and Arrangements on Heat Transfer Performance of Heat Sinks

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Abstract: In this paper, different geometries and arrangements of vortex generators for improving the heat transfer performance of heat sinks have been studied. The effect of different parameters including the inclination angle of vortex generators and the distance between them are also investigated on heat transfer performance of heat sinks. Numerical computations are done based on the finite volume method and they have been validated with available experimental data which were in accurate compatible with each other with RMSE error of less than 6%. According to the obtained outcomes, between rectangular, triangular and symmetrical NACA0012 vortex generator, heat sink with NACA0012 vortex generator has the best thermal performance. On the other hand, heat sink with rectangular vortex generator has the highest fluid flow pressure drop. So, using rectangular vortex generator with heat sink needs a fan with the highest power. Also, the results show that thermal resistance of the heat sink decreases with Reynolds number increase. Also, heat sink pressure drop increases with Re number enhancement. Meanwhile, the pressure drop rate is more sensible in higher Reynolds numbers.

Keywords: Computation Fluid Dynamics, Heat Sink, Heat Transfer, Vortex Generator

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1 INTRODUCTION

Today, Electronic industries are considered as one of the most important, basis and main fields in the world. There are lots of different sub-sets of the electronic industries which are widely used in a variety of engineering areas. Electronic packaging is applied in main industries such as military, space science, telecommunications, data centres, medicine science, etc. Meanwhile, with the advancement of new technologies, the size of recent electronic devices are reducing more and more. Hence, the heat dissipation is increasing so, the problem of electronic cooling has been become a critical issue in this area. By increasing the power of microprocessors, it is needed to benefit from more efficient cooling techniques to cool down higher heat rates. For keeping the working temperature of today's electronic devices within safe limits many cooling methods have been evolved recently.

Nowadays, because of the conventional cooling techniques limitations, new designs are investigated to increase and control heat flux to keep the working temperatures in an acceptable range [1-8]. Heat sinks are one of the most efficient ways for electronic integrated components cooling to control them working under the allowable operational temperature. Meanwhile, different geometries of heat sinks are provided by many industries to cool down the aforementioned electronic components. Nevertheless, in many cases, an appropriate heat sink geometry will be a vital need [9].

Till today, many investigations have been performed on heat sinks thermal performance. In 1982, Poulikakos and Bejan [10] investigated the behavior and role of the pins in different geometry of heat sinks. They found that the trapezoidal, rectangular and triangular pin-fin heat sinks are the best geometries in entropy generation minimization, respectively. In 2001, Culham and Muzychla [11] considered entropy generation minimization in flat heat sinks. They studied five different geometries of heat sinks considering the effect of number of fins on heat transfer rate, pressure drop and contact resistance. In their study, the optimum number of fins and also the most efficient flow speed passing through the heat sinks were reported. Feng et al. [12] designed a kind of heat sink which includes a combination of long and short fins arranged perpendicularly, to obtain the maximum free convection rate. The study results showed 15% convective heat transfer increase, compared to a plate-fin heat sink. Lee et al. [13] experimentally investigated the effect of fin numbers on natural convection heat transfer from vertical cylinders with triangular fins. They found that by decreasing spaces among the fins, Nusselt number is reduced slowly. Joo and Kim [14] studied the effect of width and length of fins on heat transfer and pressure drop of fin-pin heat sink with different arrangements. It was found that by reducing the length and width of pin-fins, heat dissipation increases significantly. Wang et al. [15] investigated the ways of optimizing micro-channel heat sink geometries considering nano-fluids inlet volume flow rate, pumping power and pressure drop across the heat sink.

Moraveji et al. [16] studied the effect of convective heat transfer coefficient in a mini-channel heat sink using nano-fluids at different Reynolds numbers and volume fraction of nanoparticles (TiO_2 and SiC). They applied a fixed arrangement of mini-channel and explained that heat transfer coefficient in mini-channels increases with the volume fraction enhancement of nanoparticles and also grows with increase of Reynolds number. Saeed and Kim [17] investigated thermal and hydraulic performance of mini-channel heat sinks by varying different geometrical parameters of them. They reported that local heat transfer coefficient associated with conventional distributor and collector headers of mini-channel heat sink is very low which occupies around 30% of the total volume of heat-sinks. Low local heat transfer coefficient and mal distribution linked with the headers in turn to reduce the overall thermal and hydraulic performance of heat sinks.

Wang [18] tested the thermal performance of the U and L shaped heat sinks for different heat fluxes. The thermal resistance of the heat sinks decreased with enhancement in heat flux and fan rotation speed. Ameni et al. [19] conducted an experimental study in which the effect of inclination angle of heat sink assisted with heat pipes based on heat transfer performance was investigated. They found that the temperature increase in the evaporator is maximum at the 90° inclination because the gravity force overcomes the capillarity effect. Meinders et al. [20-21] found that heat removal rate depends on the amount of whirling flow before pin section of a heat sink. An experimental study was done to compute the local convective heat transfer factor. Junaidi et al. [22] studied heat transfer rates in pin fin heat sinks by CFD simulation techniques. They found that 20–30% enhancement is achieved in the case of splayed pin fin under low air velocity conditions against the standard heat sink for same pumping power. The applied pin fin heat sinks were considered by advanced composite materials [23] and CFD calculations confirmed that use of composite materials can reduce total weight of the system with same thermal performance results. Khan et al. [24] investigated heat transfer rate together with entropy generation minimization of fluid flow passing through heat sinks. They assumed 2-D model by considering steady state flow regime with constant properties of the fluid. They also found the optimum heat sink dimensions and fluid speed by evaluation of effective parameters like Reynolds number. In a similar study, Hamadneh et al. [25] reported the optimum pin heat sink geometry based

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on thermal performance by minimizing entropy generation and also by comparison of three different cross section areas for plates (circular, quadrangular and oval). Salwe et al. [26] investigated the thermal performance of pin fin heat sinks numerically and compared the results with the normal ones in forced flow. It was found that pin fin heat sinks benefit from better thermal performance. Furthermore, many investigations related to pin fin heat sinks with different dimensional characteristics were done to find the most efficient thermal performances in natural and forced convection [27-32]. Until now, some investigations have been done on the role of vortex generators in thermal performance improvement in different electrical devices. As an example, Fiebig [33] conducted an investigation experimentally and numerically to enhance thermal performance and to decrease pressure drop for internal flow of tubes [33].

Torji et al. [34] investigated heat transfer increase accompanying pressure-loss reduction with Winglet-type vortex generators for fin-tube heat exchangers with different arrangements. Downstream vortex generators represented a major effect on heat transfer enhancement by disturbing thin boundary layer at the wall, so increasing local Nusselt number as shown by Habchi et al [35]. Meanwhile, adding hemispherical protrusions among the vortex generator arrays enhanced heat transfer with only a small rise in pressure drop. This increase in local heat transfer was made by increasing the temperature gradients very close to the heated wall. Bayareh et al. investigated numerically the effects of stator boundary conditions and blade geometry on the efficiency of a scraped surface heat exchanger. The results showed suitable conformity with the experimental results. A new type of blade was proposed to improve surface cleaning and turbulence intensity [36]. Jahanbakhshi et al. investigated Magnetic field effects on natural convection flow of a non-Newtonian fluid in an L-shaped enclosure. It was shown that heat transfer rate decreases for shear-thinning fluids (of power-law index, $n < 1$) and increases for shear-thickening fluids ($n > 1$) in comparison with the Newtonian ones [37]. Shirazi et al. studied numerically the mixed convection heat transfer of a nanofluid in a circular enclosure with a rotating inner cylinder. The results showed that at eccentricity of $\varepsilon = 0.0$ and 0.5 and within the entire range of Rayleigh number $103 \le Ra \le 105$ and Richardson number $0.1 \le Ri \le 100$, an increase in Rayleigh and Richardson numbers leads to an increase in average Nusselt number on the inner cylinder wall. However, at eccentricity of $\varepsilon = 0.9$, the average Nusselt number on the inner cylinder wall decreases with these dimensionless parameters. It is found that an increase in the volume fraction of the nanofluid results in an increase in average Nusselt number on the inner cylinder wall [38]. Sepyani et al. investigated the mixed convection heat transfer of a nanofluid in a square chamber with a rotating blade. The results show that an increase in Rayleigh number, volumetric percentage of nanofluid and blade length leads to heat transfer increasing in most cases, but an increase in Richardson number results in a reduction in heat transfer. It is revealed that the maximum blade rotation occurs at small Richardson numbers [39]. Bayareh et al. have done numerical simulation of heat transfer over a flat plate with a triangular vortex generator. The results showed that the Nusselt number increases and the pressure decreases with the Reynolds number. It was demonstrated that the increase in the angle from 30° to 90° has a significant effect on the Nusselt number. The pressure drop remains constant at a 60° angle with increasing Reynolds number. The results revealed that the longitudinal vortices that have an important effect on the heat transfer become stronger at larger angles of the vortex generator [40]. Bayareh et al. investigated mixed convection heat transfer of water-alumina nanofluid in an inclined and baffled C-shaped enclosure. The results showed that the Nusselt number increases with increase of Reynolds number. Adding nanoparticles always results in cooling enclosure. At high Reynolds number, increase of nanoparticles has less effect on the heat transfer rate. Furthermore, heat transfer increases with the Richardson number, the enclosure angle and the length of baffle [41].

As it was discussed, many investigations have been done numerically and experimentally on different geometries of heat sinks. However, there is not sufficient information around the considering the effect of different geometries and arrangements of vortex generator for heat transfer rate improvement in heat sinks for electronic devices cooling. So, in present study, for the first time the effect of different geometries and arrangements of vortex generators are investigated on heat sink thermal performance.

2 GOVERNING EQUATIONS

In present study, the turbulent flow regime around different geometries of heat sinks has been investigated numerically. Hence, the governing equations for fluid flow and heat transfer in terms of continuity equation in an incompressible flow, Navier-Stokes equations and energy and continuity equations are solved.

The continuity equation is considered as:

$$\left(\vec{\nabla}.\vec{V}\right) = 0 \qquad (1)$$

Where, V is velocity vector. With consideration of incompressible flow regime and constant viscosity, the form of Navier-stocks equation will be considered as following.

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$$\rho \frac{DV}{Dt} = \rho f - \nabla P + \mu \nabla^2 V \quad (2)$$

Where, V is velocity vector. P is pressure, f is body force and μ is dynamic viscosity. Energy equation with constant conduction coefficient will be defined as following.

$$C_p \left(\rho u \frac{\partial T}{\partial x} + \rho v \frac{\partial T}{\partial y} + \rho w \frac{\partial T}{\partial z} \right) = k \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) \quad (3)$$

Where, V is velocity vector and ρ is density. Also, the thermal resistance of heat sink will be defined as below:

$$R = \frac{T_{mean} - T_\infty}{Q} \quad (4)$$

Where, T_{mean} is average temperature of heat sink base plate, T_∞ is the temperature of coolant flow, and Q is the applied heat flux. Additionally, Reynolds number is defined as following:

$$Re = \frac{VD}{v} \quad (5)$$

Where, V is inlet velocity of the air, D is hydraulic diameter and v is kinematic viscosity. Also, Nusselt number is defined as:

$$Nu = \frac{hL}{k} \quad (6)$$

Where, h is the convective heat transfer coefficient of the flow, L is the characteristic length, k is the thermal conductivity of the fluid.

3 GEOMETRY AND MESHING

The conventional plate-rectangular fin heat sink is the base heat sink for thermal performance analysis ("Fig. 1"). The assembly of heat sink inside the wind tunnel is represented in "Fig. 2". The dimensions of heat sink based on the schematic of "Fig. 1" are given in "Table 1". Also, Wind tunnel test section has dimensions of 150 mm×150 mm×1300 mm. Heat sinks are placed in distance of 900 mm from the wind tunnel entrance.

Table 1 Dimensions of the base simulated heat sink (refer to "Fig. 3")

Parameter	Amount (mm)
Width (WHS)	63.5
Length (LHS)	63.5
Height (HHS)	18.3
Fin Thickness (t)	1.27
Channel Width (g)	2.54
Base Plate Thickness (b)	2.54

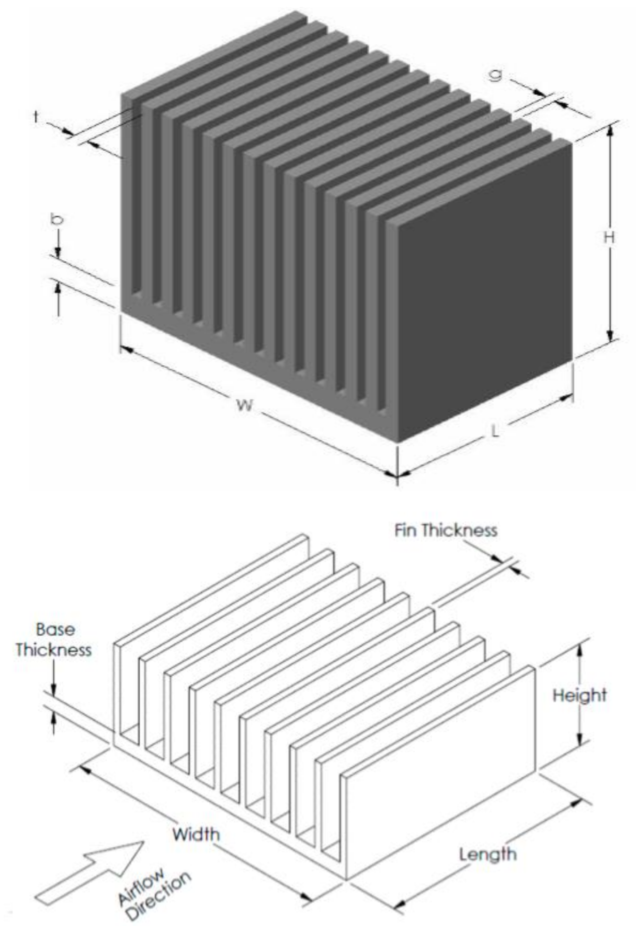

Fig. 1 Schematic of conventional plate-fin heat sink.

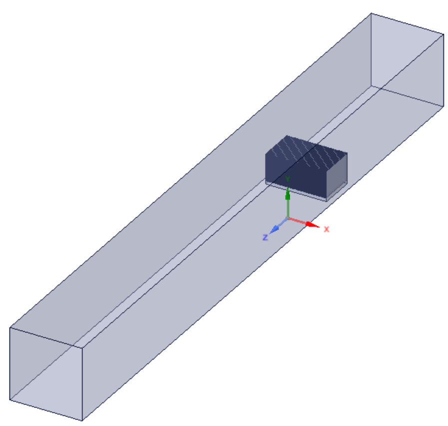

Fig. 2 Assembly of heat sinks inside the wind tunnel.

Mesh grids of the selected heat sink is represented in "Fig. 3". In this study, heat sink is considered with different geometries of vortex generators for achieving better heat transfer performance.

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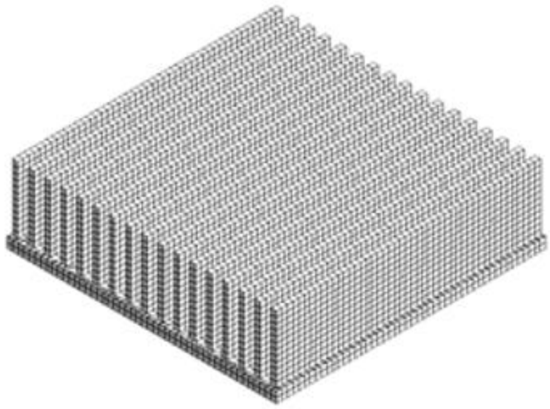

Fig. 3 Mesh grid of five different heat sinks.

The proposed geometry of different vortex generators has been brought in “Fig. 4”.

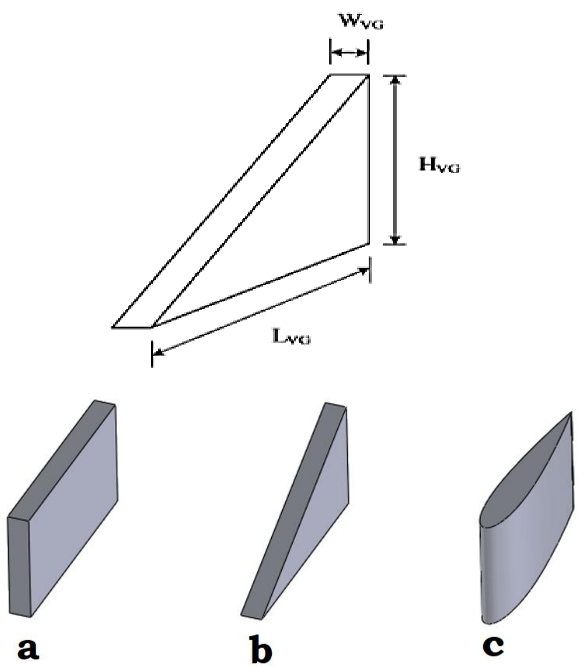

Fig. 4 Geometry of different vortex generators (Rectangular VG, Triangular VG, Symmetrical VG NACA0012).

Arrangements of vortex generators in front of heat sink are shown in “Figs. 5 and 6”. Dimensions of studied base vortex generator are written in “Table 2”. Because of the complexity of different investigated geometries, mesh grid of each parts is different from one another.

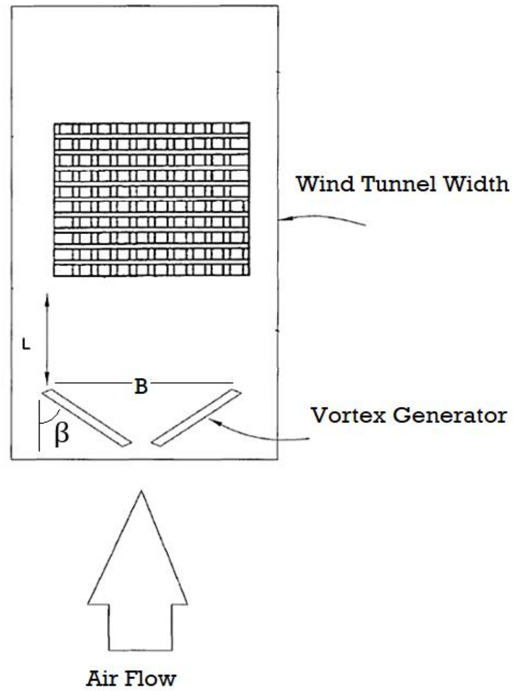

Fig. 5 Arrangement of vortex generator.

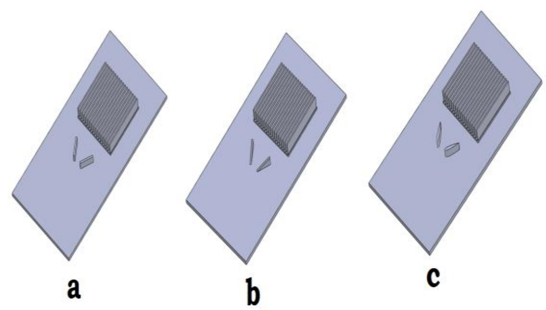

Fig. 6 Assembly of heat sink with different geometries of vortex generator a) Rectangular VG. b) Triangular VG. c) Symmetrical VG NACA0012.

Mesh of different assemblies of vortex generators in front of heat sink are seen in “Fig. 7”. After investigating mesh independency, total number of mesh grids is considered around 1.45 million.

Table 2. Dimensions of base vortex generator (refer to “Fig. 5”)

Parameter	Amount (mm)
Width (WVG)	2
Long (LVG)	9.15
Height (HVG)	9.15

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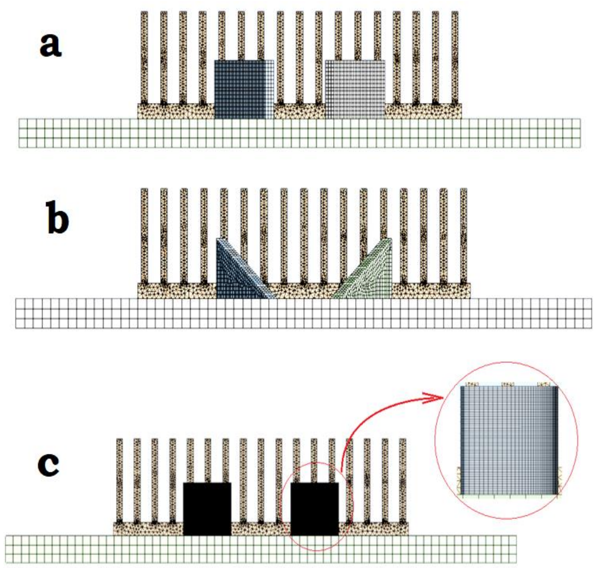

Fig. 7 Mesh of different assembly of vortex generators in front of heat sink (front view).

4 NUMERICAL SIMULATION

In this study, for the purpose of numerical simulations, ANSYS Fluent software which is based on finite volume method is used. Different geometries are modelled by SolidWorks Software. In present investigation, different geometries of vortex generators are considered based on their thermal performance. For solving the problem, different equations of continuity, momentum and energy for the fluid flow have been solved. The fluid flow is turbulent and there is fluid swirl on the vortex generators. For considering the effects of swirl on vortex generators, RNG K-ε turbulent model is considered for the simulation.

The accuracy of problem solving for convergence is considered 10^{-6}. Simulations have been done under steady state conditions. According to the fact that the heat flux is applied to the below surface of heat sink, the conduction equation inside the solid geometry will be solved. For investigation of the independency of the results on the number of geometry meshes, the problem has been solved for different mesh grid numbers. Mesh Independency of the problem for different heat sink geometries is shown in “Fig. 8”. In mesh independency evaluation, dimensions are provided in “Tables 1 and 2”. After mesh independency analysing, number of mesh grids is considered near to 1450000.

In current study, air and aluminium are considered as coolant fluid and the material of the heat sink, respectively. Furthermore, heat flux and fluid flow velocities are 7 Kw/m^2 and 1-5 m/s, respectively. In this study, the effect of using different geometries of vortex generators in order to get improvement in the thermal performance of heat sinks has been investigated. Moreover, effects of vortex generator parameters such as the height and lengths (LVG and HVG), the angle of vortex generators (β, from 30 to 60 degrees) and the distance between the vortex generators and heat sinks (LV, from 10 to 67 mm) have been studied.

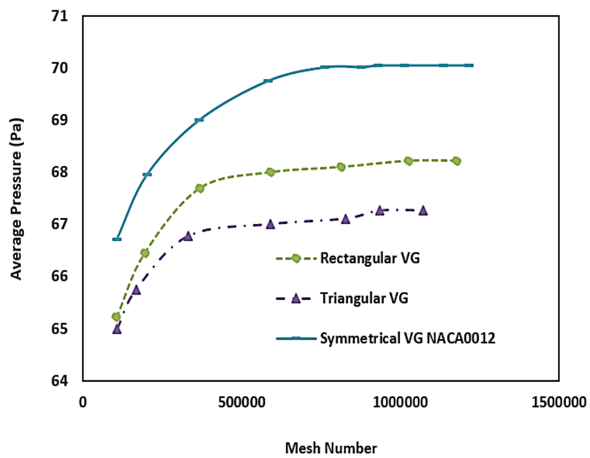

Fig. 8 Independency of problem solution to mesh grid.

5 VALIDATION OF THE RESULTS

An experimental investigation has been done by C. K. Loh et al. [42] which is used for validating the present study. In their work, a theoretical, experimental and numerical investigation was conducted on geometry of plate-rectangular fin heat sink. In that experimental study [42], a plate-rectangular fin heat sink was chosen which its specifications are provided in “Table 1”. Experimental tests were done in speed range of 1 m/s to 4 m/s. The comparison between experimental study of ref [42] and current numerical investigation has been shown in “Fig. 9”. Data analysis shows that the results of the present numerical study is very similar to the experimental results of ref [42] with the mean squared error of about only 6% which represents firmly that the accuracy of current study could be reliable.

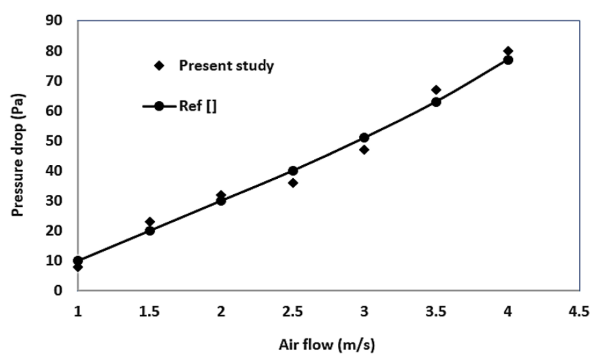

Fig. 9 Comparison between current results and ref. [42].

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6 RESULTS AND DISCUSSION

Figure 10 shows temperature distribution on the surfaces of studied heat sinks for Reynolds number of 20000. As it has been shown, temperature changes from high to low from the beginning to the end of the heat sink. This is because of the cooling fluid direction from the beginning to the end of it.

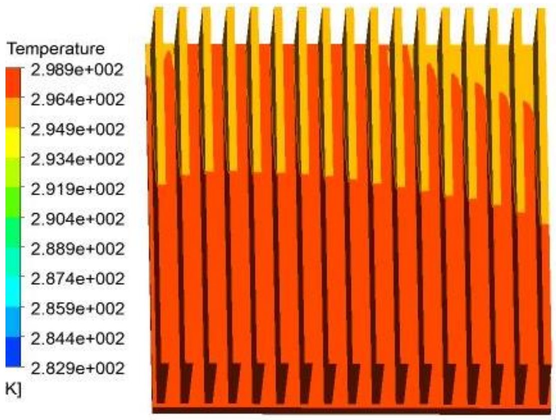

Fig. 10 Temperature distribution on surfaces of heat sink for Reynolds number of 20000.

Figure 11 shows pressure distribution on heat sinks for Re=20000. As it is shown, the pressure is more at the beginning of the heat sink geometry.

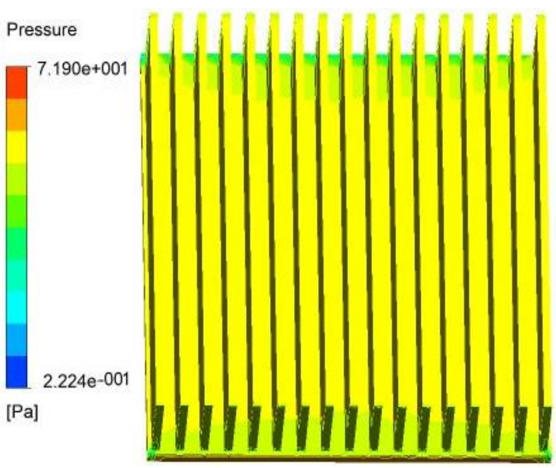

Fig. 11 Pressure distribution on heat sink geometry for Re=20000.

Figure 12 shows the effect of distance between vortex generator and heat sink on heat sink thermal efficiency. As it has been shown, in lower Reynolds numbers (Re between 10000 and 20000) the effect of vortex generator on heat resistance is significant. In higher Reynolds numbers (Re from 40000 to 50000) the effect of the vortex generator length (Lvh) on thermal resistance is insignificant.

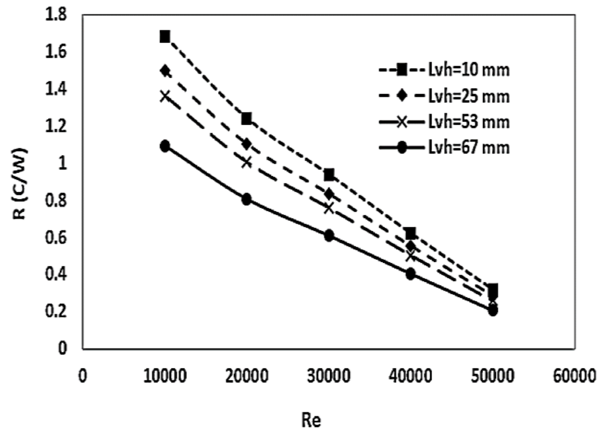

Fig. 12 Effect of vortex generator distance from heat sink on thermal performance.

Figure 13 shows the effect of distance between vortex generator and the heat sink on fluid flow pressure drop. It is notable that presence of vortex generator may lead to pressure drop enhancement. The effect of vortex generator length (Lvh) on pressure drop is more in higher Reynolds numbers (Re from 10000 to 20000). Also, in lower Reynolds numbers (Re from 10000 to 20000) vortex generator length (Lvh) has lower effect on pressure drop.

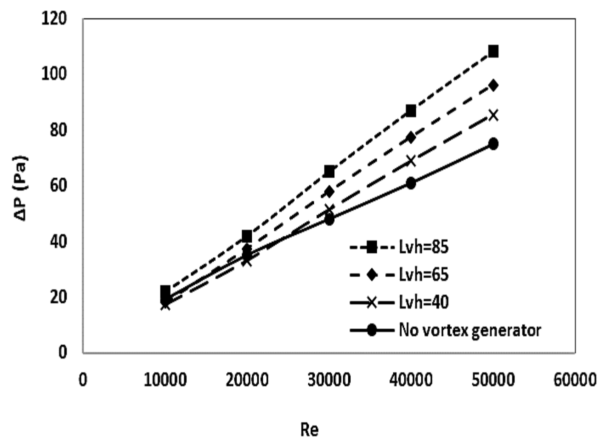

Fig. 13 Effect of vortex generator distance from heat sink on pressure drop.

Figure 14 shows the effect of the vortex generator inclination angle on heat sink thermal performance. As it is shown, thermal resistance of heat sink decreases with enhancement of inclination angle of vortex generator and it is considerable that this reduction is more tangible in lower Reynolds numbers. So, heat transfer increases while thermal resistance rate decreases. Also, the effect of vortex generator inclination angle on thermal resistance is more significant in lower Reynolds numbers (Re from 10000 to 20000). Since in higher Reynolds numbers (Re from 40000 to 50000) the effect of flow swirl on heat transfer

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rate is more sensible and the effect of vortex generator on heat transfer rate is less.

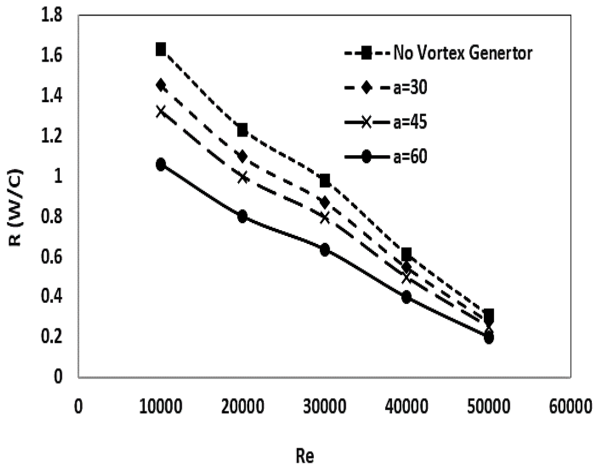

Fig. 14 Effect of inclination angle of vortex generator arrangement on thermal performance of heat sink.

Figure 15 shows the effect of vortex generator inclination angle on flow pressure drop. As it is shown, vortex generator increases flow pressure drop. Also, the effect of vortex generator on flow pressure drop in higher Reynolds number (Re from 40000 to 5000) is more. It is represented that flow pressure drop increases with the inclination angle of vortex generators enhancement.

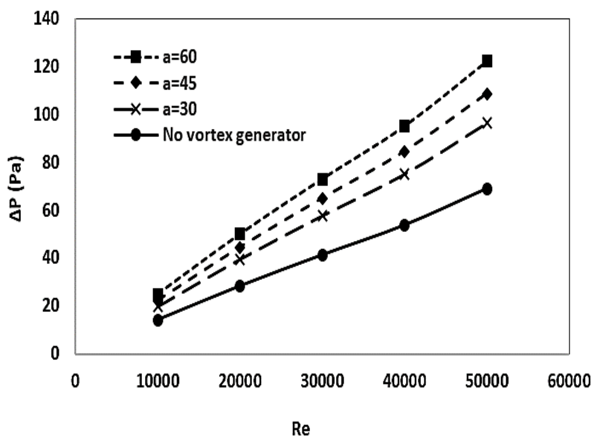

Fig. 15 Effect of inclination angle of vortex generator arrangement on flow pressure drop.

Figure 16 shows the effect of vortex generator height on heat sink thermal performance. As it has been shown, for all of the studied heights, increasing the Re number leads to thermal resistance reduction. It is clear that vortex generator height increase would decrease thermal resistance while leads to heat transfer rate enhancement. This is because of increasing the face in front of the fluid flow with increasing the height of vortex generator. So, the fluid flow pressure drop across the vortex generator increases and it makes a big flow vortex. These vortexes carry more amount of heat from the heat sink surface while decreasing more thermal resistance. On the other hand, using vortex generators decreases available area inside the channel for fluid flow. So, for equal fluid flow rate, fluid velocity increases and this action leads to better thermal performance and less thermal resistance.

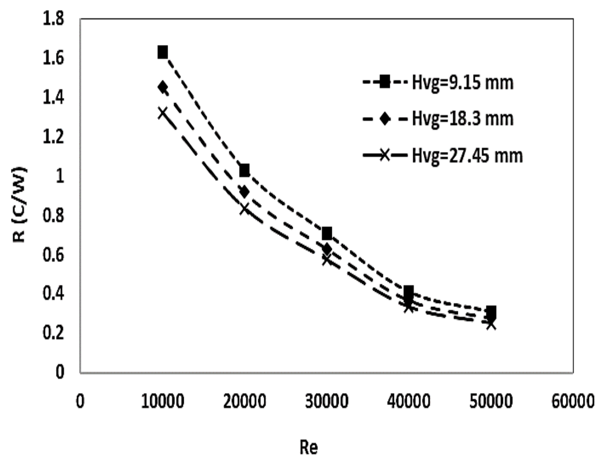

Fig. 16 Effect of vortex generator height on thermal performance of heat sink.

Figure 17 shows the effect of the vortex generator height on fluid flow pressure drop. As it has been shown, fluid flow pressure drop decreases with increasing vortex generator height and this is also because of increasing the face in front of the flow. Furthermore, the highest pressure drop is related to the vortex generator with the height of 27.45 mm.

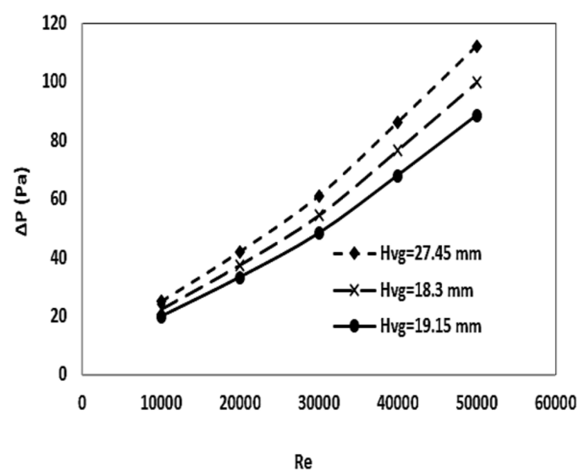

Fig. 17 Effect of vortex generator height on flow pressure drop.

Figure 18 shows the effect of using different geometries of vortex generators on thermal performance of heat sink. It has been shown that rectangular VG, triangular

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VG and NACA0012 VG has the highest thermal performance, respectively. So, the heat sink with NACA0012 VG has the best thermal performance.

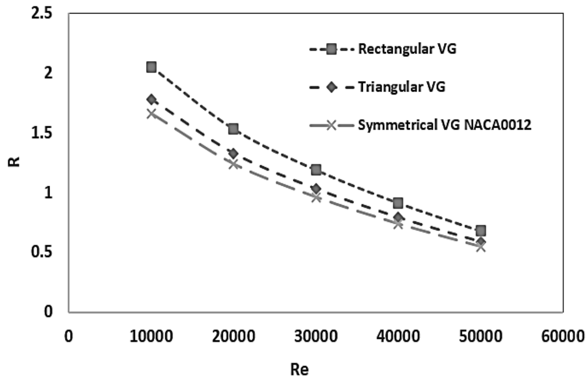

Fig. 18 Effect of vortex generator geometry on heat sink thermal performance.

Figure 19 shows the effect of using different geometries of vortex generators on fluid flow pressure drop. This figure shows that heat sink with triangle vortex generator has the lowest fluid flow pressure drop. On the other hand, heat sink with rectangular vortex generator has the highest fluid flow pressure drop. So, using rectangular vortex generator with heat sink needs a fan with the highest power.

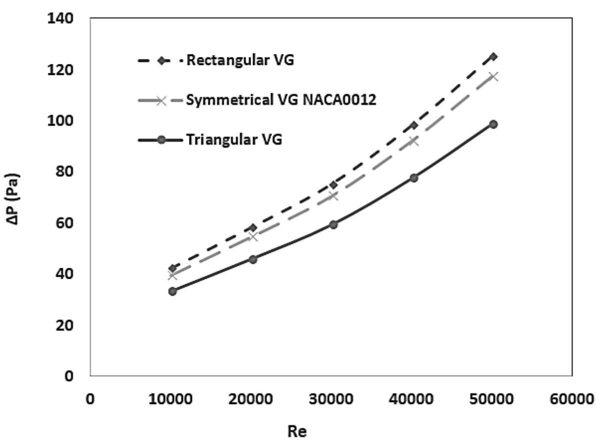

Fig. 19 Effect of vortex generator geometry on fluid flow pressure drop.

7 CONCLUSION

In present study, a numerical investigation of fluid flow regime and heat transfer analysis of different geometries of vortex generators on heat sink thermal performance were conducted. For validation purpose, the outcomes of current study were compared with available experimental results which were accurately compatible with each other with RMSE error of less than 6% which showed an acceptable enough accuracy. Heat sink thermal performance and fluid flow pressure drop were considered as two main criteria in present investigation. The effect of effective parameters including height and length of vortex generators, the inclination angle of vortex generators and also the effect of distance between vortex generators and the heat sink on the heat sink thermal performance were investigated.

According to obtained results, thermal resistance of the heat sink decreases with Reynolds number increase. Also, heat sink pressure drop increases with Re number enhancement. Meanwhile, the pressure drop rate is more sensible in higher Reynolds numbers. Furthermore, it has shown that increasing the distance between two inline vortex generators leads to flow pressure drop increase. Also, results show that in low Re numbers (Re number between 10000 and 20000) the effect of vortex generator on thermal resistance is high.

Heat sink thermal resistance decreases with increasing the inclination angle of vortex generator which the mentioned decrease is more significant in lower Reynolds numbers. Also, the effect of vortex generator inclination angle on thermal resistance is more tangible in lower Reynolds numbers (Re from 10000 to 20000).

Vortex generator may increase the flow pressure drop. Additionally, the effect of vortex generator on flow pressure drop in higher Reynolds number (Re from 40000 to 5000) is more sensible. It is shown that flow pressure drop increases with inclination angle enhancement of vortex generators. Increasing vortex generator height leads to thermal resistance reduction and heat transfer rate enhancement. Also, the fluid flow pressure drop decreases with increasing vortex generator height.

The heat sink with NACA0012 VG has the best thermal performance. On the other hand, heat sink with rectangular vortex generator has the highest fluid flow pressure drop. So, using rectangular vortex generator with heat sink needs a fan with the highest power.

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