Computational Investigation of Heat Transfer Analysis through Perforated Pin Fins of Different Materials

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Abstract. The present work investigates the enhancement of heat transfer rate through staggered perforated pin fins of different materials with increasing number and size of perforations. Three dimensional CFD simulations have been carried out to analyze the effects of fin number, size and materials of fin to enhance heat transfer rate against pressure loss. Results show that the heat transfer rates of perforated fins up to certain perforation number and size are always greater than the solid ones and with the change of fin material heat transfer rate also improves significantly. On the other hand pressure drop through heat sink decreases not only with increasing perforation number but also with size of perforations.

Keywords: Perforated fin; System performance; Nusselt number; Reynolds number; Pressure drop

INTRODUCTION

Extended surfaces (fins) are widely used in heat exchanging devices to increase heat transfer between a primary surface and the surrounding fluid. Various attempts have been made to design optimized fins to improve the transfer of heat. Fins are generally optimized by either reducing the fin weight at a specific heat removal capacity or increasing heat removal rate at a specific fin weight. Making perforations in fins is one of the most useful methods to enhance the heat transfer rate. The effect of the perforations on these aspects is motivated by comparing the perforated fin to its solid counterpart. Introducing perforations to the fin body, the surface area and heat dissipation rates are increased for a given range of perforation dimension. Perforated fins have better contact surface with the fluid when compared to their solid counterparts in comparison with the solid fins. Moreover, perforated fins have higher friction and low pressure drag than solid fins.

Several research works have been carried out to improve heat transfer rate by using perforated fin. AlEssa [1] worked on one dimensional finite element heat transfer solution of triangular perforated fin. Performance of fin is enhanced due to modification in perforation geometry. Shaeri and Yaghoubi [2] analyzed numerically, the turbulent convective heat transfer through solid and perforated fin array. They concluded that the longitudinal perforation improves heat transfer significantly than solid fins. Elshafei [3] experimented on natural convective heat transfer through perforated circular pin fin under natural convection. Results showed that temperature difference between the base plate and surrounding improves with increasing pin fin diameter and perforated fin has better heat transfer performance than solid fin. Karabacak and Yakar [4] investigated the effects of perforation on a perforated finned heat exchanger subjected to convective heat transfer experimentally by making perforation on circular fins at six different angular points. Li *et al.* [5] analyzed field synergy on fluid flow and convective heat transfer of novel triangular perforated fin. This showed that triangular perforated fin has higher heat transfer performance than serrated fin for Reynolds number between 200 to 1960. Heat transfer enhancement through triangular perforated fin is caused by secondary flows and vortices which improve synergy between velocity and temperature gradient. Chin *et al.* [6] carried out a research on enhancement of forced convective heat transfer through perforated fins where perforated pin fin has 45% higher Nusselt number and 18% lower pressure drop than solid pin fins. Ismail *et al.* [7] numerically investigated turbulent heat convection between solid and longitudinally perforated rectangular fins. Results showed that circular perforated fin has outstanding heat transfer enhancement and less pressure drop than square perforated fin. Huang *et al.* [8] carried out a research to design perforation diameter of pin fin array for heat transfer improvement. The result shows that base plate temperature of heat sink gets reduced by 1.5% to 2% of the original design. Al-Damook *et al.* [9] investigated thermal air flow from perforated pin heat sinks both experimentally and computationally. The results show that performance of multiple perforated fins are better due to heat transfer increment and decrease in pressure drop. Maximum heat transfer is obtained when perforations are aligned with dominant flow. Yang *et al.* [10] experimentally determined the maximum dimensionless heat transfer rate of a cylindrical pin fin heat sinks keeping total heat sink and fin material volume as fixed. Pressure drop is also considered to evaluate hydraulic performance of the system.

In view of these existing works it appears that research works it has been observed that previous research works were carried out with only kind of fin materials (most of the time aluminium). Fins of different materials were not used before to make a comparison between their performances. The present paper reports on a computational study of steady state incompressible forced convective heat transfer through staggered solid and perforated pin arrays where fins are made of Copper (Cu) and Aluminium (Al). Three dimensional CFD simulations have been presented to analyze the effect of perforation number (N_{pf}) and diameter of perforations (D_p) in fin as well as materials of fin to enhance heat transfer rate against pressure loss.

METHODOLOGY

Three dimensional incompressible flow and heat transfer though pin fin arrays are simulated by ANSYS 14.0 Fluent software Fins are mounted on a square base plate of thickness 3 mm. On the base plate pin fins are arranged in a staggered way with different rows and columns. The whole fin setup model is covered in three dimensional rectangular domains except the lower surface of the base plate. The dimension of the domain is as follows: length (l) 1.05 m, width (b) 0.12 m, height (t) 0.063 m. There are two endings of the domain of which one is inlet and another is outlet. Fin arrangement is placed inside the domain between inlet and outlet. Distance of base plate from inlet is around 705 mm and from base plate to outlet is 345 mm. Domain walls are considered to be adiabatic. There are 14 pin fins of height of 50 mm each. Fins are arranged in a staggered manner at 25 mm. gap from each other horizontally and vertically both.

TABLE 1. Circular fin with increasing perforation number and size

Number of perforations (N_{pf})	**Solid**	**1**	**2**	**3**	**4**	**5**			
Diameter of perforations (D_p) in mm.	0	4	4	4	4	2	3	4	5

Perforations in fin increase according to table 1. At first number of perforations (N_{pf}) increases from 0 to 5 by keeping perforation diameter (D_p) same as 4 mm and then D_p increases by keeping N_{pf} constant as 5.The equation of motion which contains continuity equation, energy equation and Navier-Stokes equation is solved using Finite Volume Method. Realizable κ-ε model is used to simulate turbulence [6]. Velocity and pressure coupling is achieved by Coupled algorithm. Boundary condition is provided in following way: (i) constant heat flux of 5903 W/m^2 at fin base (ii) inlet velocity 4 m/s to 12 m/s where turbulence intensity is 10% and hydraulic diameter is 0.067 m. The thermal energy is transferred at the base of fin array and being dissipated through forced convection.

Continuity equation

$$\nabla.\left(\rho\vec{v}\right) = 0 \tag{1}$$

Momentum equation

$$\rho\vec{v}.\nabla\vec{v} = \mu\nabla^2\vec{v} - \nabla P \tag{2}$$

Energy equation:

$$\rho c_p \nabla.(\vec{v}T) = \nabla.(k\nabla T) \tag{3}$$

κ-ε realizable transport equations:

$$\frac{\partial}{\partial x_j}(\rho\kappa u_j) = \frac{\partial}{\partial x_j}[(\mu + \frac{\mu_t}{\sigma_k})\frac{\partial\kappa}{\partial x_j}] + G_\kappa + G_b - \rho\varepsilon + Y_M \tag{4}$$

$$\frac{\partial}{\partial x_j}(\rho\varepsilon u_j) = \frac{\partial}{\partial x_j}[(\mu + \frac{\mu_t}{\sigma_\varepsilon})\frac{\partial\varepsilon}{\partial x_j}] - \rho C_2 \frac{\varepsilon^2}{k + \sqrt{\upsilon\varepsilon}} + C_{1\varepsilon}\frac{\varepsilon}{k}C_{3\varepsilon}G_b \tag{5}$$

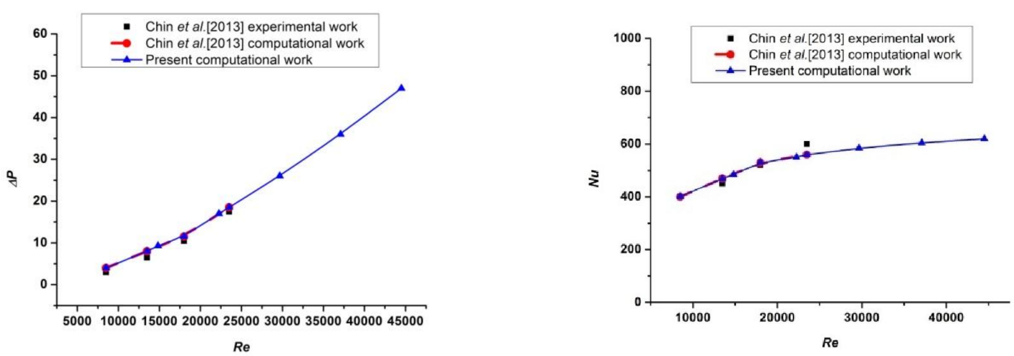
$$Nu = \frac{qD_h}{k_{air}(T_w - \frac{T_{in} + T_{out}}{2})} = \frac{hD_h}{k_{air}} \;\; ; \;\; \eta = \frac{Nu}{\Delta P / 0.5\rho u_i^2} \tag{6}$$

$$\mathrm{Re} = \frac{\rho u_i D_h}{\mu} \;\; ; \;\; \Delta P = P_{in} - P_{out} \tag{7}$$

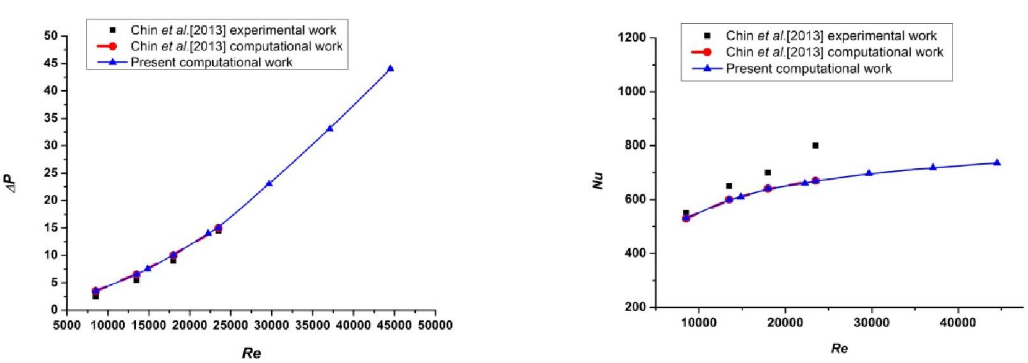
Nu = Nusselt number, *Re* = Reynolds number, *ΔP* = Pressure drop, P_{in} = Inlet pressure (Pa), P_{out} = Outlet pressure (Pa), T_w = Base temperature (K), T_{in} = Inlet temperature (K), T_{out} = Outlet temperature (K), u_i = inlet velocity (ms^{-1}), ρ = Density of air (kgm^{-3}), D_h = Hydraulic diameter (m), q = Heat flux (Wm^{-2}), k_{air} =Thermal conductivity of air ($Wm^{-1}K^{-1}$), η = System performance.

RESULTS AND DISCUSSION

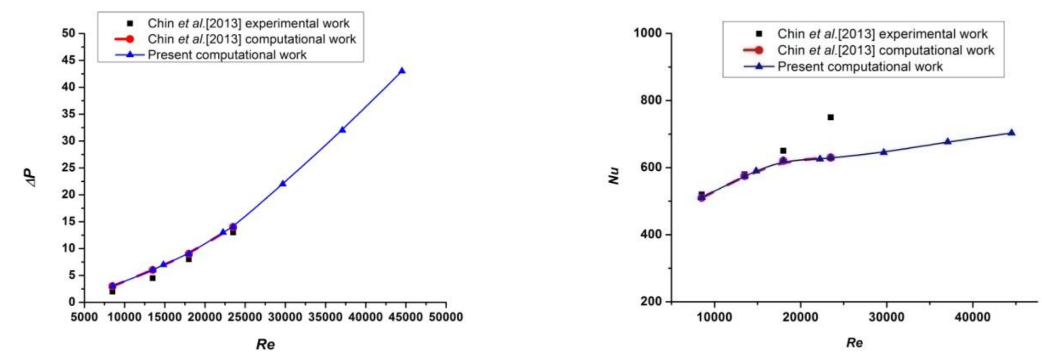
Validation of present work with existing numerical and experimental work



(i) *Solid pin fin*



(ii) N_{pf}=5, D_p=3 mm



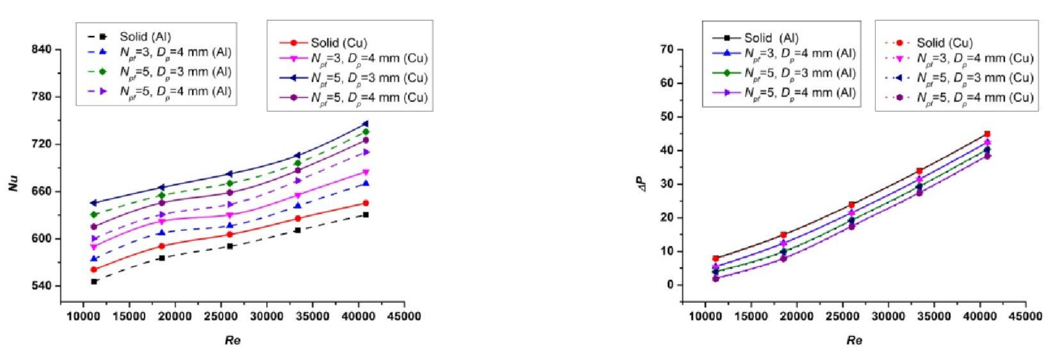
(iii) N_{pf}=5, D_p=4 mm

(a) (b)

FIGURE 1. Comparison between present computational results with computational and experimental results [6]: (a) ΔP vs. *Re*, (b) *Nu* vs. *Re*

Figure 1 shows the variations of pressure drop (ΔP) and Nusselt number (*Nu*) with the variation of Reynolds number (*Re*) among solid and perforated fins. In these figures a comparison has been drawn between present computational results and computational and experimental work done by Chin *et al.* [6]. Validated results are showed for three different cases: (i) solid pin fin, (ii) pin fin with 5 numbers of perforations of each 3 mm perforation diameter and (iii) pin fin with 5 numbers of perforations with each perforation of 4 mm diameter. It has been observed that both ΔP and *Nu* are increased with increasing value *Re*. *Re* increases with increment of velocity of flow, which causes accession in forced convection results in increment in heat transfer and P_{out} also increases with increment of flow velocity and Re which causes accession in ΔP. In this figure simulation result gradually goes higher than experimental and simulation results of Chin *et al.* [6], because of the fact that this simulation has been extended to higher *Re* than published work. It has been observed that pressure drop gradually decreases from solid pin fin to perforated pin fin of N_{pf} = 5 with 4 mm perforation diameter (D_p = 4). Alternatively, solid fins offer a larger obstruction in fluid flow than perforated fins resulting wake leeward of each pin that causes the higher pressure losses. Increasing number of perforation and perforation diameter also increase the exit pressure (P_{out}) and thus ΔP decreases in perforated pin fin. *Nu* also increases gradually in present simulated result as compared to experimental and simulated results of Chin *et al.* [6] due to higher *Re* in current simulation. Furthermore, *Re* is highly influenced by inlet velocity of air (u_i) and thus higher *Nu* is achieved.

- Effects of perforation and fin material characteristics on heat transfer performance and pressure drop



(a) (b)

FIGURE 2. Effect of perforations on (a) *Nu*; (b) *ΔP*

Figure 2 shows that for both fin materials, Nusselt number is increased with the increase in Reynolds number. Higher *Nu* value causes higher thermal dissipation and thermal dissipation occurs more in perforated pin fins than solid ones as depicted in Fig. 2a. Increasing number of perforation results in increasing surface area of convection which causes higher heat dissipation. However, heat transfer rate is highly influenced by the size of perforation also. When size of perforation increases, heat transfer rate increases at first and after a specific perforation size, it decreases gradually with further increment of perforation dimension. Again, as heat transfer rate decreases, T_{out} also gets reduce causing the decrement of *Nu* as expressed in Eqs. (6). In this analysis perforated fins of N_{pf} = 5, D_p = 3 mm show maximum *Nu* than other perforation irrespective of fin material. In case of fin materials copper fin show higher Nu than aluminium fin because of its higher conductivity. It is necessary to mention here that thermal conductivity (*k*) of copper is 353W/mK where *k* of aluminium is 167 W/mK.

Variation of pressure drop with the change of *Re* with increasing number and size of perforation has been shown in Fig. 2b. It is observed that as *Re* increases, *ΔP* decreases. Pressure drop attains its highest value in case of solid fins. Solid fins provide a larger blockage than perforated fins resulting wake leeward of each fin and thus cause increment in P_{out} and according to Eqs. (7) higher pressure loss occurs. However, ΔP decreases with increasing number of perforation and increment in perforation size. Due to smaller *ΔP,* perforated pin fin works more effectively. On the other hand it has been observed that change of pressure drop is affected by difference in fin materials.

- Effect of perforation and fin material characteristics on system performance (η)

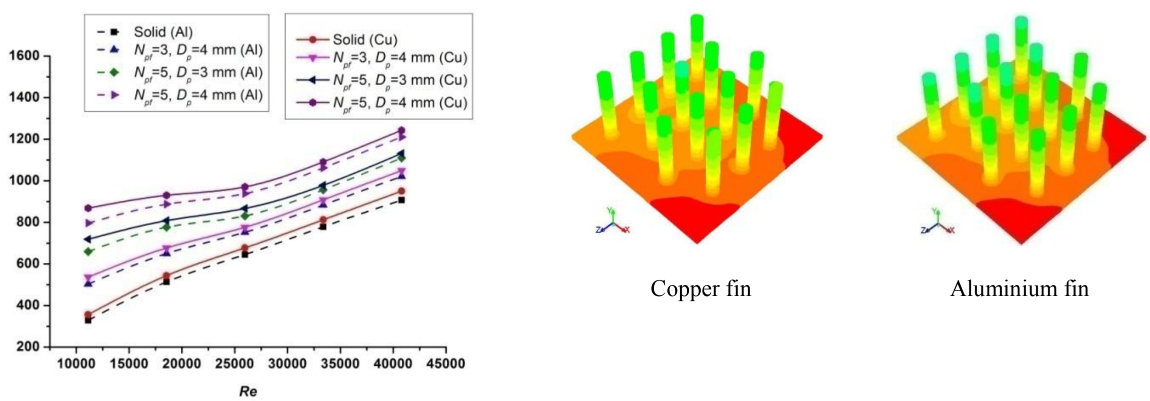


FIGURE 3. Effect of perforation on system performance (*η*) for Al and Cu fin with N_{pf} = 5, D_p = 3 mm

System performance of a fin is the relation between Nusselt number (*Nu*) and pressure drop (Δ*P*). It has been clearly observed in Fig. 3 that system performance increases with increment of Reynolds number. This is due to increasing thermal dissipation with increasing Reynolds number. Beside that *η* increases with increasing number of perforation as well as size of perforation. However, the rate of increment of system performance gradually decreases with the increase in Reynolds number. It has been already observed that with the increase in number and size of perforation *Nu* increases and Δ*P* decreases, thus according to Eq. (6) system performs better with the increment of number and size of perforations. Moreover copper fin performs better than aluminium fin due to its higher Nusselt number. Highest *η* is has been observed in copper fin with N_{pf} =5, D_p=4 mm. From above figure temperature distribution of Al and Cu fin with N_{pf} = 5, D_p = 3 mm has been observed where base plate temperature is around 330K for both fins and temperature of fin tip are around 311K and 315K for aluminium and copper fin respectively.

CONCLUSIONS

3D incompressible steady state forced convective heat transfer through staggered pin fin with increasing number and size of perforation for different fin elements has been investigated computationally to evaluate their heat transfer characteristics. Heat transfer performances, pressure drops and system performances of different perforated fins are compared with solid fins of various geometries. The conclusions of above study are

- For the cases of fins with different materials *Nu* increases with increasing number and size of perforations up to N_{pf} =5, D_p=3 mm, but when perforation size increases again, *Nu* decreases due to lower thermal dissipation. *Nu* increases with change of fin material from aluminium to copper due to increase in thermal conductivity.

- Pressure drop through heat sink decreases with increasing number and size of perforations. Perforated fins works better than solid fins. On the other hand variation in pressure drop is irrespective of fin elements.

- In case of system performance, η increases with increasing number and size of perforations. Moreover copper fin performs better than aluminium fin. Highest η is has been observed in copper fin with N_{pf} =5, D_p=4 mm.

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