Effect of Porous Medium on Thermo-Hydraulic Performance of Micro Channel Heat Sink

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Abstract

Micro channel heat sink has been widely used for cooling of high heat flux device in variety of electronic application. In the present work, Influence of porous medium on fluid flow and heat transfer characteristics for Reynolds number ranging from 100 to 400 has been investigated numerically. A Three Dimensional Micro Channel Heat Sink of dimensions 16.5mm*6mm*1mm with water as coolant subjected to 6.9W is considered for the study. The performance of micro channel heat sink is studied by varying the position and thickness of porous medium for different porosity. A Non Dimensional parameter, Figure of Merit is used to access the performance. The hydraulic and thermal performance of Micro channel heat sink are obtained by solving the Navier - Stokes equation and energy equation. Results reveal that position and thickness of porous medium has more influence on hydrodynamic and heat transfer characteristics of micro channel heat sink .The entire study is carried out by using the commercially available software FLUENT.

Keywords: Micro Channel, Heat Sink, Porosity, Figure of Merit

1. INTRODUCTION

With the advancement in technology, the size of electronic components have reduced drastically. The critical factor which accesses the life span of electronic component is operating temperature. Thermal Management has become very important in electronic

product design. It is a great challenge for thermal engineers to design suitable cooling system which can dissipate maximum heat flux through small surface area. Micro channel heat sink, render the advantage of compact size, minimum thermal resistance, minimum inventory and uniform temperature distribution in addition to this Micro channel heat sink equipped with metal foam has the advantage of greater dissipation area compared to conventional micro channel. This technique has attracted many researchers.

Material consisting of solid matrix with interconnected void is called porous media. Pease and Tucker man [1] were the first to propose micro channel heat sink by forcing coolant through small channels and concluded heat transfer co efficient is a strong function of channel width .Abel M. Siu-Ho et al. [2] experimentally investigated pressure drop and heat transfer in a single phase micro pin-fin heat sink for different Reynolds number subjected to constant heat flux. Pressure drop and Heat transfer characteristic have been explored numerically for heat sink with pin fin structures by Shafeie et al. [3] T.J. John et al. [4], and Turker Izci et al. [5], Weilin Qu et al.[6] experimentally and numerically studied pressure drop and heat transfer in a single phase rectangular micro channel heat sink using de ionized water for laminar flow subjected to constant heat flux. Paisarn Naphon et al. [7] experimentally investigated heat transfer and pressure drop in micro channel heat sink under constant heat flux for Reynolds number ranging from 200-1000.Hasan [8] numerically investigated micro pin-fin heat sinks using water and nano fluids and observed that there is enhancement of convective heat transfer in heat sinks using nano fluids in comparison with water. Porosity is defined as ratio of total volume voids to total porous media volume [9].According to Darcy law the fluid flow in porous media is proportional to pressure drop and viscosity of fluid [9] this was limited to low velocity. Further the effect of form drag on fluid flow was studied by dupuit [10].Fluid flows in porous media are categorized by Reynolds number .They are laminar flow, transition from Darcy regime to forchheimer regime and turbulent regime. Studies [11] show that heat transfer can be greatly enhanced using metal foams which act as porous media. Vafai et.al [12, 13] proposed an exact solution for flow inside a channel with porous media and studied the effect of wall and inertia on hydrodynamic and heat transfer characteristics they observed heat transfer characteristics are greatly influenced by metal foams. Amiri et.al [14] and Hsu [15] explored the effect of thermal dispersion in porous medium. Mohamad et.al [16] investigated enhancement of heat transfer characteristics of heat exchanger with metal foam subjected to constant wall temperature.Mahdi et.al [17] numerically investigated heat transfer and fluid flow through aluminum foams with circular heat source through rectangular channel. The effect of aluminium foam angle was studied result indicate that average nusselt number decreases with increase in pore density. Arun et.al [18] compared the performance of un scaled stacked multilayer channel with scaled multilayer channel, concluded than overall pressure drop can be greatly reduced by increasing stacked layer and pressure drop in multilayer porosity scaled channel is low compared to un scaled layer. Ameri [19] et.al numerically compared temperature and velocity

distribution of conventional fluid with nano fluids in rectangular channels for flow with and without porous media.

From the literature it is observed lot of experimental, analytical and numerical investigation has been carried out for flow inside micro channel in the past two decades, later the undeniable advantage of metal foam has attracted the researcher to employ porous medium in micro channel heat sink and study its influence on heat transfer and pressure drop. In the present work effect of thickness and position of porous medium for different porosity has been investigated using Finite Volume Method.

2. NUMERICAL SIMULATION
2.1   Problem Description
A Three Dimensional Micro Channel Heat sink of dimension 16.5mm*6mm*1mm considered for the study is as shown in figure 1.The dimension were selected from literature [8].Firstly for a given thickness the position of porous medium of porosity 14% was varied along the length of channel, Later the thickness of porous medium was increased along the axial direction of Micro Channel heat sink and finally study was carried out for different porosity. To investigate flow and heat transfer characteristics of heat sink water was used as coolant and aluminum heat sink with constant properties as shown in table I.
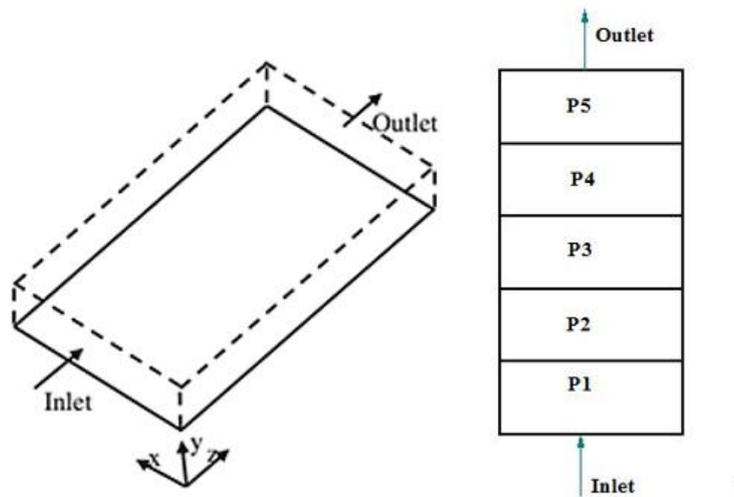

Figure 1. Three Dimensional Micro channel Heat sink with different position of porous medium

2.2 Assumptions

i.) Flow is steady and laminar ii.) Fluid is Newtonian and incompressible. iii.) No slip condition at walls. iv.)There is no viscous dissipation v.) Body forces are neglected.

2.3 Governing Equation

Based on the above assumption, the following equation is solved to compute velocity and temperature distribution

Continuity equation

$$\nabla . \rho V = 0 \qquad (1)$$

Momentum equation

$$(V.\nabla)\rho V = -\nabla P + \mu \nabla^2 V \qquad (2)$$

Energy equation

$$\rho C(V.\nabla T) = \nabla .(K \nabla T) \qquad (3)$$

Governing equation for heat sink is given by

$$\nabla .(\nabla T) = 0 \qquad (4)$$

Porosity (φ) is defined as ratio of the volume occupied by the fluid to the total volume of the material [18].The form coefficient and viscous coefficient were calculated for porosity =14%, using Brinkman- Hazen-Dupit-Darcy equation [18]. Constant Cf is taken as 0.55 (1/m) and Permeability (Kp) is fixed as 10-7   [19].Form coefficient is defined as

$$FC = \frac{Cf}{\sqrt{Kp}} \qquad (5)$$

$$\frac{1}{\alpha} = \frac{\varphi}{Kp} \qquad (6)$$

$$C2 = 2 \times FC \times \phi^2 \qquad (7)$$

Flow through porous media is modeled by considering an extra source term in momentum equation

$$S_i = -\left(U_i \frac{\mu}{\alpha} + \frac{1}{2}C2\rho UU_i\right) \qquad (8)$$

2.4 Boundary Condition

The fluid velocity was computed based on flow Reynolds number $\mathrm{Re} = \frac{\rho u d_h}{\mu}$ and imposed at inlet, u = v = 0 and w = win. The inlet fluid temperature at the entry was set to be Tin= 293K.The flow is assumed to be fully developed at the outlet of the channel and no slip condition is defined at the solid boundaries. Uniform heat flux is imposed on the base surface of the solid substrate and an adiabatic condition is assumed for the upper wall, right wall and the left wall. Thus, $\frac{\partial T}{\partial x} = 0$ and $\frac{\partial T}{\partial y} = 0$. The

inertial resistance and viscous resistance for different porosity are calculated using equations discussed above and tabulated in table II.

Table I: Properties of Coolant and Heat Sink

	ρ (Kg/m^3)	c_p (J/Kg-K)	K (W/m-K)	μ (Kg/m-s)
Fluid (water)	981.3	4189	0.643	0.000598
Heat Sink	2719	871	273	---------

Table II: Porosity Parameters

Porosity	Viscous Resistance (1/m^2)	Inertial Resistance (1/m)
14%	14.54×10^5	73.5
18%	18.17×10^5	114.9
22%	22.71×10^5	179.5
28%	28.3×10^5	280.5

2.5   Solution Methodology

The governing continuity, momentum and energy equations were solved using the Finite Volume Method. Convective terms were discretized using second order upwind scheme and a simple algorithm was used for pressure-velocity coupling to obtain the pressure field. Segregated solver was used to solve the conservation scheme. The convergence criteria for continuity, momentum and energy equation was set to 10^{-6}. The entire work was carried out using FLUENT software.

A Mesh dependent study was carried out to find an appropriate mesh which gives accurate solution. Table III shows the variation of outlet temperature for three different element sizes. The difference in outlet temperature for 162110 and 195640 elements compared with 122100 elements were 0.26 % and 0.31% respectively. Since the difference in percentage change were very negligible. It was found that a structured hexahedral grid with 122100 elements was sufficient for the study.

Table III: Mesh Independent Study

Number of elements	Outlet temperature (K)
122100	303.9
162110	303.1
195640	302.93

3   RESULTS AND DISCUSSION

3.1   Validation

The present work was validated for pressure drop and thermal resistance with Arun. K. Karunanithi [18] in which the model presented consist of mini channel. Flow rate was defined at channel inlet at 293K and bottom of mini channel was maintained at 80W with other walls being insulated. Figure 2 shows the variation of pressure drop for single layer unscaled mini channel for different flow rates. The result clearly shows pressure drop increases with increase in flow rate and are in good agreement with available literature [18] .With increase in flow rate the force exerted by fluid increases due to viscous action of fluid and porous medium, which strongly affects the pressure drop. Hence pressure drop increases with flow rates. Figure 3 shows the variation of thermal resistance with flow rate. Maximum thermal resistance decreases with flow rate .The Thermal resistance calculated from present work slightly under predicts literature work this may be due to element size.

In the present work the influence of thermal resistance and pumping power is employed to achieve optimum design of micro channel heat sink. The thermal resistance and pumping power is calculated using (9) and (10)

$$R_{th} = \frac{T_{s,\max} - T_{f,in}}{q} \qquad (9)$$

$$PP = \frac{m \times \Delta P}{\rho} \qquad (10)$$

The thermal resistance and pumping power obtained are nondimensionalzed using thermal resistance and pumping power with porosity as shown in (11) and (12).

$$R_{th,non} = \frac{R_{th,porous}}{R_{th,withoutporous}} \qquad (11)$$

$$PP_{non} = \frac{PP_{porous}}{PP_{withoutporous}} \qquad (12)$$

Figure of Merit (FOM) is calculated by using Weighted Average Method. FOM is calculated using the relation (13).The value of n1 and n2 is varied to determine FOM as per objective of the design. Equal weightage is defined for n1 and n2,n1=n2=0.5.Since FOM is inversely proportional to pumping power and thermal resistance, higher FOM indicates better performance of Micro channel heat sink.

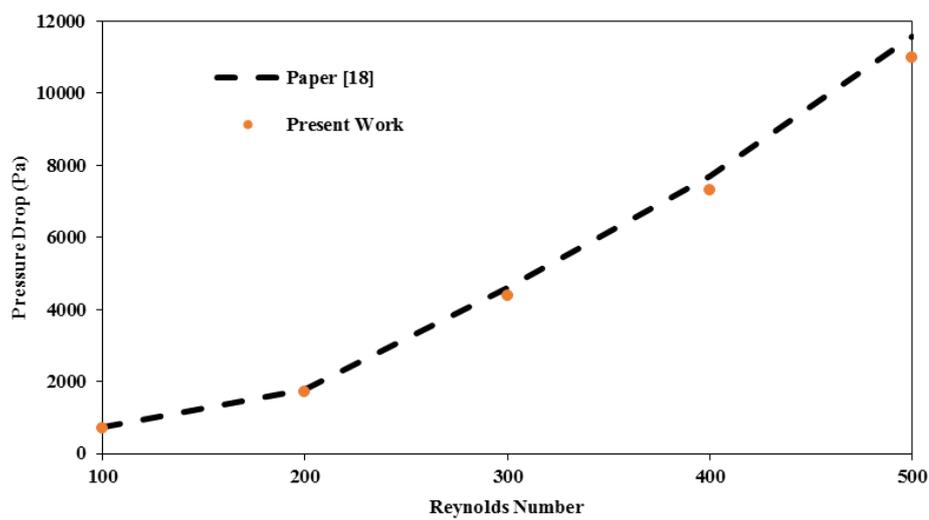$$FOM = \frac{1}{(n_1 \times R_{th,non}) \times (n_2 \times pp_{non})} \qquad (13)$$

Where n1+n2=1

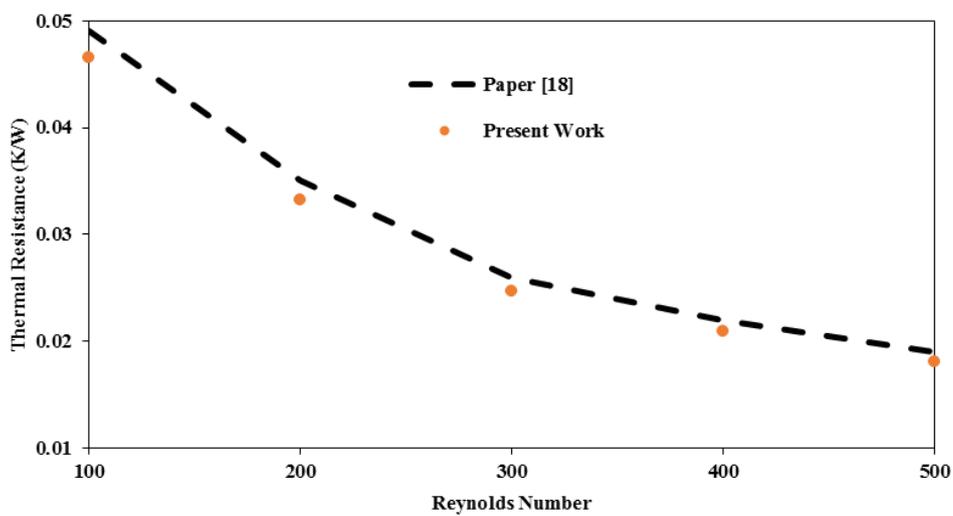**Fig 2:** Comparsion of pressure drop obtained from present work with Ref [18]

Fig 3: Comparsion of Thermal resistance obtained from present work with Ref [18]

In the present work three different cases were studied .In case 1, location of porous medium is varied , in case 2, thickness of porous medium is changed along the length of micro channel heat sink and finally in case 3 the effect of porosity is studied, to investigate the performance of micro channel heat sink.

3.2   Effect of position

In case 1 total length of micro channel is divided into five division of equal length namely P1,P2, P3,P4 and P5.initially porous medium is placed at p3 i.e., at the centre of micro channel, later porous medium is inserted on either side (P2,P3 and P4) finally the entire micro channel is filled with porous medium.(P1,P2,P3,P4 and P5).

Fig. 4 shows the variation of FOM with Reynolds number for different location of porous medium discussed above. FOM decreases with increase in Reynolds number for different location discussed in case 1, the reason behind this is at low Reynolds number, decrease in thermal resistance is more dominant compared to change in pressure drop, whereas at high Reynolds number change in pressure drop dominates FOM, hence FOM decreases with increase in Reynolds number. FOM is better when porous medium is placed at P3, compared to other location. When porous medium is placed at P3 and P2, P3, P4, fluid travels inside micro channel heat sink through non porous medium and porous medium, heat transfer increases due to forced convection and turbulence with penalty in pressure drop. When Fluid travels from higher resistance region i.e., porous region to nonporous region the flow velocity increases which improves heat transfer by forced convection due to acceleration of fluid and generates turbulence resulting in momentum transfer between adjacent fluid layers which further enhances heat transfer. The presence of porous medium offers viscous resistance to fluid flow, resulting in increase in pressure drop. When entire Micro channel is filled with porous medium(P1,P2,P3,P4 and P5) the resistance offered by porous medium is very high resulting in increase in pressure drop without much rise in heat transfer, the main reason is contribution of turbulence is very less when entire micro channel is packed with porous medium. Hence FOM is less when entire micro channel is packed with porous medium.
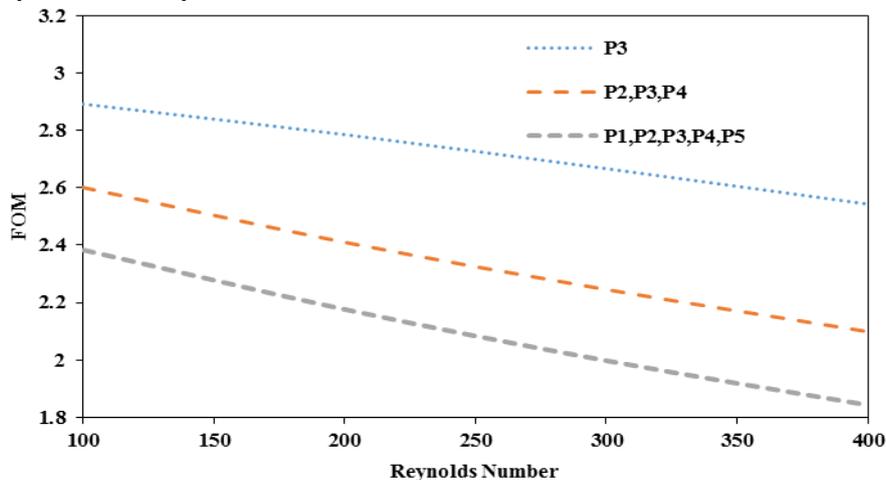

Fig 4: FOM vs Reynolds number for different position of porous medium

3.3   Effect of thickness

In case 2 the thickness of porous medium is increased along the length of Micro channel heat sink in equal proportion from entry to exit and its effect on FOM is studied. FOM is maximum for thickness=3.3mm and decreases with increase in thickness of porous medium as shown in figure 5. When thickness of porous medium increases along the flow direction, the viscous resistance offered by porous medium increases with rise in pressure drop .On the other hand the average flow velocity decreases leading to drop in turbulent intensity and convective heat transfer , resulting in rise in thermal resistance. The combined effect of rise in pressure drop and thermal resistance decreases the performance of heat sink with increase in thickness of porous medium, hence thickness of porous medium has greater influence on FOM.

3.4   Effect of porosity

In case 3 performance of micro channel heat sink is investigated for different porosity, considering the porous medium to be placed at centre (P3) .Fig 6 and Fig 7 shows the variation Pressure drop and heat transfer coefficient with Reynolds number for different porosity when porous medium is placed at centre (P3) of micro channel heat sink. The viscous resistance and inertia resistance for different porosity are calculated using relation (6) and (7) and are tabulated in table II.

The result indicates, there is a rise in pressure drop with increase in fluid velocity. At low flow velocity, boundary layer is formed due to viscous effect of fluid, the wall effect and shear stress are responsible for pressure drop. Whereas at larger velocity the end wall effect becomes negligible, the force exerted by the fluid due to viscosity increases, leading to boundary layer separation resulting in rise in pressure drop. Fig 7 illustrates variation of Heat transfer coefficient $h = \left(\dfrac{Q}{A(T_{sur,avg} - T_{in})} \right)$ with Reynolds number for different porosity. For Micro channel heat sink equipped with different porosity, HTC increases with Reynolds number. As flow velocity increases, the thermal boundary layer thickness decreases thereby dissipating a large amount of heat from the base surface to the adjacent fluid leading to increase in heat transfer coefficient. The surface area for heat dissipation increases with porosity, enhancing flow disturbance, resulting in heat transfer enhancement with increase in porosity as shown in fig 7.

The FOM is used to access the performance of microchannel heat sink for different porosity by considering the combined effect of pressure drop and heat transfer. Fig 8 clearly shows, FOM decreases with increase in porosity. The reason is that porosity is more sensitive to flow resistance compared to enhancement of heat transfer.
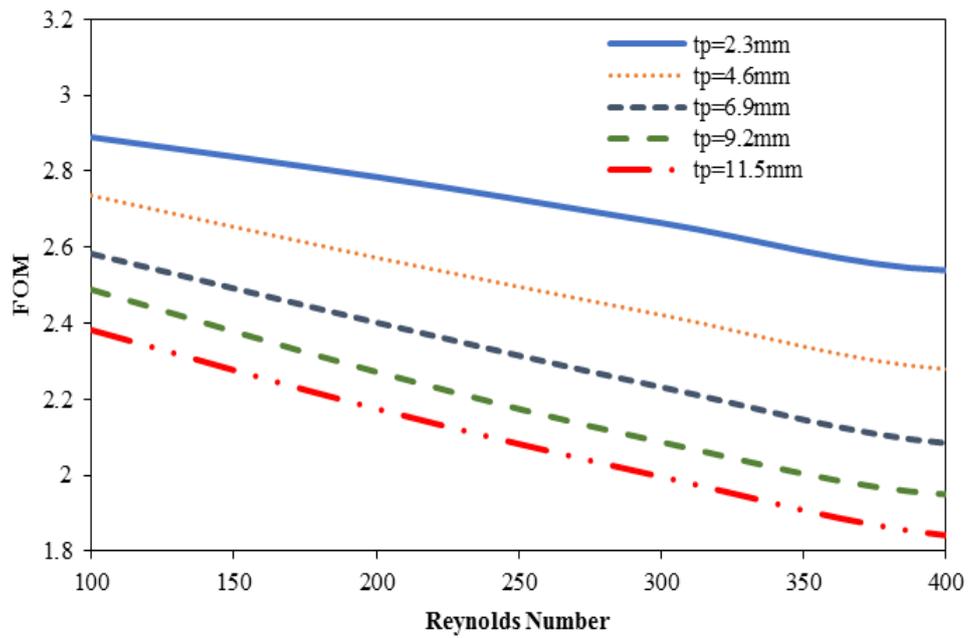
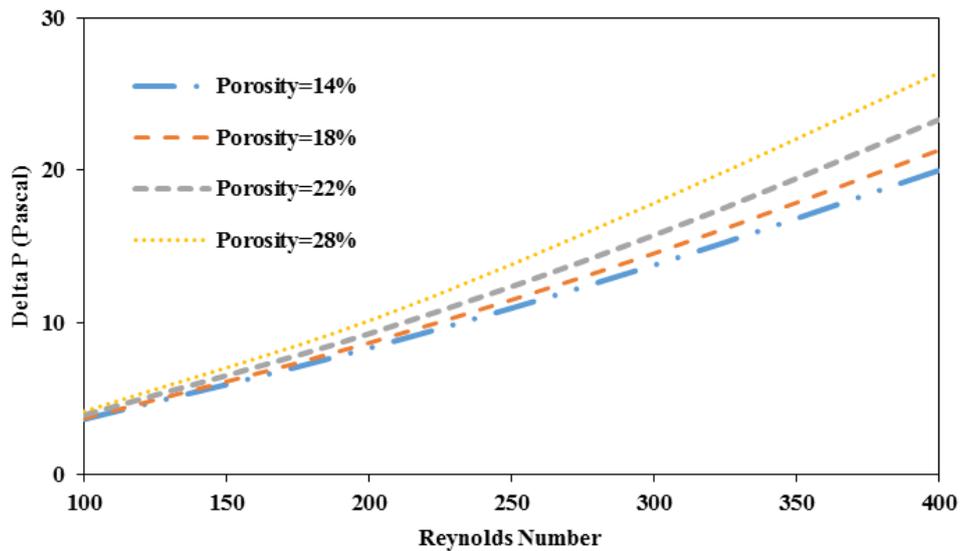**Fig 5:** FOM vs Reynolds number for various thickness of porous medium

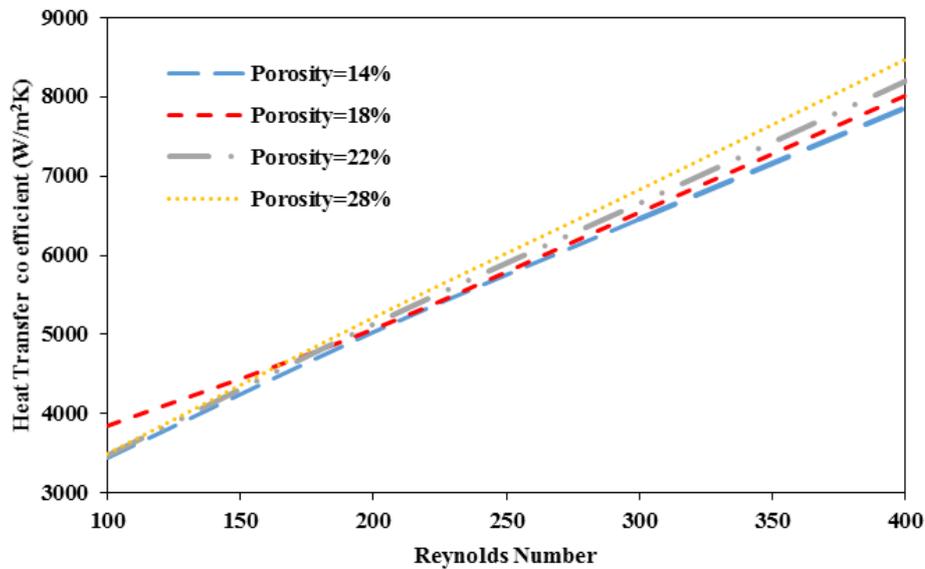**Fig 6:** Variation of pressure drop with Reynolds number for different porosity

Fig 7: Variation of heat transfer coefficient with Reynolds number different porosity
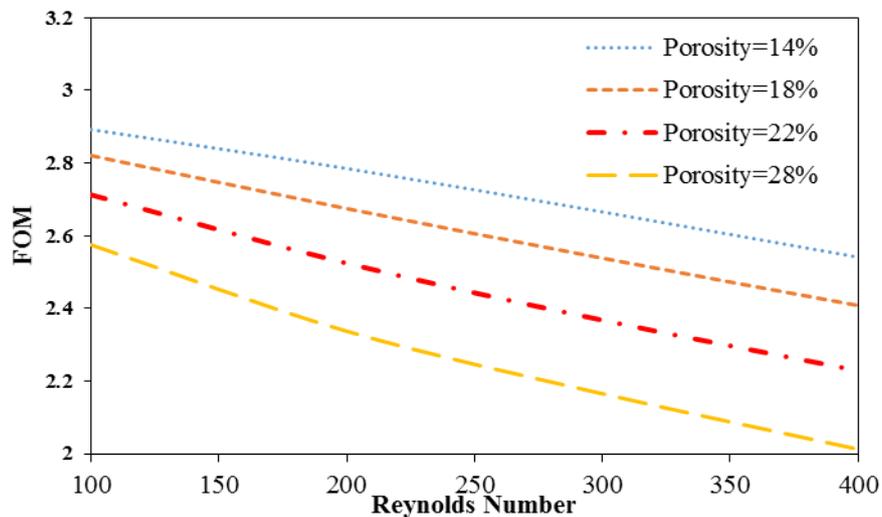

Fig 8: Variation of FOM with Reynolds Number for different porosity

CONCLUSION

The performance of micro channel heat sink with porous medium are studied in the present work. The performance of heat sink is determined using FOM which considers the combined effect of both pressure drop across heat sink and thermal resistance. The effect of variation in position and thickness of porous medium on FOM is studied.

Based on the study the following conclusion are drawn

A non-dimensional parameter, FOM was used to access the performance of micro channel heat sink

The performance of micro channel heat sink is superior when porous medium is placed at center and FOM increases by 12% compared to heat sink equipped with complete porous medium.

The overall performance of micro channel heat sink decreases with increase in thickness of porous medium. The Porosity of the metal foam is more sensitive to flow resistance compared to heat transfer enhancement, Microchannel heat sink performs better at low porosity.

REFERENCES

[1] Tuckerman,D.B., and Pease.,1981, RFW,"High-Performance Heat Sinking for VLSI," IEEE Electronic Devices Letters., EDL-Vol. 2, pp. 126-129.

[2] **[1]**   Ning, X., and Lovell, M. R., 2002, "On the Sliding Friction Characteristics of Unidirectional Continuous FRP Composites," ASME J. Tribol., 124(1), pp. 5-13.

[3] Abel,M. Siu-Ho., Weilin Qu., Frank Pfefferkorn.,2006, "Pressure drop and heat transfer in a single phase micro pin-fin heat sink." Proceedings of IMECE,ASME International Mechanical Engineering Congress and Exposition.,November 5-10, Chicago, Illinois, USA

[4] Haleh Shafeie, Omid Abouali, Khosrow Jafarpur, Goodarz Ahmadi, 2013,"Numerical study of heat transfer performance of single-phase heat sinks with micro pin-fin structures.," Applied Thermal Engineering, vol. 58,2013

[5] John,T.J., Mathew,B., and Hegab,H., 2010, "Parametric Study on the Combined Thermal and Hydraulic Performance of Single Phase Micro Pin-Fin Heat Sinks Part I: Square and Circle Geometries," International Journal of Thermal Science. vol. 49, pp. 2177–2190.

[6] Türker İzcia, Mustafa Koza & Ali Koşara.,2015, "The Effect of Micro Pin-Fin Shape on Thermal and Hydraulic Performance of Micro Pin-Fin Heat Sinks." Heat Transfer Engineering, vol. 36, Issue 17.

[7] Weilin Qu, Issam Mudawar., 2002, "Experimental and numerical study of pressure drop and heat transfer in a single-phase micro-channel heat sink, International Journal of Heat and Mass Transfer, vol. 45, pp. 2549–2565.

[8] Paisarn Naphon, Osod Khonseur.,2009, "Study on the convective heat transfer and pressure drop in the micro-channel heat sink," International Communications in Heat and Mass Transfer., vol. 36, pp. 39-44.

[9] Mushtaq ismael hasan, 2014, "Investigation of flow and heat transfer characteristics in micro pin-fin heat sink with nano fluid," Applied Thermal Engineering., vol. 63,pp. 598-607, Issue 2.

[10] Nield. D, Bejan. A.,2006, Convection in porous media. 3rd ed. New York: Springer .

[11] Mohamad, A., 2003. "Heat transfer enhancements in heat exchangers fitted with porous media part i: constant wall temperature". International Journal of Thermal Sciences., Vol. 42(4), pp. 385 – 395.

[12] Hsu, C., and Cheng, P., 1990, "Thermal dispersion in a porous medium". International Journal of Heat and Mass Transfer., Vol. 33(8), pp. 1587 – 1597.

[13] Vafai, K., and Kim, S., 1989, "Forced convection in a channel filled with a porous medium: an exact solution". Journal of heat transfer., Vol. 111(4), pp. 1103–1106.

[14] Vafai, K., and Tien, C., 1981. "Boundary and inertia effects on flow and heat transfer in porous media". International Journal of Heat and Mass Transfer., vol. 24(2),pp. 195 – 203.

[15] Amiri, A., and Vafai, K., 1994. "Analysis of dispersion effects and non-thermal equilibrium, non-darcian, variable porosity incompressible flow through porous media". International Journal of Heat and Mass Transfer., vol. 37(6), pp. 939 – 954.

[16] Hsu, C., and Cheng, P., 1990. "Thermal dispersion in a porous medium". International Journal of Heat and Mass Transfer., vol. 33(8), pp. 1587 – 1597.

[17] Mohamad, A., 2003. "Heat transfer enhancements in heat exchangers fitted with porous media part i: constant wall temperature". International Journal of Thermal Sciences., 42(4), pp. 385 – 395.

[18] Arun, K. Karunanithi., Fatemeh Hassanipour., 2014, "Heat Sink With Stacked Multi-Layer Porous Media," Proceedings of the 5th International Conference on Porous Media and its Applications in Science and Engineering ICPM5 june 22-27, Kona, Hawaii, USA

[19] Mahdi, R.A., Mohammed, H.A., Munisamy, K.M., Saeid, N.H., 2014, "Influence of various geometrical shapes on mixed convection through an open-cell aluminium foam filled with nano fluid.", J Comput Theor Nanosci, vol. 11:pp. 1275–89.

[20] Amrei Hashemi, Dehkordi, A.M., 2014, "Modeling and CFD simulation of a mixed-convection flow of regular fluids and nanofluids in vertical porous and regular channels", Heat Transf—Asian Res., vol. 43:pp. 243–269.

[21] Raed Abed Mahdi, H.A. Mohammed, K.M. Munisamy , N.H. Saeid,2015, "Review of convection heat transfer and fluid flow in porous media with nanofluid," Renewable and Sustainable Energy Reviews., vol. 41,pp.715–734

Notations

A - Cross sectional area (m^2)	**Greek Symbols**
C - Specific heat (J/Kg-K)	ρ - Density (Kg/m^3)
Cf-constant	Δ – Delta
C2-Inertial factor	μ - Dynamic Viscosity (Kg/m-s)
D-Diameter (m)	α - 1/viscous resistance (1/m^2)
FC-Form Coefficient	φ- Porosity
h - Heat Transfer co efficient (W/m-K)	Subscripts:
R-Resistance	avg – Average
K - Thermal conductivity (W/m^2-K)	F-Fluid
Kp-Permeability	h – Hydraulic
m-Mass flow rate (Kg/s)	in – Inlet
p - Constant Pressure	max-maximum
pp – Pumping power	out – Outlet
Q - Heat dissipated (W)	P - Pressure (Pa)
Re - Reynolds Number	Sur – Surface
u - Velocity in x direction (m/s)	th-thermal
v - Velocity in y direction (m/s)	P1,P2,P3,P4 and P5 Position of porous medium along micro channel
w - Velocity in z direction (m/s)	ρ - Density (Kg/m^3)
tp-Thickness of porous medium	