CFD Analysis in a Liquid-Cooled Carbon Nanotube Based Micro-channel Heatsink for Electronic Cooling

M.A.I. Rashid, M.F Ismail, and M. Mahbub*

***Abstract* — In this paper, the 2D and 3D CFD simulations have been carried out in liquid-cooled carbon nano tube based (CNT) micro-fin cooling architectures. The effect of heat transfer due to fluid velocity, pressure difference in the micro-fin assembly and thermal expansion due to temperature rise in the cooling assembly have been analyzed in this paper. The analysis indicates that fluid speed is the key factor of heat transfer and 2D carbon nanotube fin array shows greater thermal performance than that of 1D carbon nanotube fin array. The pressure drop between inlet and outlet of the cooling device is an important cause to limit the fluid speed.**

Index Terms— CNT; micro-fin; CFD; cooling assembly; thermal expansion.

I. Introduction

Carbon nanotubes (CNTs) were discovered in 1991. They are allotropes of carbon with a nanostructure that have a length-to-diameter ratio greater than 1000000. Figure 1 shows the structure of single-walled carbon nanotubes (SWNTs). A CNT is formed when the two-dimensional sheet of graphene is rolled into a seamless cylinder. CNTs can range from ~1 nm to ~100 nm in diameter and have lengths in the micrometer range. Based on the chemical arrangement of carbon atoms, a discrete number of unique CNTs can be formed. CNTs are made from cylindrical carbon molecules which are very special in thermal, electrical and mechanical properties. A thermal conductivity up to 6600W/m·K has been reported [1]. Copper, silver and gold, which are some of the best known thermally conductive materials, have thermal conductivities of 400 W/m·K, 430 W/m·K and 320 W/m·K at room temperature respectively. As a new material, CNTs are attracting more and more attention, and they are potentially very useful in nanotechnology, electronics, optics and aeronautics. CNTs can be manufactured by Chemical Vapor Deposition (CVD) at suitable temperature. During the CVD process, process gas (such as ammonia, nitrogen, hydrogen, etc.) and carbon-containing gas (such as acetylene, ethylene, ethanol, methane, etc.) are demanded as reactors, and catalyst particles such as nickel, cobalt and iron are also needed. Therefore, to promote a good thermal contact on the interfaces between the multi-walled CNTs and their growth substrate, adhesion layers consisting titanium, molybdenum or chromium were often deposited onto the substrates before fabrication [2-4]. Other studies showed that the multi-walled CNT free ends' interface had significant higher resistance compared to that at the multi-walled CNT growth substrate interface; and this problem could be solved by using a thin layer of indium to weld the multi-walled CNT ends to opposing substrate. CNT grows at high temperatures of about 750°C. In order to prevent the chip from being damaged, the nanotubes could be grown on silicon substrates and there after transferred onto the chip. The bond between the CNTs and the chip is crucial.

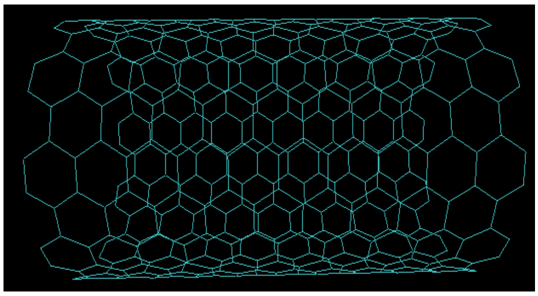

Fig.1. Single-walled carbon nanotubes

II. Micro-channel Cooler

Micro-channel cooler is a very promising approach to meet the requirements of microelectronics package cooling. A lot of investigations about micro-channels have been undertaken in the past years. A silicon micro-channel can remove 790W/cm^2 heat with a temperature rise of 71 degrees between the substrate and the coolant. The width and height of the silicon channel are 50 μm and 302 μm separately. However, as the trends in the electronics industry moves towards higher packaging density, the high-pressure drop problem limits the performance of traditional silicon heat sink. Replacing the silicon fins with nanotube fins to enhance the thermal exchange rate between cooling liquid and substrate is one way to overcome this problem. Growing aligned nanotubes on the whole substrate is another one. A typical micro-channel cooler includes cover on the top; silicon substrate at bottom with the micro-channels is showed in Figure 2. Channels are etched and covered by plexiglass on the top and ultimately formed a complete structure [2]. The basic principle of micro-channel heat is that bottom is in touch with the heat and fluid flows through the entrance to the export to take away heat. In practice, with increasing heat, when the micro-cooler maximum temperature exceeds the fluid's temperature, convection heat is generated between wall and fluid until the heat balance is stabilized and micro-cooler works into the stable working condition. Replacing the silicon fins with nanotube fins or growing

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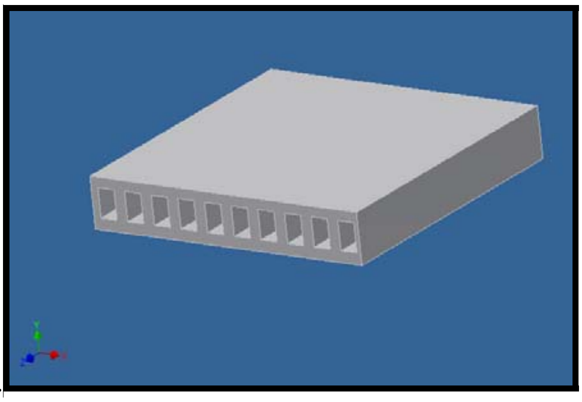

Fig.2. Micro-channel cooler

III. CNT Based Micro-channel

CNT as fin material was introduced by Liu and his research group in 2004. By combination of the high thermal conductivity material with the high heat transfer efficiency structure, it is a tempting and promising scheme for thermal issues in electronics. In a bare silicon chip was chosen as the substrate and. After CVD synthesis, CNTs array [5-7] was grown from the catalyst as cooling fins (Fig. 3). Finally, a lid was bonded to seal the CNTs and form the microchannels. Figure 3 shows the flow chart. Figure 4 shows the SEM pictures of the one-dimensional and two-dimensional CNTs arrays respectively.

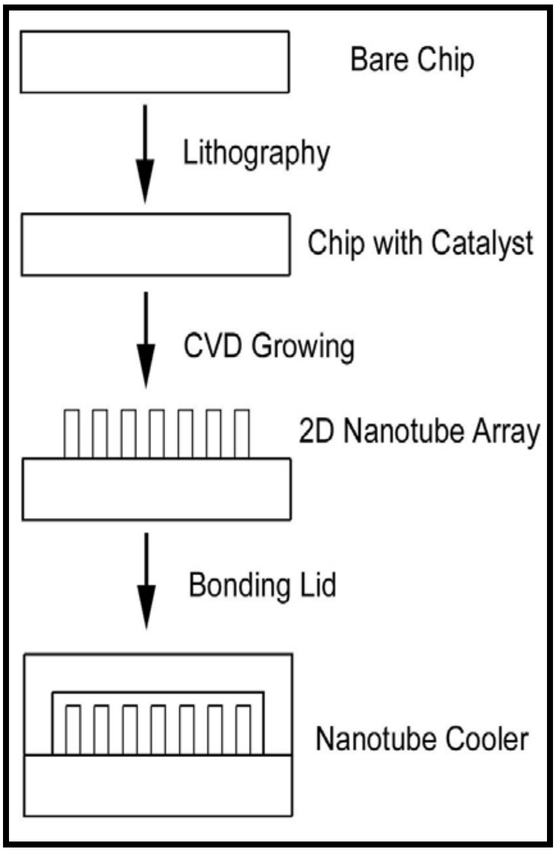

Fig.3. Process to manufacture CNT based micro-cooler

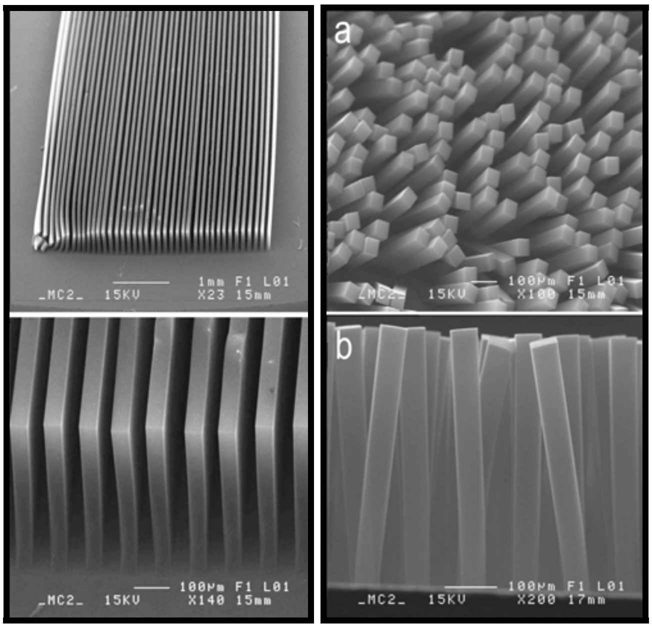

Fig. 4. SEM picture of CNT with one and two dimensional array [5].

IV. CFD Simulation Model

A. *Theoretical Analysis*

A coolant flows through a micro channel heat sink described before takes away heat from heat component attached below (constant heat flux). The top face is made of insulated material (such as glass) and the bottom material is silicon. The heat transfer contains two parts: conduction in the solid and convection between the solid and coolants. By continuities of temperature and heat flux, the solid region and fluid region are coupled. Some simplifying assumptions are considered as follows:

(1) Laminar flow;
(2) Incompressible flow;
(3) Hydro dynamically and thermally fully developed;
(4) No radiation of the wall;
(5) Negligible convection of air out of the cooling assembly;
(6) Constant solid and fluid properties.

B. *Governing Equations and Mathematical Model*

In this study (Fig.5) two and three dimensional works were investigated. For this cases the energy conservation equation, which can theoretically predict the value of temperature rise between the inlet and outlet, was used for simulation validation in this work. Following the adiabatic boundary conditions in this simulation, the energy supplied by the chip should be equal to the heat removed by the coolant. T_{in} is inlet temperature of the channel (20^0 C). A typical parallel plate heat sink is considered for the micro-fin. The CNT array was grown on a 10 mm X 10 mm area. The thickness of the underneath silicon substrate (base height,BH) is 50 µm. The channel is long enough so that fully developed flow can be attained. For 1D fin array arrangement from the following figure L=W=10 mm. Height H= 0.65 mm. Fin pitch (S) and fin thickness (t) are equal to 0.5 mm. (Fig. 5-7)

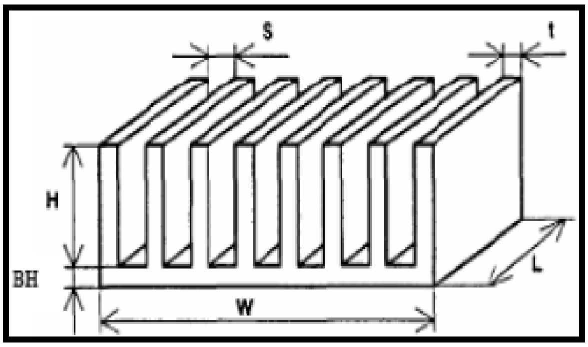

Fig. 5. Parallel plate heat sink showing all the dimensions

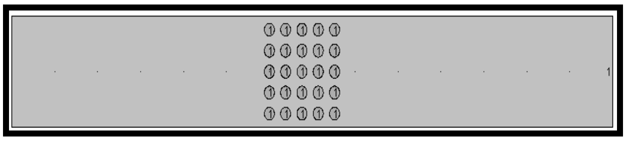

Fig. 6. 2D computational model for circular pin fin heat sink

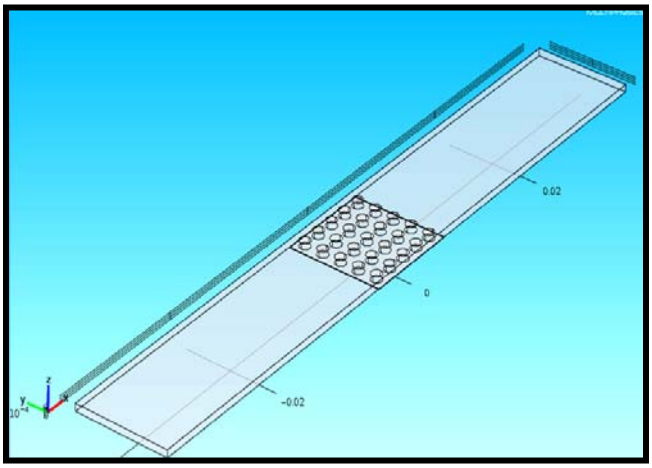

Fig. 7. 3D computational model for circular pin-fin heat sink

If L_w is width of cooler model then for 2D case

$$\frac{\int_0^{L_W} \rho_f c_{p,f} V(y)[T_{out}(y) - T_{in}]dy}{L_W} = W_{chip} \tag{1}$$

For the three dimensional analyses the mathematical model was-

Continuity equation-

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{2}$$

Momentum equation

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \nu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) \tag{3}$$

$$u\frac{\partial \upsilon}{\partial x} + v\frac{\partial \upsilon}{\partial y} + w\frac{\partial \upsilon}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial y} + \nu\left(\frac{\partial^2 \upsilon}{\partial x^2} + \frac{\partial^2 \upsilon}{\partial y^2} + \frac{\partial^2 \upsilon}{\partial z^2}\right) \tag{4}$$

$$u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial z} + \nu\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right) \tag{5}$$

Energy equation:

$$u\frac{\partial T}{\partial x} + \upsilon\frac{\partial T}{\partial y} + w\frac{\partial T}{\partial z} = \alpha\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) \tag{6}$$

V. Mesh Generation

Conjugate heat transfer module is used to treat the solid and fluid as a unitary computational domain, and to solve the above governing equations simultaneously. The mesh in every channel should be fine enough (Fig.8-9), since the velocity gradient is very high in z-direction (400 W/m.K) and low in x and y direction (40 W/m.K).

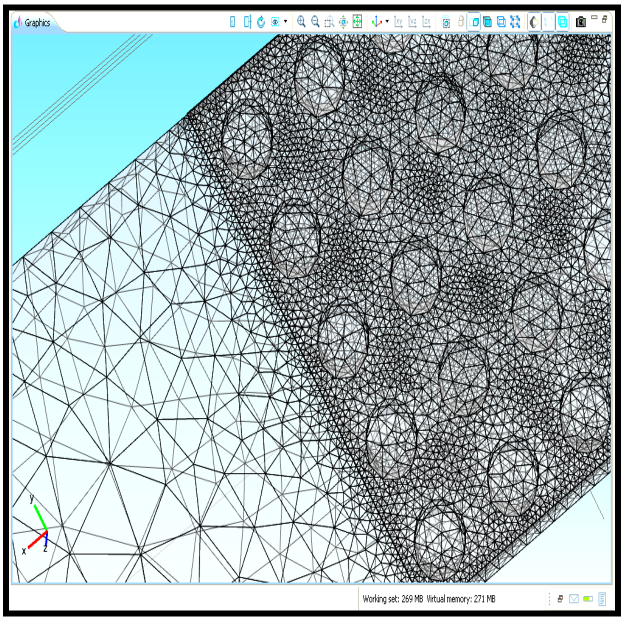

Fig. 8. 3D Mesh generation at fin assembly

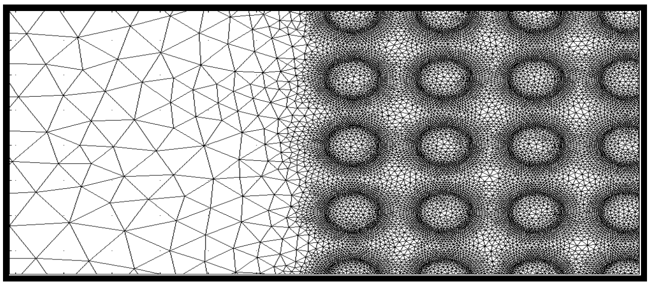

Fig. 9. 2D Mesh generation at fin assembly

VI. Simulation Results And Analysis

Here three dimensional models are simulated for different fluid and fluid velocity, different types of fin geometry such as-rectangular fin with one dimensional array; rectangular fin with two dimensional array, circular pin fin or circular fin with two dimensional array, rectangular fin of two dimensional array with 45^0 orientation with the flow. The inlet temperature was set 20^0 C and the heat flux was 15 W/cm^2 (Fig.10-14).

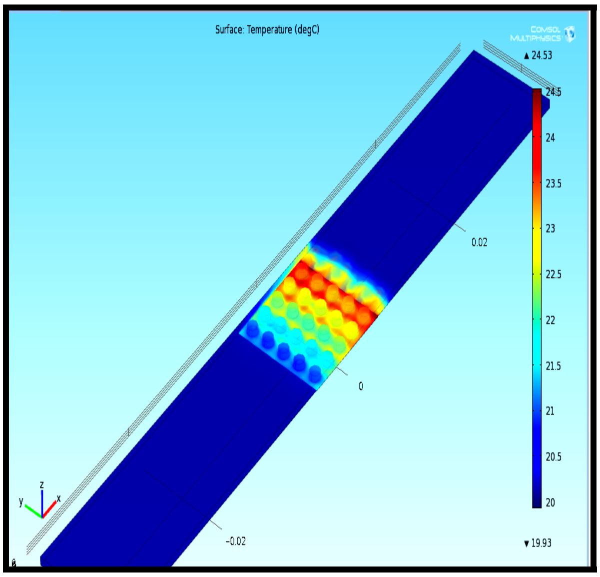

Fig. 10. 3D Temperature distribution for 2D circular fin array

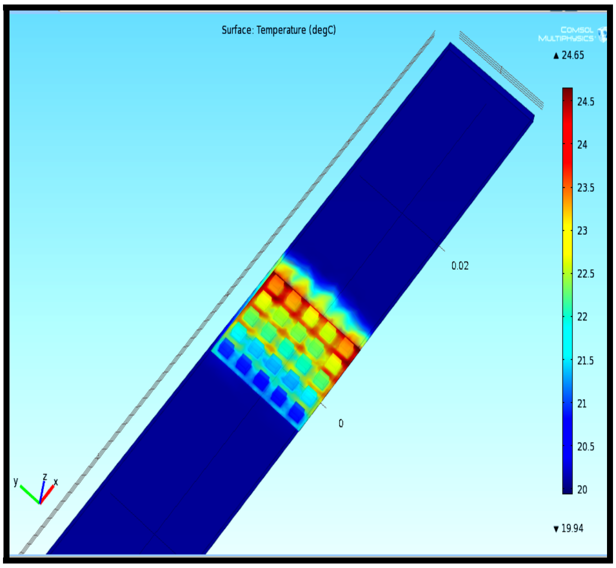

Fig.11. 3D Temperature distribution for 2D rectangular fin array

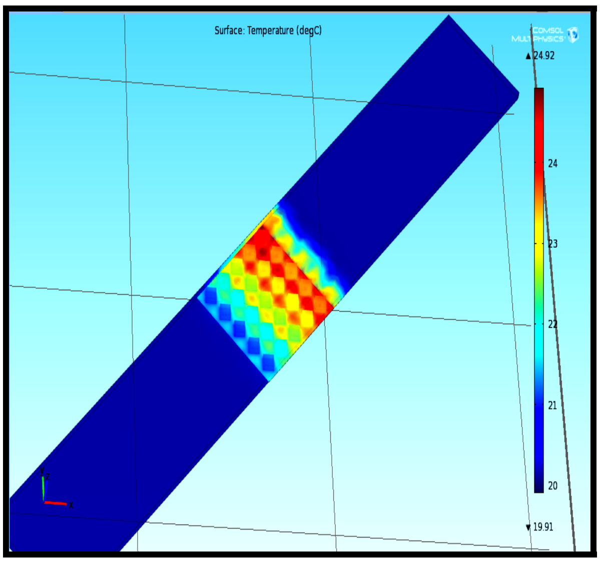

Fig.12. 3D Temperature distribution for 2D rectangular fin array with 45 degree orientation with the flow

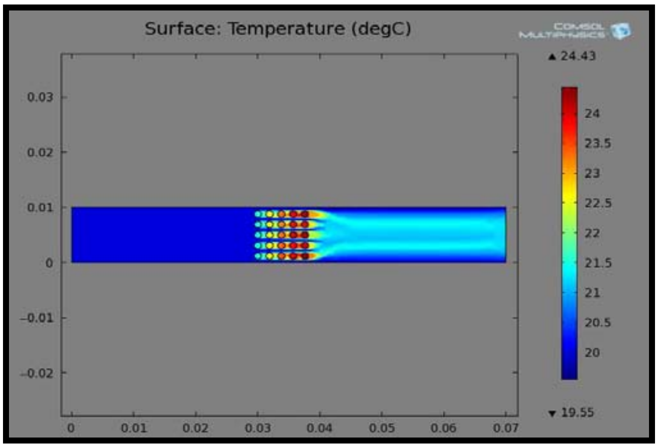

Fig.13. 2D Temperature distribution for 2D circular fin array

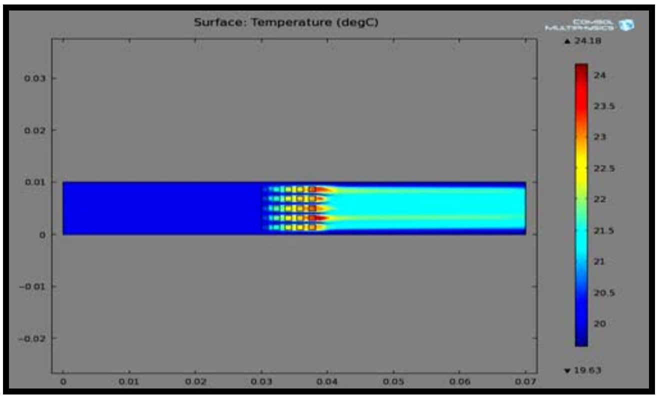

Fig.14. 2D Temperature distribution for 2D rectangular fin array

A. Effect of Fluid Velocity

The simulation result shows that maximum fin temperature decreases with increase of fluid velocity. Here four velocities are taken-0.1 m/s, 0.25 m/s, 0.5 m/s and 0.75 m/s (Fig.15).

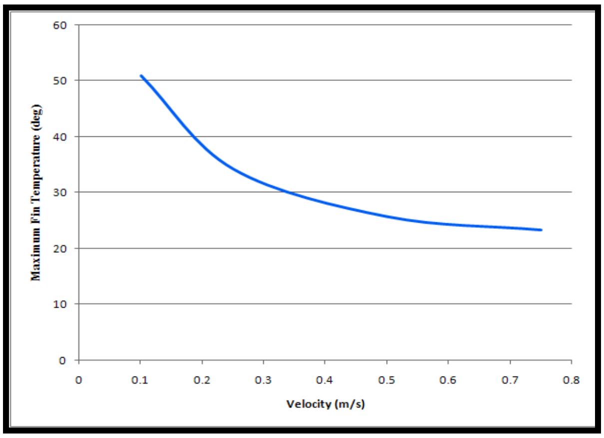

Fig.15. Maximum fin temperature Vs. Velocity graph.

B. Effects of Micro-Fin Structure

Four types of geometry are used to simulate the above model- 1D pattern array, 2D rectangular pattern array, 2D rectangular pattern with 45^0 orientations, 2D circular fin array. The simulation results showed that 2D fin array is the efficient one among these fin geometries (Fig.16 and Fig.17).

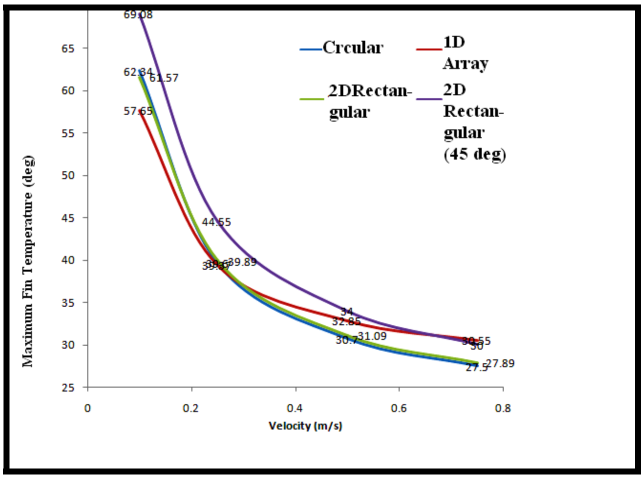

Fig.16. Fin temperature Vs. Velocity for Different fin geometry for glycol

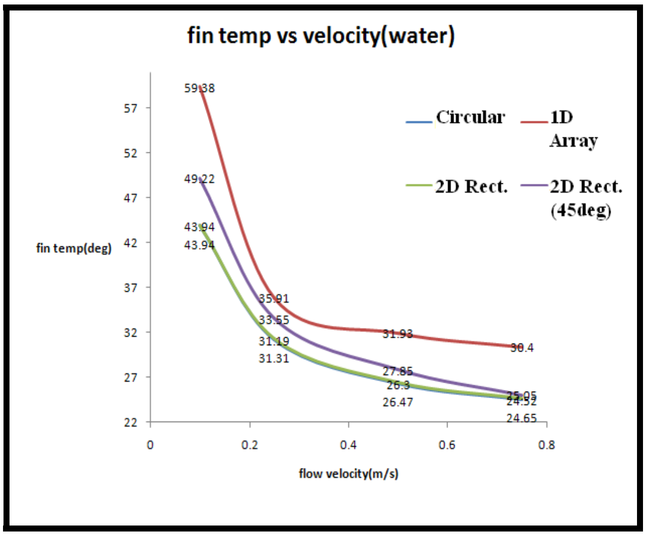

Fig.17. Fin temperature vs. Velocity for different fin geometry for water

C. Effects of Fluid

The heat transfer capability is dependent on the properties of working fluid, the most frequently used coolant in the micro channel heat sink is water. Better results may be possible with other fluids. So, one of the methods for changing heat transfer is to use the different working fluids. Here the model is simulated for two fluids-water and ethylene glycol (Fig.18).

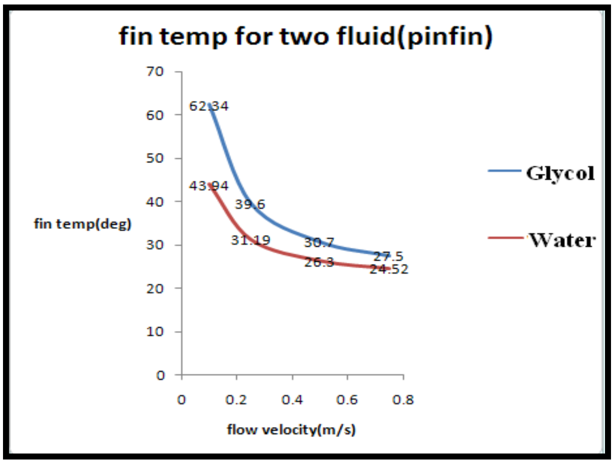

Fig.18. Comparison graph for the effectiveness of different fluids.

D. Heat extraction for Different Fin Structure

From the analysis it is investigated that for a fixed source (chip) temperature circular pin fin array can extract more heat from source than 2d rectangular array (Fig.19).

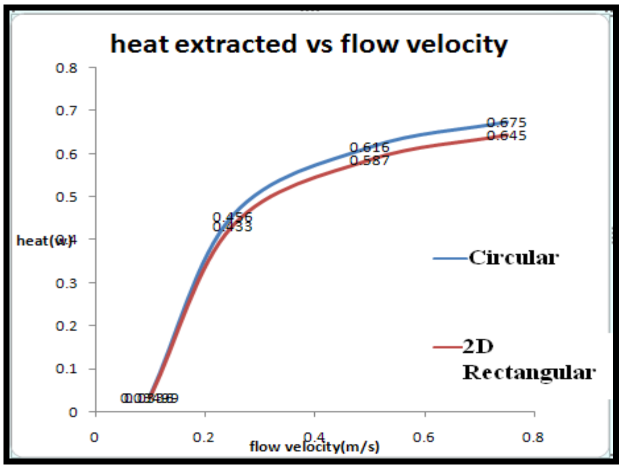

Fig.19. Heat extraction graph for rectangular and circular fin array

VII. Thermal Stress Analysis

Adhesives are widely used to fabricate CNT on the silicon substrate. Bonded structures are often lighter in weight, lower in cost, and easier to assemble than those mechanical methods. The mismatch in thermal expansion co-efficient (CTEs) will introduce a thermal stress at the bond area when temperature changes. Because of the low modulus of elasticity (E) of adhesives and the thin layer geometry that adhesives are applied in practical usage, the thermal stress caused by adhesives is usually ignorable compare with the stress caused by different CTEs of the bonded parts. But the effects of the adhesives do exist, and can become considerable when other effects have been well controlled. Experiences from optical engineers and opticians show that local fringes can be seen localizing at the bond area due to temperature change. The phenomenon shows that the thermal stress cause by adhesives is able to deflect the mirror surface. This will cause a problem in high requirement system. So it will be helpful to study how the stress develops at the bond area, how it affects the surface, and how it related to the material properties and geometry of adhesives. When two materials with different CTEs are bonded together, for example adhesive and glass, the strain will be forced to be the same (assume the bond does not fail). But the different expansion tendency will cause a stress at the interface. Considering the adhesive joint connecting two parts- the adhesive usually has much higher CTE than the connected parts, this makes the adhesive tends to expand more than the jointed parts. The interior part of the adhesive bond is constrained by the adhesive around it, so it can only expand in the direction normal to the bond interface which is not constrained. The difference of expansion between adhesive and jointed parts is small at this area. But the adhesive near the edge is free to bulge laterally, where the adhesive tend to expand more differently to the jointed parts. Thus, the distribution of expansion tendency will introduce a stress distribution (Fig.20). Here for thermal stress analysis all the thermal and physical properties are equal to copper as an assumption [8].

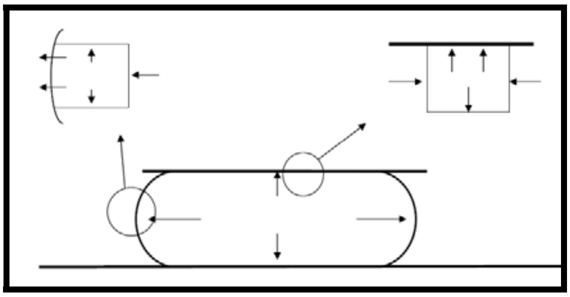

Fig. 20. Thermal expansion of adhesive bond

Thermal stress is described by the following equations-

$$L_2 - L_1 = \alpha L(T_2 - T_1) \quad (7)$$

$$\Delta L = \alpha L \Delta T \quad (8)$$

$$\varepsilon = \frac{\Delta L}{L} = \alpha \Delta T \quad (9)$$

Where α is the coefficient of thermal expansion (CTE); ε is the thermal strain.

VIII. Stress Analysis Result

Here both rectangular and circular- two dimensional fin array is investigated. Investigation shows that developed pressure and thermal expansion due to temperature difference and fluid flow is less for the circular pin fin array (Fig. 21-25).The maximum pressure in circular fin array is 10.08 MPa and rectangular fin array is 15.14 MPa.

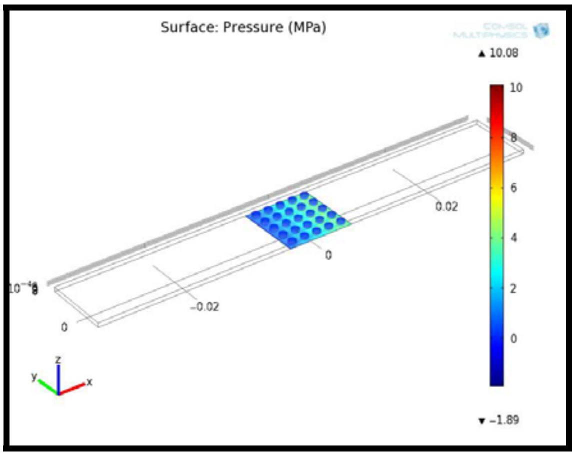

Fig. 21. Pressure distribution in circular fin array

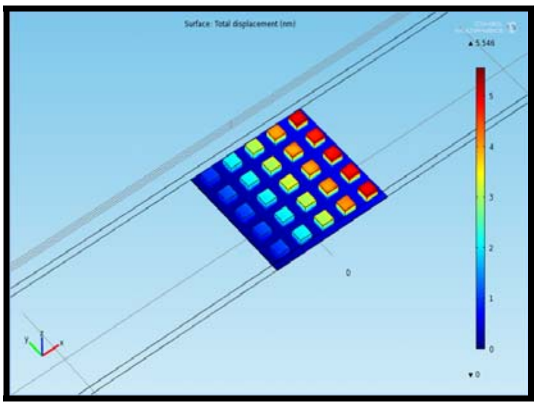

Fig. 22. Thermal expansion of rectangular fin array

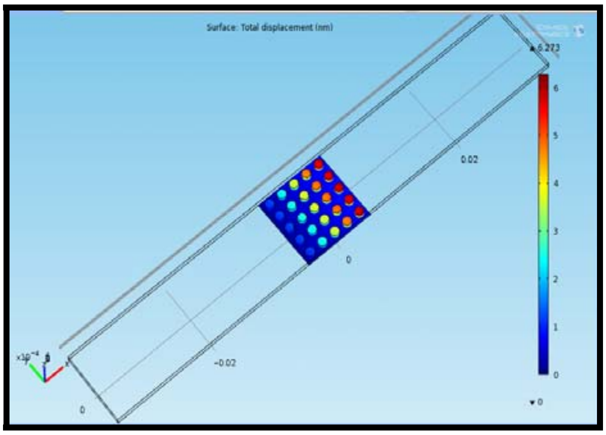

Fig. 23. thermal expansion of circular fin array

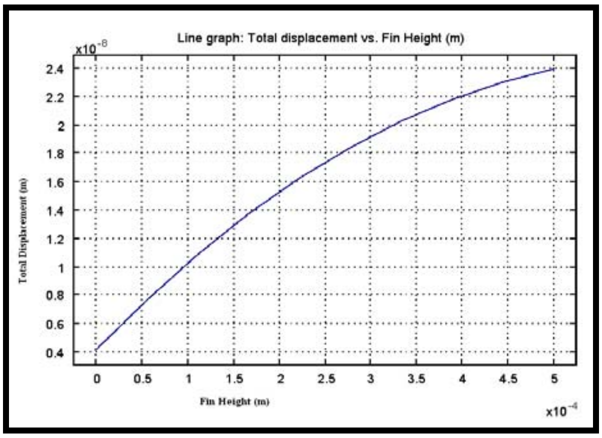

Fig. 24. Total displacement curve along the fin height for circular fin array.

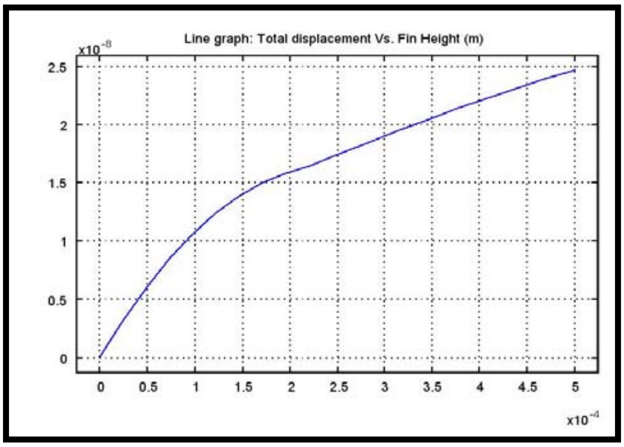

Fig. 25. Total displacement curve along the fin height for rectengular fin array.

IX. Conclusion

Different fin geometries having the same wetted surface area are compared from the point of views of heat transfer, maximum fin temperature, maximum pressure drop and maximum thermal stress. For same fluid (water) velocity 0.75 m/s, maximum temperature of the 2D rectangular fin array and circular pin fin array is almost same and it is about 24.5^{0}c. Due to this, maximum von-mises stress is also same and it is about 10 MPa. But the pressure drop in 2D rectangular fin array is more (15MPa) than the circular pin fin array (10.5Mpa). Again for the same fluid (water) velocity (0.75m/s), the circular pin fin array extracts more heat (0.675 W) than the rectangular (0.645W) one. It is concluded that circular pin fin carbon nano-tube based micro-channel heat sink shows better thermal performance than the others investigated in this paper.

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REFERENCES

[1] Hone J., “Carbon Nanotubes: Thermal properties,” Dekker Encyclopedia of Nanoscience and nanotechnology, Marcel Dekker Inc., 2004, pp. 603-610.

[2] Jun Xu, Timothy S. Fisher, “Enhancement of thermal interface materials with carbon nanotube arrays,” International Journal of Heat and Mass Transfer, vol. 49 (2006), pp. 1658–1666.

[3] Zhimin Mo , Raluca Morjan, Johan Anderson, Eleanor E.B. Campbell and Johan Liu,“Integrated Nanotube Microcooler for Microelectronics Applications,” Electronic Components and Technology Conference,California,USA, 2005, pp.51-54.

[4] Zhong, Xiaolong, Yi Fan, Johan Liu, Yan Zhang, Teng Wang, and Zhaonian Cheng, “A Study of CFD Simulation for On-chip Cooling with 2D CNT Micro-fin Array,” International Symposium on High Density Packaging and Microsystem Integration , China, 2007, pp.442-447.

[5] B. X. Wang & X. F. Peng , “Experimental investigation on liquid forced convection heat transfer through microchannels,” International Journal of Heat and Mass Transfer, vol. 37, pp. 73–82, 1994.

[6] J.Liu, Y.Fu, T. Wang, “Recent Progress of Carbon Nanotubes as Cooling Fins in Electronic Packaging”, International Conference on Electronic Packaging Technology & High Density Packaging, Shanghai, China, 2008,paper id: E3-01.

[7] T. Tong, Y. Zhao, L. Delzeit, A. Kashani, M. Meyyappan, A. Majumdar, “ Dense vertically aligned multiwalled carbon nanotube arrays as thermal interface materials,” IEEE Transactions on Components and Packaging Technologies , vol. *30*, pp. 92-100,2007.

[8] K. Kordas, G. Toth, P. Moilanen, M. Kumpumaki, A. Uusimaki, “Chip cooling with integreted carbon nanotube microfin architecture”, Applied Physics Letters, vol. 90, pp.123105, 2007.

[9] S. Wang, Y. Zhang, Y. Fu, X. Wang, Z. Cheng, “A Study of Heat Transfer Characterstics of the Micro-Channel Heatsink,” International Conference on Electronic Packaging Technology & High Density Packaging,shanghai, china, 2009,pp.255-259.

[10] S. Khandlikar, S. Garimella, S. Colin, & M.R. King “Heat Transfer and Fluid Flow in Minichannels and Microchannels,” USA: Elsevier Ltd.,2006,ch.3.

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