A Preliminary Investigation of Liquid Cooling of an Electronic Chip using COMSOL

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Abstract- In this study, an attempt is made to simulate heat transfer characteristics of an electronic chip, using liquid coolants. Simulations have been carried out using the multi-physics software COMSOL. A slender cubical geometry is chosen to model a Silicon chip. Channels of rectangular cross-section of copper tubing carrying liquid coolants are placed in contact with the chip. The investigation shows significantly enhanced cooling effects by liquids, as expected, with nano-fluids as the best performer. Several parameters were varied in the study, and both steady state and unsteady state behavior were considered.

Keywords – Liquid Cooling, Simulation, Electronic Chip, COMSOL

I. INTRODUCTION

Electronic devices and systems have made incredible progress in the recent past; technology has afforded growth from a few hundred components to millions of transistors on a single chip. However, the cooling of electronic equipment with a large number of components and chips on a printed circuit board, has not kept up with the pace. Primarily, we are still using a 'fin-and-fan' air cooling configuration with minor variations - no novel breakthrough has come about in the past two or three decades [1,2,3]. Liquids have a higher heat capacity and thermal conductivity compared to gases and, are inherently able to transport more heat while flowing. The only liquid cooling currently commercially used in miniaturized electronic devices are heat pipes - non-moving devices that utilize phase change in a slender pipe whose inner wall is wick-lined. Hence, an immense opportunity exists for making significant changes in the way electronic components and systems are cooled; a viable alternative would be to use a hermetically sealed tube or pipe with a liquid flowing inside it [4,5,6].

The failure rate of electronic equipment increases exponentially with temperature. Also, the high thermal stresses in the solder joints of electronic components mounted on circuit boards resulting from temperature variations are major causes of failure. When thousands or even millions of such components are packed in small volume, the heat generated increases to such high levels that its removal becomes a formidable task and a major concern for the safety and reliability of the electronic devices. Therefore, thermal control has become increasingly important in the design and operation of electronic equipment.

In this study, a preliminary investigation is conducted using the COMSOL simulation package, to see the effects of heat generation by a single chip, and the ability of various liquids to cool it. For comparison, the effects of air as a cooling fluid as used in the established fin-and-fan mechanisms, have also been simulated. As expected, the liquids water and nano-fluids show significant improvement in cooling as compared with air, for all configurations, flow regimes and time-dependent or independent scenarios.

II. SIMULATION AND MODEL OF A SILICON CHIP USING COMSOL

A. Description of Chosen Geometry

The simulated model that was designed to study heat transfer from a single chip using the COMSOL multi-physics package, consisted mainly of three parts. A slender cubical block of Silicon was taken as the electronic chip, acting as a heat source. Two rectangular conduits one above and one below the chip were placed in the model to permit the transfer of heat to the flowing fluid.

The electronic chip was modeled as a rectangular block of Silicon with dimensions as 1.5 x 1.5 x 0.2 cm respectively. The model of the chip was taken from one of the examples discussed in the COMSOL Tutorial manual [7]. The block material was assumed to be made of Silicon and acted as the heat dissipating source.

Rectangular conduits were used as channels to pass fluids as cooling agents. The dimensions of the conduits were in accordance with the electronic chip. The length of the conduits was 5-6 times the dimension of the chip. This was to ensure that the fluid had spent sufficient time in contact with the heat source. The width of the conduits was kept the same as that of the chip, so as to maintain complete overlap over the chip. The height of the conduits was made an addition of 10% over the original height of the chip. Therefore the dimensions of the conduits were taken as 8.75 x 1.5 x 0.22 cm respectively. The material chosen for the conduits was copper. Furthermore, the thickness of the metal was kept minimal of 0.002 cm. Fig 1 shows the geometric model that was used to perform the simulation study. It can be observed from the figure the chip is sandwiched in between the conduits passing above and below. The arrow marks show the direction of the fluid flow.

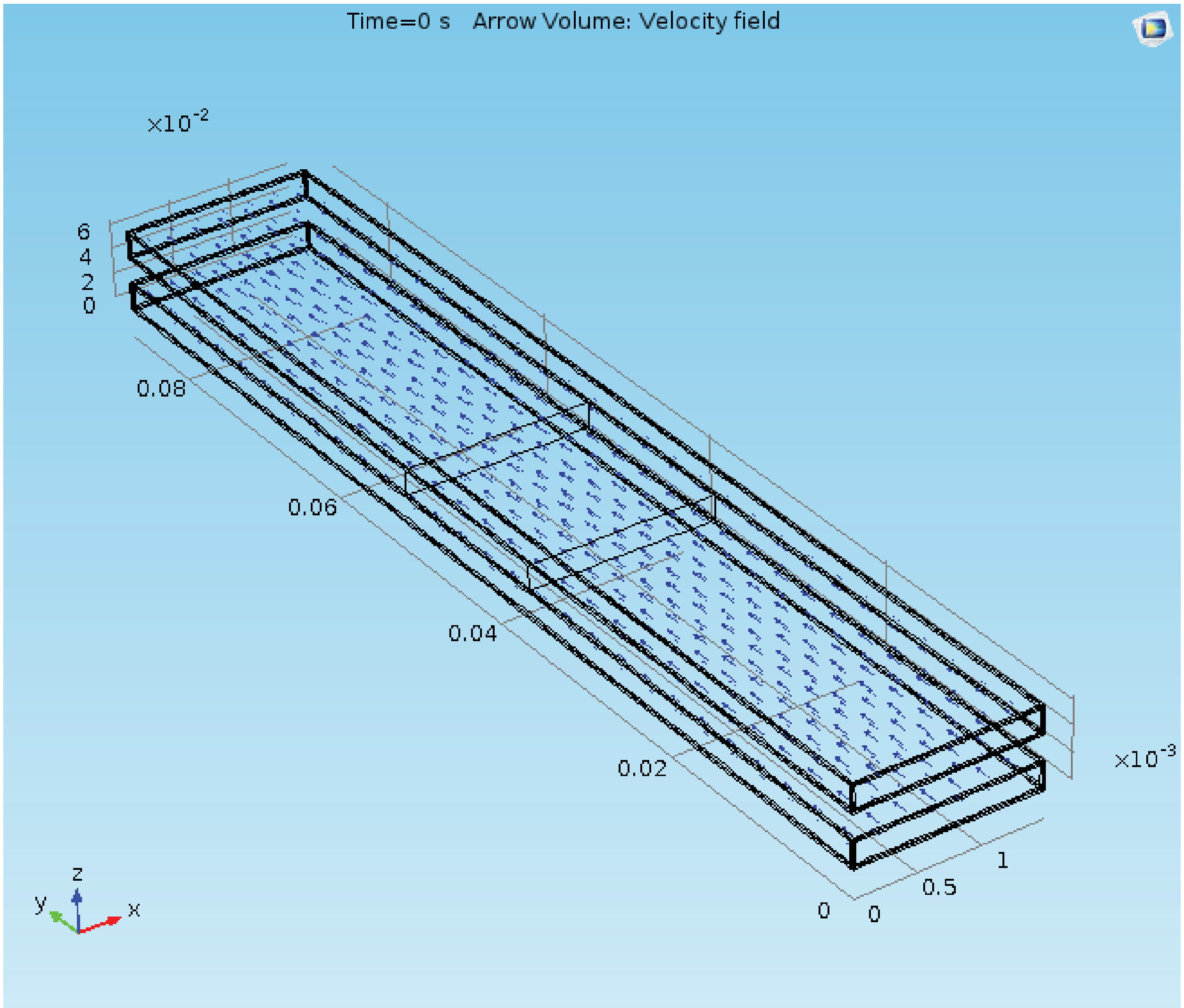


Figure1. Diagram of the geometric model used in the Simulations

The fluids chosen for the study were Air, Water, Ethylene Glycol, Nano-fluid1 and Nano-fluid2. Nano-fluid1 was a dispersion of Al_2O_3 in water with a concentration of 0.3% and Nano-fluid2wasa dispersion of Al_2O_3 in water with a concentration of 2 % [8]. To study the effect of the fluids on cooling, the concentration values were taken directly from the reference quoted. To examine the effect, the lowest and highest concentration values were chosen. The Fluid flow parameters were strictly in the Laminar Region (Reynolds Number, Re , 11-267) and the fluid was passed over the chip in a co-current fashion in all the test runs. Heat generation from the chip was simulated with the values of 1W and 5W.

II. SIMULATION DETAILS

For each fluid two studies were performed - one stationary (steady-state) and the other time dependent. The fluids chosen were Air, Water, Ethylene Glycol, Nano-fluid1 and Nano-fluid2 . The pertinent equations used for simulation of heat transfer and associated fluid flow, and the estimation of fluid properties are listed below:

A. Flow and heat transfer Equations for time Independent Study (Stationary State)

Heat transfer equation in solids used was;

$$\rho C_p \mathrm{u} \nabla T + \nabla . \mathrm{q} = Q + Q_{rad} \qquad (1)$$

$$\mathrm{q} = -k \nabla T \qquad (2)$$

Heat transfer equation used for fluids was;

$$\rho C_p \mathrm{u} . \nabla T + \nabla . \mathrm{q} = Q + Q_p + Q_{vd} \qquad (3)$$

$$\mathrm{q} = -k \nabla T \qquad (4)$$

The laminar flow of the fluids was simulated using the equations;

$$\rho (\mathrm{u} . \nabla) \mathrm{u} = \nabla . [-p\mathrm{I} + \mu(\nabla \mathrm{u} + (\nabla \mathrm{u})^T)] + F \qquad (5)$$

$$\rho \nabla . (\mathrm{u}) = 0 \qquad (6)$$

Further the Inlet conditions were set at laminar Inflow and the equation involved was;

$$L_{entr} \nabla_t . [-p\mathrm{I} + \mu(\nabla_t \mathrm{u} + (\nabla_t \mathrm{u})^T)] = -P_{entr} \mathrm{n} \qquad (7)$$

The outlet equations were;

$$[-p\mathrm{I} + \mu(\nabla \mathrm{u} + (\nabla \mathrm{u})^T)] = -\hat{P}_0 \mathrm{n} \qquad (8)$$

$$\hat{P}_0 \leq P_0$$

The Boundary conditions included velocity at the inlet of the conduit, pressure at the outlet and no-slip at the wall.

B. Flow and heat transfer Equations for time Dependent Study

Heat transfer equation in solids used was;

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \mathrm{u} \nabla T + \nabla . \mathrm{q} = Q + Q_{rad} \qquad (9)$$

$$\mathrm{q} = -k \nabla T \qquad (10)$$

Heat transfer equation used for fluids was;

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p u \nabla T + \nabla . q = Q + Q_{vd} + Q_p \qquad (11)$$

$$q = -k\nabla T \qquad (12)$$

The laminar flow of the fluids was simulated using theNavier-Stokes and continuity equations;

$$\rho \frac{\partial u}{\partial t} + \rho(u . \nabla)u = \nabla . [-pI + \mu(\nabla u + \left(\nabla u\right)^T - \frac{2}{3}\mu(\nabla . u)I\Big] + F \qquad (13)$$

$$\frac{\partial \rho}{\partial t} + \nabla . (\rho u) = 0 \qquad (14)$$

The effects of entrance and exit lengths were assumed nominal.

C. Equations used to estimate the Nano-fluid properties:

As stated earlier, Al_2O_3 particles suspended water with different concentrations was used as Nano fluids. The physical properties of the Nano-fluids were estimated based on previously published established procedures, as available in the literature [8,9]. Water was taken as the base fluid. The basic thermal and physical properties of the fluids like thermal conductivity, heat capacity, density and dynamic viscosity were calculated using the following given equations.

$$k_{eff} = \varphi k_{np} + (1-\varphi)k_b \qquad (15)$$

$$C_{nf} = (1-\varphi)C_f + \varphi C_p \qquad (16)$$

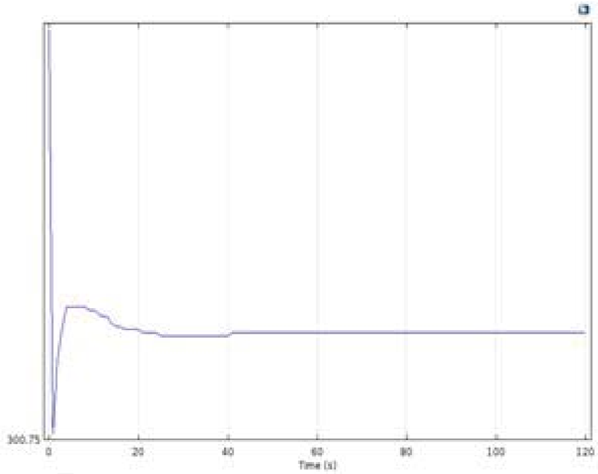
$$\rho_{nf} = (1-\varphi)\rho_f + \varphi \rho_p \qquad (17)$$

$$\mu_{nf} = (1+2.5\varphi)\mu_b \qquad (18)$$

The nomenclature used in all the above equations is as below:

C_p - Heat Capacity at Constant Pressure,J/kg.K
ρ - Density, kg/m^3
u – Velocity,m/s
T – Temperature, K
q – Heat flux,W/m^2
Q –Heat generation rate, W
Q_p- Heat generation rate of particles (Solid), W
k - Thermal Conductivity, W/m.K
p – Pressure, Pa
$\mathbf{I}$ – Normal Vector
F – Body Force, N
L_{entr} - Entrance Length, m
F_{entr} – Force stream pressure, Pa
$\mathbf{n}$ - Normal Vector
μ - Dynamic Viscosity, Pa.s
k_{eff} - Effective thermal Conductivity of the fluid, W/m.K
k_{np} - Thermal Conductivity of Nano Particle, W/m.K
k_b - Thermal Conductivity of Base Fluid, W/m.K
φ - Concentration or mol-fraction
C_{nf} - Heat Capacity of nano fluid, J/kg.K
C_f - Heat Capacity of fluid , J/kg.K
ρ_{nf} - Density of Nano fluid, kg/m^3
ρ_f - Density of fluid,kg/m^3
ρ_p - Density of Suspended Particles, kg/m^3
μ_b - Dynamic Viscosity of Base Fluid, Pa.s
μ_{nf} - Dynamic Viscosity of Nano-fluid, Pa.s

Figures 1-10 depict plots of the temperature vs. time of the chip, for various fluids at different velocities, at a heat generation rate of 1W. The duration of each run was 120 seconds. Plots were obtained with different fluids and at different velocities of 5cm/s and 10 cm/s. The point or the co-ordinate at which temperature readings taken was (0.0075, 0.04375, 0.0032) respectively, lies at the dead center of the chip. The first fluid used was air whose plots are given in images 1-2 with 5 cm/s and 10 cm/s speed. The trend shows a steady temperature value of about 300 K in both cases, after an initial fluctuation. The next fluid passed was water whose temperature plots are given in Figures 3-4 with velocities of 5cm/s and 10 cm/s . After an initial transient period of about 5 seconds, the rate at which temperature increased shows a steady decline in both the cases, In case of higher velocities, the rate at which temperature increased is observed to be low. At the end of 120 seconds, the temperature of the chip was noted as 293.75 K and 293.58 K respectively.



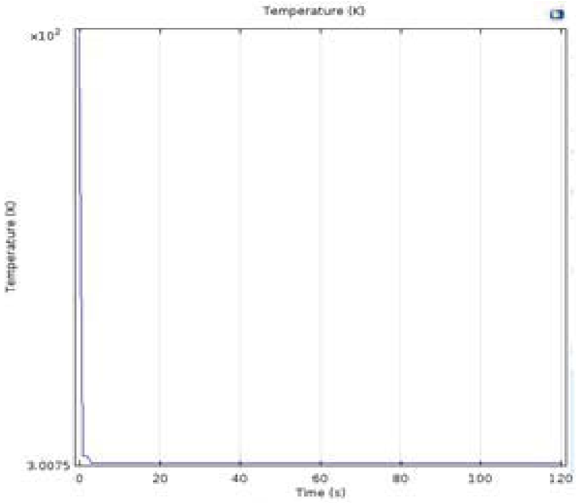
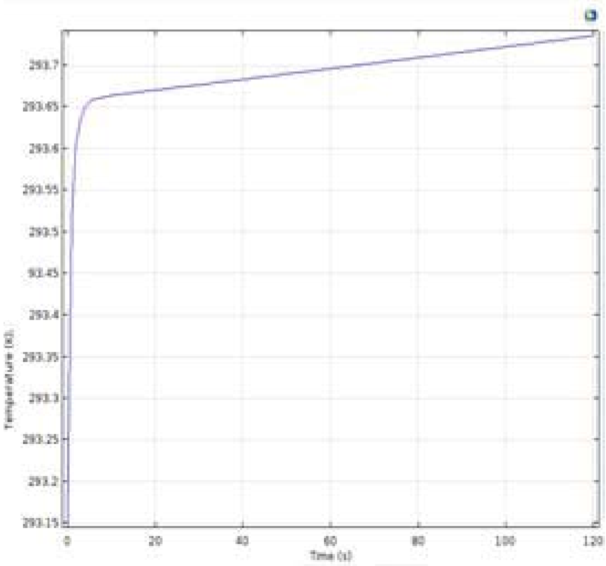


Figure 1. Air at 5cm/s

Figure 2. Air at 10 cm/s



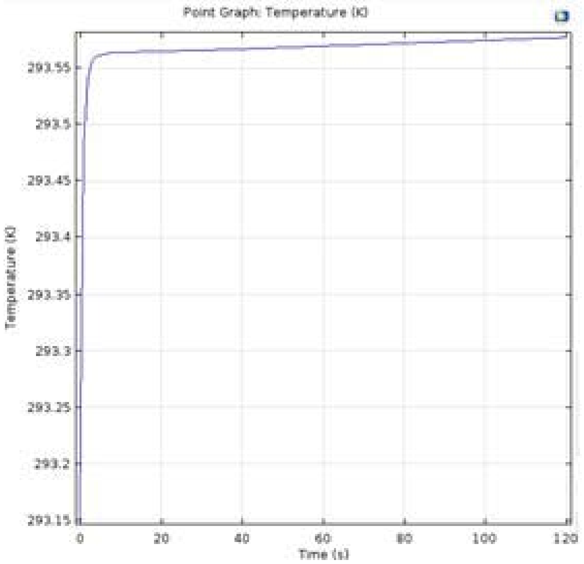
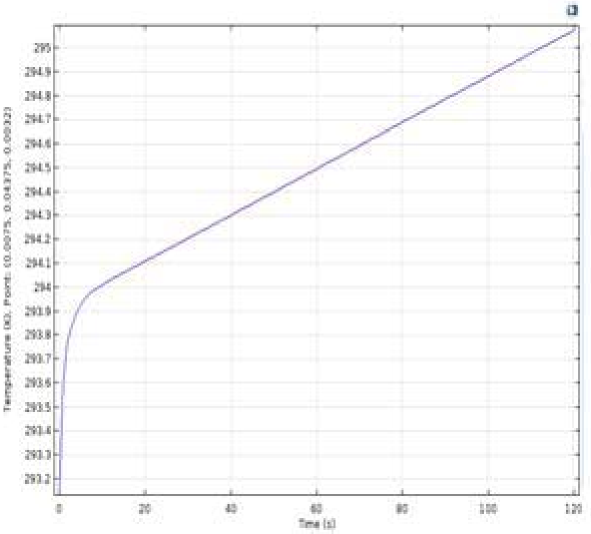


Figure 3. Water at 5cm/s

Figure 4. Water at 10 cm/s

Figures 5 and 6 correspond to temperature vs. time plots of the chip, where ethylene glycol was passed through the conduits. In this case the rate of increase of temperature was observed to be the highest of any case in this study. After an initial transient time of 10 seconds, the temperature increased nearly linear with respect to time. The temperature noted at the end of 120 seconds was 295.07 K and 294.34 K respectively, for each of the two fluid velocities.



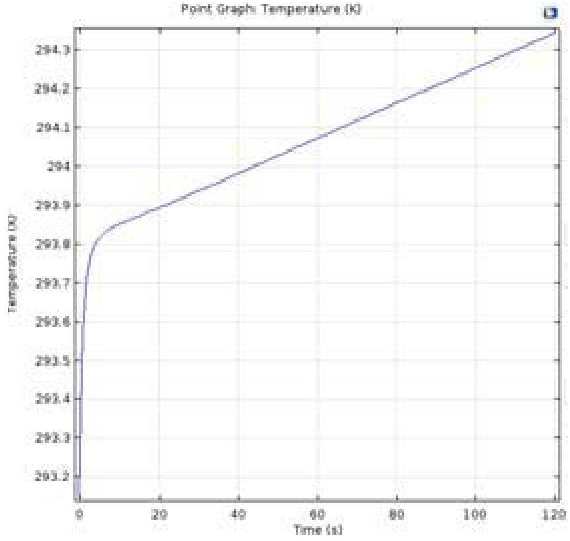


Figure 5. Ethylene Glycol at 5cm/s

Figure 6. Ethylene Glycol at 10cm/s

Figures 7 and 8 show the temperature vs. time plot, when Nano-fluid1 was passed, through the channels. The transient time noted for both the cases was different i.e. at 5cm/s it was 8 seconds and with 10cm/s it was 4 seconds. After the initial transient temperature rise, the rate of temperature rise was observed to be low in the 1st case and in second case was nearly negligible.

At the end of 120 seconds, the temperature was noted as 293.7 K and 293.56 K respectively.

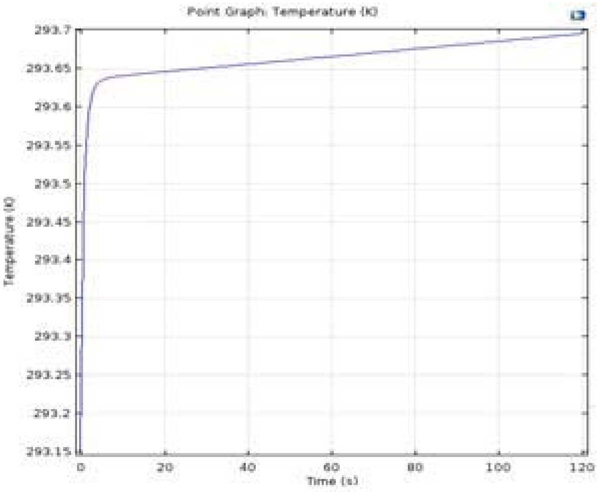


Figure 7. Nano Fluid 1 at 5cm/s

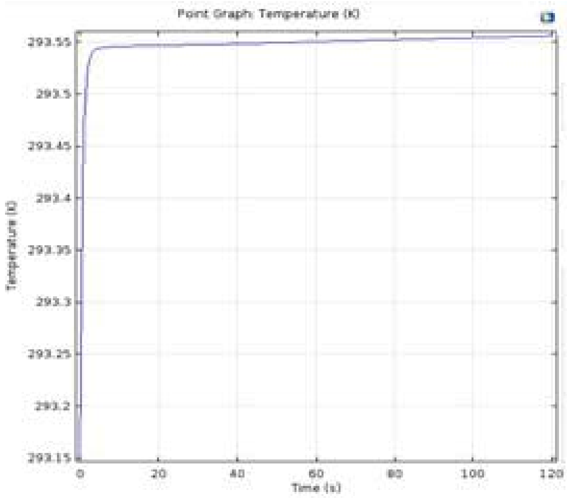


Figure 8. Nano Fluid 1 at 10cm/s

Figures 9-10 show the temperature vs. time plot, where Nano-fluid2 was passed through the conduits. As observed earlier in the case of Nano-fluids, the transient times noted was different for different speeds, a 8 seconds transient for 5cm/s and a 10 seconds transient for 10cm/s. The rate of temperature rise has been nearly negligible in these cases after the initial transients, thereby giving best results in this study. The temperature noted at the end of 120 seconds was 293.49K and 293.47K. The nano-fluids behavior is somewhat different from the other chosen fluids, primarily because of the solid loading. This seemingly helps in achieving a significantly faster heat removal rate, when compared with the other fluids.

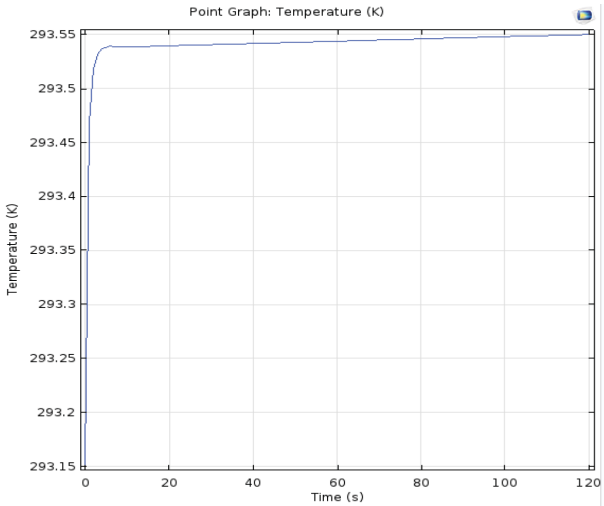


Figure 9. Nano 2 at 5cm/s

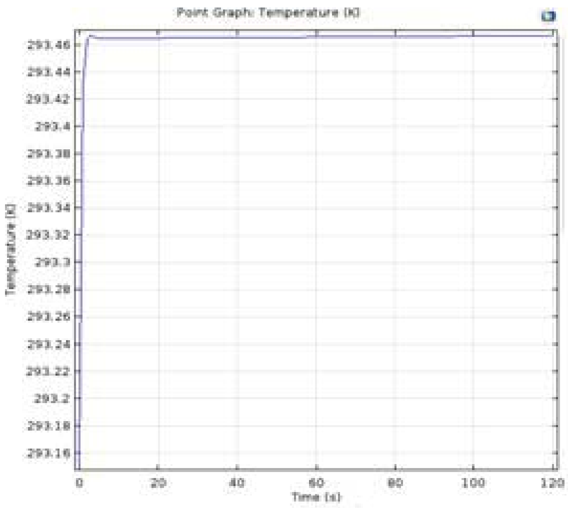


Figure 10. Nano 2 at 10 cm/s

A. Variation of Power Dissipation by the chip - some results at 5 W.

The following plots, Figures 11 through 16, were obtained keeping the power source at 5W and passing various fluids through the conduits at 5cm/s. The first plot (Figure 11.) was obtained when air was passed through the conduits. After some initial fluctuations the temperature vs. time plot levels off. The temperature of the chip was noted to be 331.15K. Figure 12 shows the plot, when ethylene glycol was passed through the conduits. Although the rate of increase of temperature appears linear in this case, after an initial transient time of about 5 seconds, the temperature noted at the end of 120 seconds was 301.75 K, which shows a noticeable difference of 29.4K, with respect to air cooling.

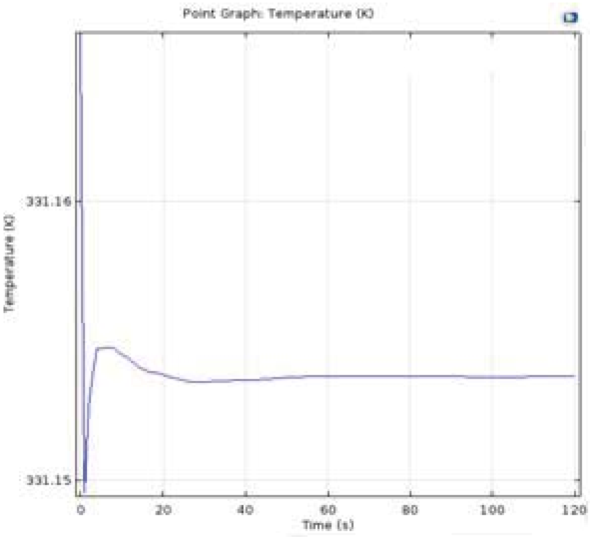


Figure 11. Air with 5W at 5cm/s

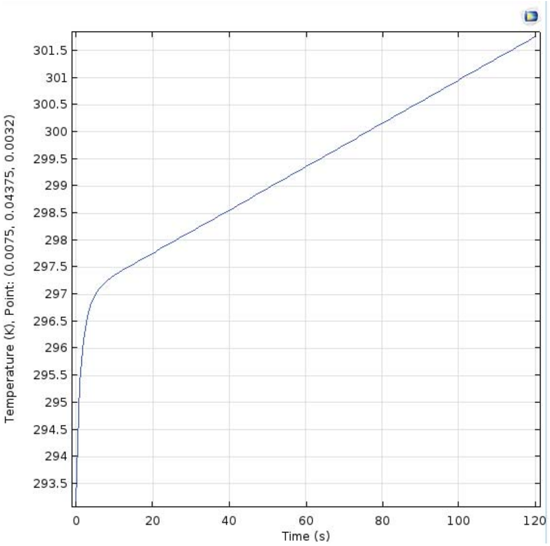


Figure 12. Ethylene-Glycol with 5W at 5cm/s

Figure 13 shows a temperature. Vs time plot when water was passed through the conduits. After the initial transient time of about 5 seconds, the rate of temperature increase leveled off and the temperature noted at the end of 120 seconds was 296.05K. The difference between the temperature of air and water cooling was found to be 35.45K. Figure 14. Similarly was obtained using Nano-fluid1 and Figure 15 for Nano-fluid2. Both Nano-fluids exhibited a very short transient time and attained a steady state temperature of about 296K and 295K, for Nano-fluid 1 and 2, respectively. This results in an effective temperature difference in the Silicon chipof about 36.5K, when compared with air cooling.

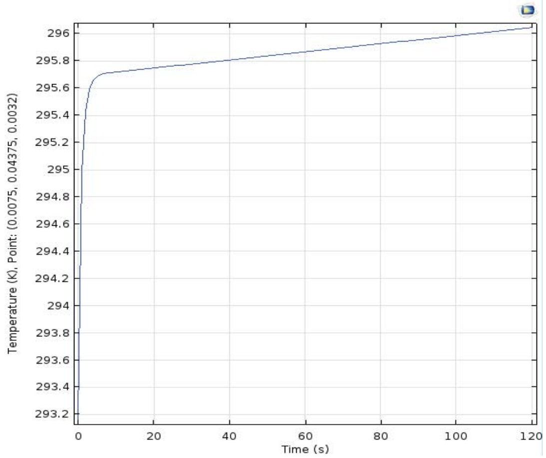


Figure 13.Water with 5W at 5cm/s

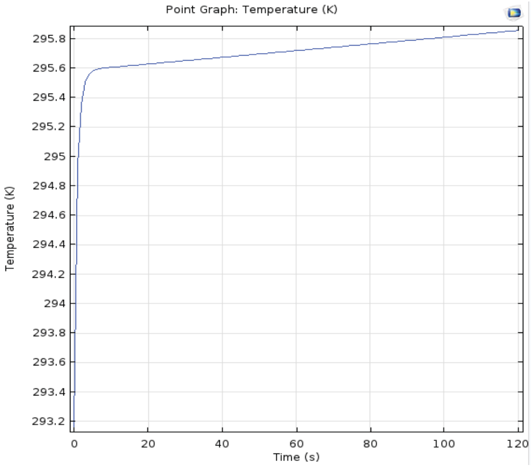


Figure 14. Nano 1 with 5W at 5cm/s

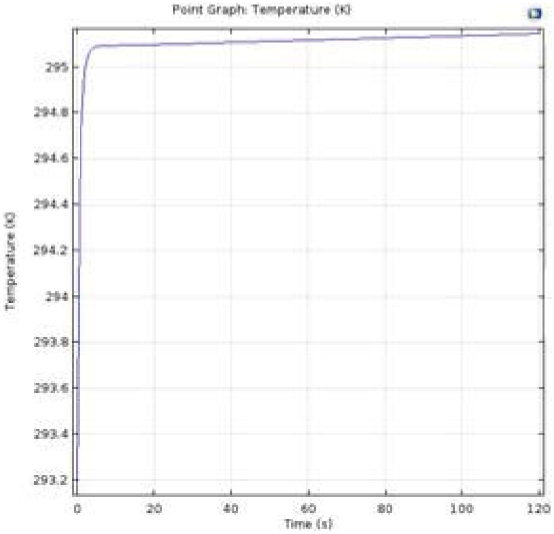


Figure 15. Nano 2 with 5W at 5cm/s.

B. *Color coded images of time independent studies*

The following pictorial representations, Figures 16 through 20 were recorded for stationary studies for different fluids at 5cm/s of fluid velocity and power of 1W.Figure 15-20 show the color coded images of the chip with different fluids being passed through the conduits. The brighter colors show the higher temperature regions which are generally towards the outlet side. At the inlet the fluid is allowed to enter, at a temperature of 293 K; as the fluid advanced towards the outlet, it heated up.

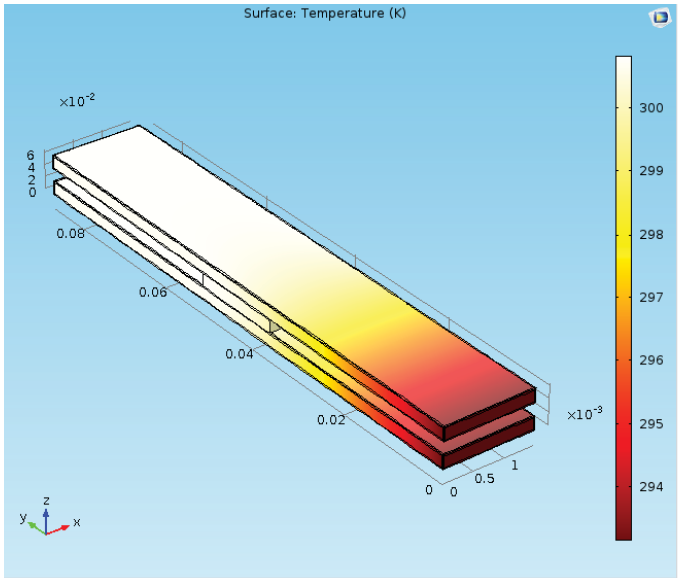


Figure 16. Air

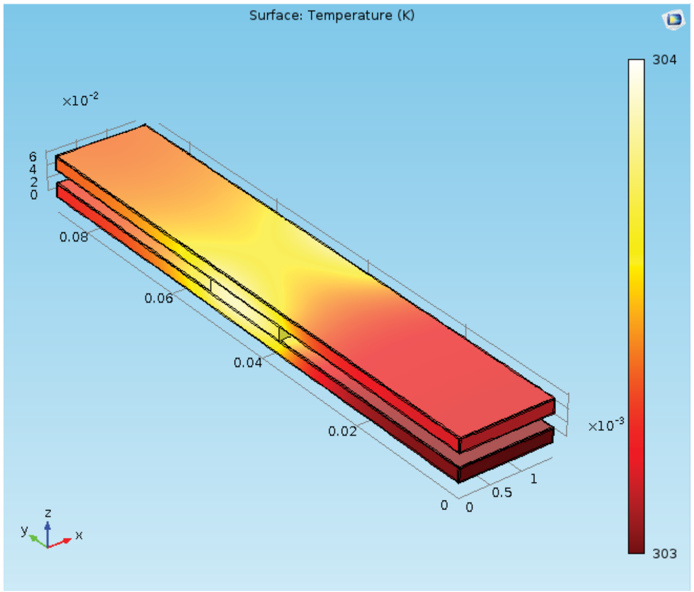


Figure 17.Ethylene glycol

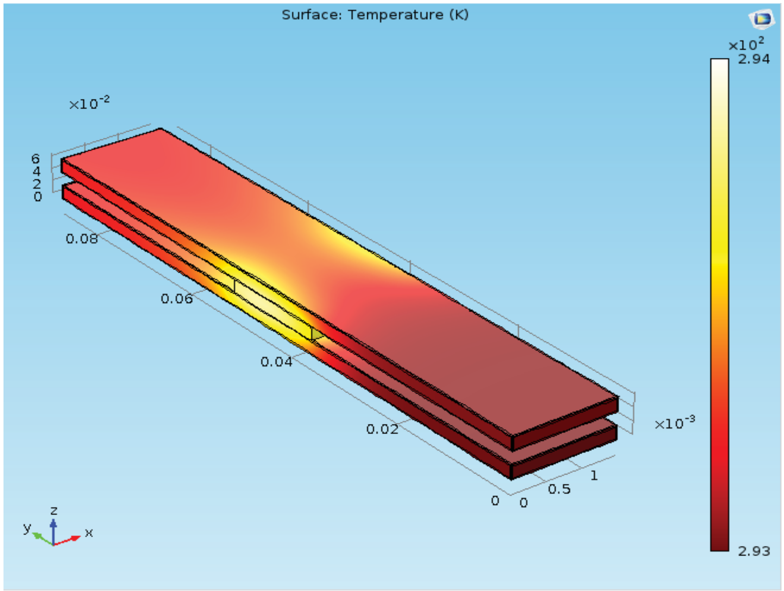


Figure 18.Water

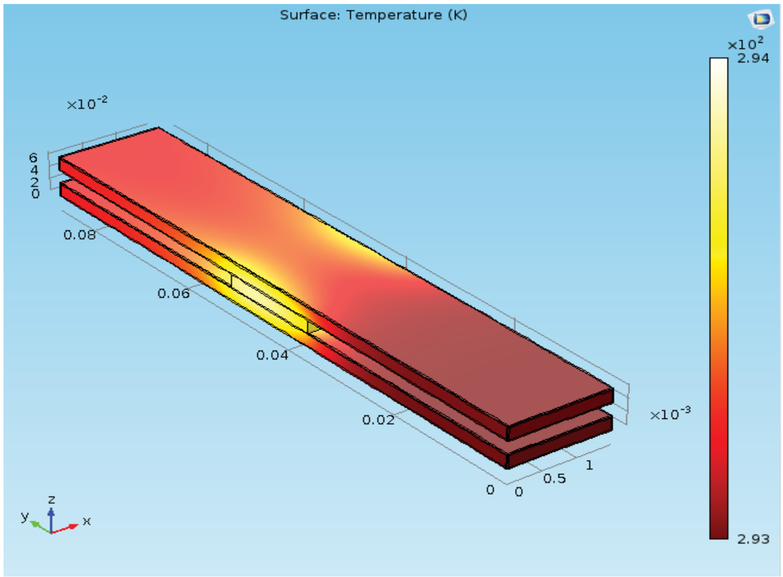


Figure 19.Nano fluid1

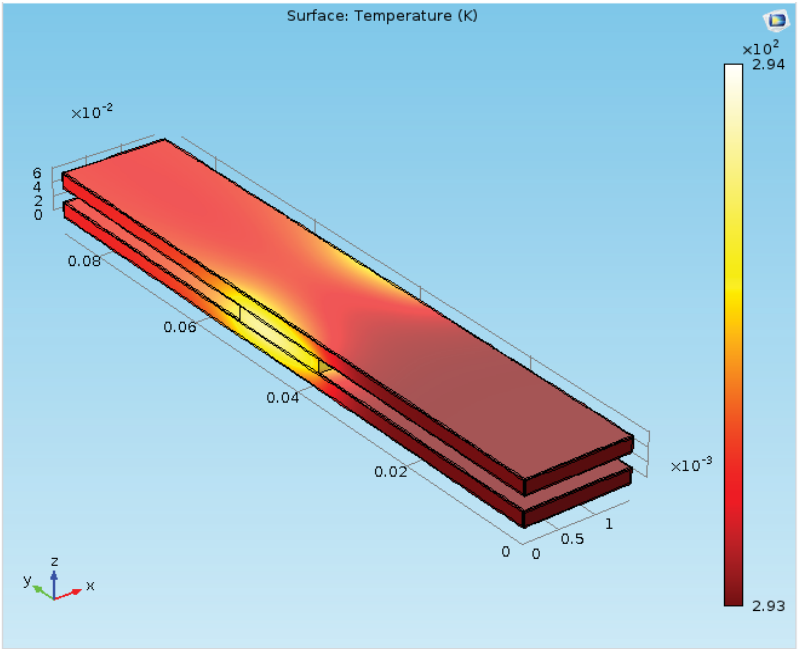


Figure 20.Nano-fluid

C. Calculation of Heat Transfer Coefficients :

Heat Transfer Coefficients were calculated based on the Dittus -Boelter Equation given below:

$$Nu = 0.023 \times Re^{0.8} \times Pr^{0.33}$$

Reynolds number was calculated using characteristic dimension (D), which id given as follows:

$$D = 4 \times \frac{Wetted\ Area}{Wetted\ Perimeter}$$

And as per the dimensions of the model, D was found out to be 3.7820 $\times 10^{-3}$ m.

Table 1 Shows the heat transfer coefficient h, for various runs; these values were calculated for the heat source at 1W. As is evident from the last column of heat transfer coefficient values, the nano-fluids show the maximum numbers, followed by water, ethylene glycol and lastly air. These values were computed using the Dittus-Boelter equation, as mentioned earlier, and available in the literature [10]. The heat transfer coefficients increased in value,with increasing Reynolds's numbers (increasing velocities). Ethylene Glycol, was somewhat of an anomaly; it has a lower Reynolds Number and a higher Prandt'l number, and according to the Dittus-Boelter equation, a higher Reynolds number has a higher value of heat transfer coefficient.

Table1: Heat Transfer Coefficients

Sl.No	Fluid	Velocity (m/s)	Reynolds Number	Prandt'l Number	Heat Transfer Coefficient (W/m^{2}K)
1.	Air	0.05	11.85	0.7751	0.997
2.	Water	0.05	191.477	7.063	453.44
3.	Ethylene Glycol	0.05	12.992	149.5384	63.28
4.	Nano-fluid 1	0.05	191.75	6.3935	488.5
5.	Nano-fluid 2	0.05	135.3	5.306	615.5
6.	Air	0.1	23.7	0.7751	1.3812
7.	Water	0.1	382.9	7.063	788.19
8.	Ethylene Glycol	0.1	25.98	149.5384	110.112
9.	Nano-fluid 1	0.1	383.50	6.3935	851.446
10.	Nano-fluid 2	0.1	270.6	5.306	1069.98

IV. CONCLUSIONS

The present study investigated enhanced heat transfer effects from a Silicon chip using a variety of liquid coolants. Simulation results were presented in the form of color-coded diagrams, graphs of Temperature versus time, and calculated heat transfer coefficients, based on the Dittus-Boelter equation. The study showed a significant improvement in all liquids when compared with air, in terms of the fluids' ability to transport away heat from the heat dissipating source, the Silicon chip. Numerous parameters such as liquid flow velocity, rate of heat dissipation, types of coolants and steady/unsteady-state behavior were varied; the nano-fluids (Aluminum Oxide in water) showed the most promise according to our simulation results, and their use in cooling of electronic systems should be further investigated in depth. An experimental set-up to corroborate the computer simulation will be part of a future study.

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