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Conjugate Heat Transfer Analysis of Different CPU Cooling Processes Using Computational Fluid Dynamics

Sajih Bin Suja, Md Rhyhanul Islam Pranto, Raydah Nudrat Turna, Zahir U. Ahmed*
Department of Mechanical Engineering, Khulna University of Engineering & Technology, Khulna-9203, BANGLADESH

ABSTRACT

In the last few decades, a significant amount of technological advancements had occurred in computer systems. Such advancements primarily focused on performance increases and capabilities of the CPUs, which results in development of high heat fluxes and temperature. High temperature can damage the electrical components; therefore, cooling systems are necessary to design to optimize performance. Modern CPUs use air-cooling systems to regulate the temperature. However, the air-cooling system is not the most efficient heat dissipation system available and it also faces some problems due to space limitations. Nowadays high-performance liquid cooling systems imperative of modern technologies are widely being used in the CPU cooling process. In this regard, a comparative investigation is performed using finite volume based numerical simulation for conjugate heat transfer analysis of the CPU cooling system using both air and liquid cooling processes. For liquid cooling, water and nanofluids are used. Nanofluids are currently being a solution for more efficient heat transfer. In this study, CuO-Water nanofluid and Al_2O_3-Water nanofluid both with volume fraction of 0.5% and 2.0% are used as coolants. Results show that for the maximum flow rate, the maximum temperature difference was around 0.22K between water and 2% CuO-Water nanofluid. For the same mass flow rate, water has the heat transfer coefficient 1758.936 W/m^{2}K and 2% Al_2O_3-water nanofluid has 1804.039 W/m^{2}K. Heat transfer coefficient for 2% CuO-Water nanofluid is 1818.093 W/m^{2}K for a certain Reynolds number. The thermal resistance of 0.5% CuO-Water is 1.54%, 0.5% Al_2O_3-water nanofluid is 0.7% and 2% Al_2O_3-water nanofluid is 2.75% less than water. Therefore, the results show that, nanofluid coolant performed better than the conventional air cooling in terms of improving the heat conductivity. It was also found that increasing the volume concentration resulted in better heat transfer characteristics. The numerical results are found to be encouraging and provide a future scope for designing a better nanofluid based cooling system for CPUs.

Keywords: Conjugated Heat Transfer, Nanofluid, CPU, Cooling, CFD.

1. Introduction

The central processing unit or CPU is the core of the computer. These CPUs often have a maximum operating temperature limit, beyond which CPUs may not work as desired and may even be damaged [1]. The CPUs therefore need to be cooled down to achieve maximum efficiency. Among various methods used, forced convection air cooling is known to be the most used [2]. However, considering the heat modern electronics generate nowadays, reaches a high degree heat flux within a few square centimeters area, forced convection air cooling is not sufficient. Many researchers and engineers have been working to build a better thermal management system to cool the CPUs efficiently. Murshed and Castro [3] projected that microprocessor heat flux may reach higher than 190W/cm^2 in 2020 and mentioned several other methods such as liquid cooling, heat pumps, micro-channel, PCM cooling.

For most researchers, liquid cooling has been an intriguing method. Naphon et al. [4] numerically studied the heat transfer and fluid flow characteristics of deionized water in a mini rectangular fin heat sink. Hu et al. [5] presented an analytical study of a water cooled thermoelectric cooler and investigated the effects of mass flow rate and velocity.

Nanofluids are the newest solution to thermal management. Nanofluids are nanometer sized, basically metallic particles sized less than 100 nm that are distributed in base fluids such as, water, engine oil or ethylene glycol [6]. Al-Rashed et al. [7] studied the effect of CuO-Water nanofluids in two different volume fractions for CPU cooling in contrast to conventional water cooling. Sun and Liu [8] have studied the effect of Cu-Water and Al_2O_3-Water nanofluids in CPU heat box and reported that nanofluids had a better convective heat transfer coefficient compared to deionized water. Nazari et al. [9] have investigated CNT-Water nanofluids for CPU cooling analytically and reported 22% decrease in final temperature and 13% increase in heat transfer coefficient compared to conventional water cooling. Pantzali et al. [10] studied the effect of nanofluid in mini plate heat exchangers and concluded that nanofluids are encouraging in heat exchanger systems. C. Qi et al. [11] experimentally studied the effect of nanofluid in CPU cooling and concluded that increased mass fraction may not result in better heat transfer characteristics and 23.2% reduction in CPU temperature was reported for Al_2O_3-Water nanofluids.

These kinds of results can be expected as different metals such as Cu, Ti, Al, Zn, Au, Ag and metal oxides like SiO_2, Al_2O_3, CuO, TiO_2 are used for preparing nanofluid. These materials possess high thermal conductivity e.g. Cu has a thermal conductivity of 401 W/m.K, and its oxide CuO

*Corresponding author. Tel.: +8801829464338
E-mail addresses: binlabib538@gmail.com

k=76.5 W/m.K. Carbon Nanotubes(CNTs) have a thermal conductivity of 2000-3000 W/m.K which may be used for excess heat transfer [6,12,13].

Previous literature review indicates that the study of heat transfer analysis of CuO-Water nanofluids and Al_2O_3-Water nanofluids in CPU cooling hasn't been as comprehensive as it needs to be. Previous studies don't provide proper information about other heat transfer characteristics (Nusselt number, thermal resistance, local heat transfer coefficient) of coolants used. This study is motivated by need to compliment the limited knowledge about other heat transfer characteristics of various CPU cooling processes and precisely the impact of nanofluids in this field of study. Thus, heat transfer performance of CuO-Water nanofluids and Al_2O_3-Water nanofluids are performed for two different volume fraction, 0.5% and 2%. Performance of both nanofluids are compared to base fluid performance and conventional forced convection air cooling.

2. Methodology

Two different heat sinks were considered for the problem as heat sinks for air cooling and liquid cooling have different geometry.

2.1 Computational Method

Heat sink shown in Fig.1 provides information of the geometry used for forced convection air cooling and Fig.2 provides information of the geometry used for water and nanofluid. For the given geometries, Reynolds number (*Re*) is determined in between two adjacent walls of the fins. *Re* is found to be in the turbulent for the geometry in Fig. 1 as a maximum flow rate of 49 cfm is considered at the inlet. On the other hand, *Re* is found to be within the laminar region for the geometry in Fig. 2, as the mass flow rate at the inlet was considered as 0.056 kg/s.

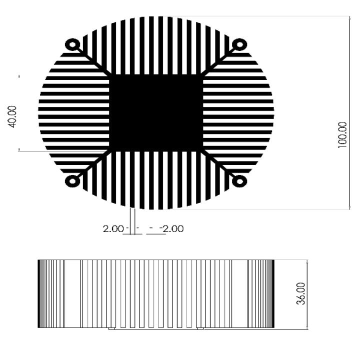

Fig.1 Schematic diagram of investigated sink used for air cooling.

For Fig.2, for a three dimensional laminar steady-state flow is assumed. The governing equations for such flow can be written as [14,15] :

Continuity equation:

$$\frac{\partial(\rho v_x)}{\partial x}+\frac{\partial(\rho v_y)}{\partial y}+\frac{\partial(\rho v_z)}{\partial z}=0 \tag{1}$$

Momentum Equation:

$$\nabla\cdot(\rho\vec{v}\vec{v})=-\nabla P+\nabla\cdot(\overline{\overline{\tau}})+\rho\vec{g}+\vec{F} \tag{2}$$

Energy equation:

$$\nabla\cdot(\vec{v}(\rho E+P))=\nabla\cdot(k_{eff}\nabla T-\sum_j h_j\overrightarrow{J_j}+(\overline{\overline{\tau}}_{eff}\cdot\vec{v})) \tag{3}$$

For air flow cooling system standard k-ε viscous model is used to demonstrate the turbulence effect.

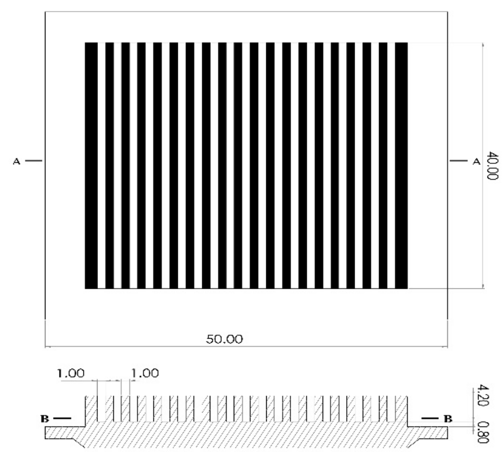

Fig.2 Schematic diagram of investigated sink used for water and nanofluid cooling.

2.2 Data Analysis

Density of nanofluids for a volume fraction are determined from [16]:

$$\rho_{nf}=(1-\phi)\cdot\rho_{bf}+\phi\cdot\rho_p \tag{4}$$

Specific heat of nanofluids are calculated as follows [16]:

$$(\rho C_p)_{nf}=(1-\phi)\cdot(\rho C_p)_{bf}+\phi\cdot(\rho C_p)_p \tag{5}$$

Thermal conductivity is calculated from [6]:

$$k_{nf}=[\frac{k_p+2k_{bf}-2\phi(k_{bf}-k_p)}{k_p+2k_{bf}+\phi(k_{bf}-k_p)}]\cdot k_{bf} \tag{6}$$

Viscosity of nanofluids are calculated from the empirical relation given in [17]:

$$\mu_{nf} = (1-\phi)^{2.5}\mu_{bf} \tag{7}$$

Reynolds number in between two adjacent wall of heat sink is calculated from [18]:

$$\mathrm{Re} = \frac{\rho v_m D_h}{\mu} \tag{8}$$

Local heat transfer coefficient, thermal resistance, local Nusselt number and friction factor is calculated from [19]:

$$h = \frac{\dot{q}}{A_c \Delta T_{\ln}} \tag{9}$$

$$R = \frac{\Delta T}{\dot{q}} \tag{10}$$

$$Nu = \frac{hD_h}{k} \tag{11}$$

$$f = \frac{2\Delta P D_h}{\mu L {v_m}^2} \tag{12}$$

Table 1 Thermophysical properties of nanofluids

Nano-fluid	Φ (%)	ρ (kg/m^3)	C_p (J/kg.k)	k (W/m.k)	μ (kg/m-s)·10^{-4}
CuO-Water	0.5	1024.78	4069.55	0.617	9.9
CuO-Water	2	1104.34	3765.29	0.645	9.54
Al_2O_3-Water	0.5	1012.7	4118.09	0.616	9.9
Al_2O_3-Water	2	1056.2	3936.9	0.643	9.54

2.3 Boundary Conditions

At the inlet, a fixed temperature of 298K is considered for air, water and nanofluids. For air, a maximum flow rate of 49 cfm is considered at the inlet. For water and nanofluids, a mass flow inlet was considered and fluid flow of 0.056 kg/s was imposed. For further simulations fluid flow was ranged from 0.02 kg/s to 0.08 kg/s. The amount of heat dissipated by the CPU at CPU-sink contact surface area of 0.0016 m^2 was considered to be 115W for all the coolants.

2.4 Mesh Generation and Wall Treatment:

The cut-cell hex dominant mesh was created for better convergence and control of the wall function, shown in Fig.3 and Fig.4. The inflation was set to 1.20 and growth rate 1.05 for better mesh quality. For both sinks proximity size function was implemented with a minimum edge length of 0.4 mm. The maximum y$^+$ value for the air-cooled heat sink mesh was 80 which is within the effectiveness range (30-300) for k-ε turbulence model for modeling the log-layer region.

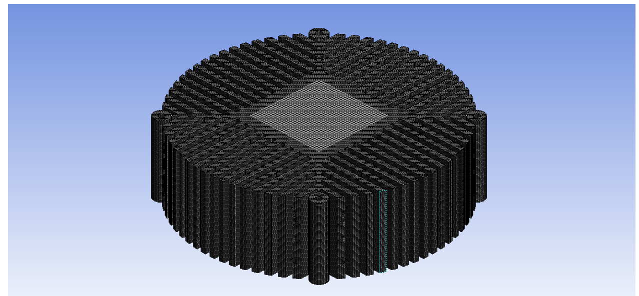

Fig.3 Mesh for heat sink used in air cooling process.

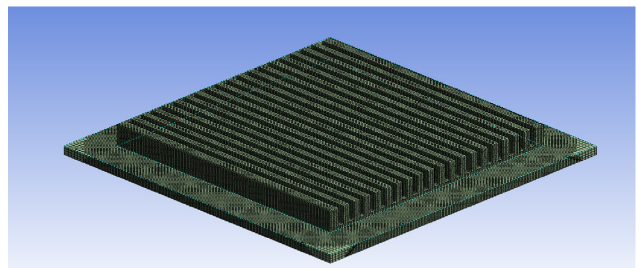

Fig.4 Mesh for heat sink used in liquid cooling process.

2.5 Grid Independence Test

Table 1 Grid independence test results for heat sink in Fig.1

Number of Elements	Dissipated heat, $\dot{q}$ (W)
9.63×10^5	111.93
1.78×10^6	112.85
3.11×10^6	112.97
5.68×10^6	112.97

Table 2 Grid independence test results for heat sink in Fig.2

Number of Elements	Dissipated heat, $\dot{q}$ (W)
1.56×10^6	114.74
1.86×10^6	114.53
2.17×10^5	114.49
2.58×10^5	114.48

A series of simulations were performed to find the mesh independent solutions for both air cooling and liquid cooling processes. Mesh containing 3.11×10^6 and 2.17×10^5 number of elements were select for further simulation process.

3. Results & Discussion:

For the steady-state analysis of CPU air cooling process, a commercial heat sink 'Wrath Spire' was used with a cooling fan of maximum flow rate 49 cfm. For this flow rate, the Reynolds number is 8.27×10^3 thus the flow region is turbulent. Standard k-ε turbulence model is used in the analysis to showcase the turbulence effect near the heat sink wall. Fig.5 shows that the temperature distribution of heat sink and the CPU. After the steady-state analysis, the CPU surface temperature is found 321.11 K for air cooling. The surface temperature at the heat sink adjacent to the inlet fan was found to be 305 K. The maximum heat transfer rate was found to be 112.97 W. In real world applications, this temperature decrease is not ideal for optimal CPU performance. Later on, the CPU surface temperature for liquid cooling is found to be below 309 K as seen in Fig. 6. Which is much less than the CPU surface temperature found for air cooling.

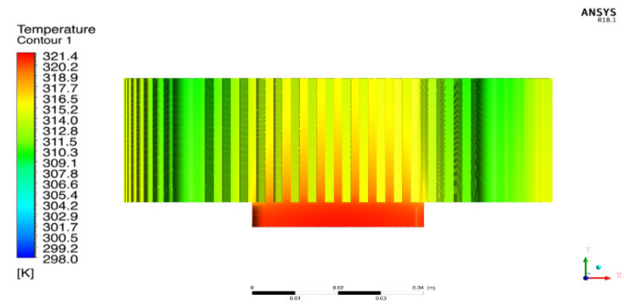

Fig.5 Temperature contour of heat sink used in air cooling

To analyze the liquid cooling processes coolants used are water and two different volume fractions nanofluid (0.5% and 2%) of CuO-water and Al_2O_3-water.

The temperature distribution over the CPU surface for various Reynolds number ranging from 400-1700 are shown in Fig. 6. For these Reynolds numbers the flow is in the laminar region. It can be seen from the figure that there is a decrease in CPU surface temperature with increasing Reynolds number for all fluids. The CPU surface temperature is the highest for water and the lowest for CuO-water nanofluid. For the maximum flow rate the maximum temperature difference was around 0.22K between water and 2% CuO-water nanofluid.

The changes in local heat transfer coefficients along with increasing Reynolds number are depicted in Fig. 7. 2% CuO-water nanofluid has the maximum local convective heat transfer coefficient when compared to the other liquid coolants. For instance, heat transfer coefficient for 2% CuO-water nanofluid is 1818.093 W/m^2K for Reynolds number 1191. For the same mass flow rate, water has the heat transfer coefficient 1758.936 W/m^2K and 2% Al_2O_3-water nanofluid has 1804.039 W/m^2K.

The variation of Nusselt number are shown in Fig.8 along with Reynolds number. Nusselt number indicates the amount of heat transfer between the moving fluid and the solid body. It shows the ratio of convection to conduction. 2% CuO-water nanofluid has the highest Nusselt number which indicates that it has better convection characteristics compared to the other liquids, whereas water has the least among the liquids.

The effect of Reynolds number on thermal resistance of the liquids are shown in Fig. 9. Thermal resistance indicates the resistance to heat transfer in the fluids. 2% CuO-water nanofluid shows the least thermal resistance compared to other liquids. For mass flow rate of 0.08 kg/s, the thermal resistance of 2% CuO-Water nanofluid is less than water by 3.68%. On the other hand, thermal resistance of 0.5% CuO-Water is 1.54%, 0.5% Al_2O_3-water nanofluid is 0.7% and 2% Al_2O_3-water nanofluid is 2.75% less than water.

The variation of frictional coefficient against Reynolds number is shown in Fig. 10. The friction coefficient decreases with increasing Reynolds number. There is no significant change in the frictional resistance for the different liquids.

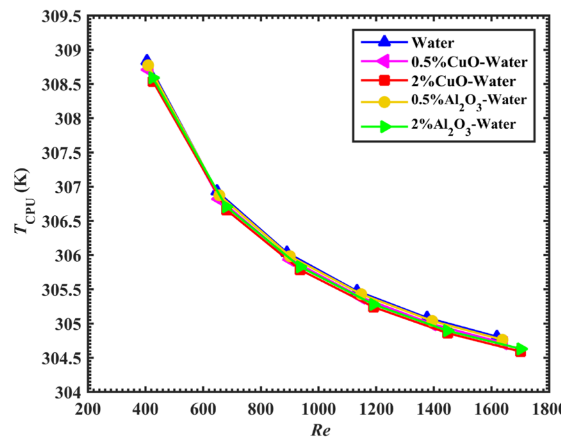

Fig.6 CPU surface temperature values for water and nanofluids for a dissipated heat of 115W.

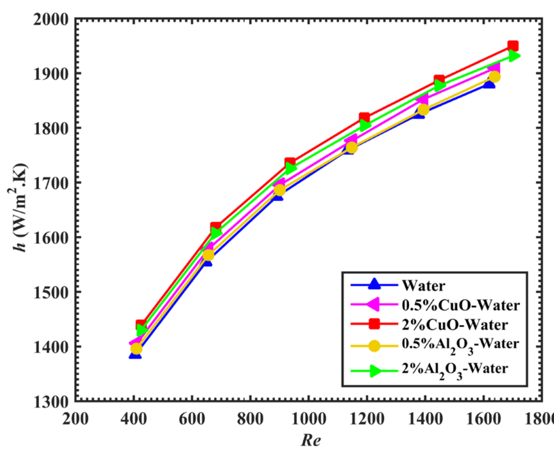

Fig.7 Local heat transfer coefficient values for water and nanofluids for a dissipated heat of 115W.

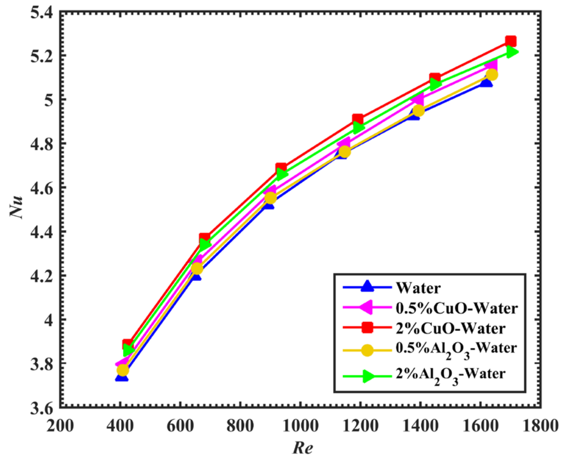

Fig.8 Local Nusselt number values for water and nanofluids for a dissipated heat of 115W

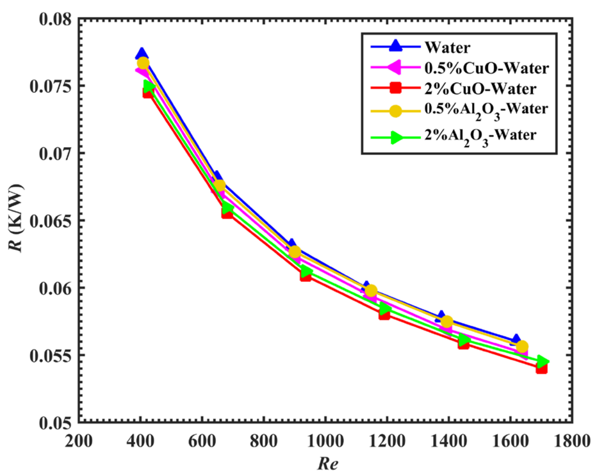

Fig.9 Thermal resistance values for water and nanofluids for a dissipated heat of 115W.

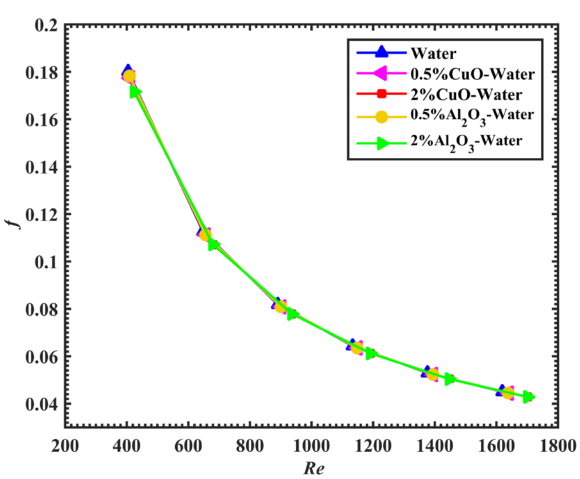

Fig.10 Frictional coefficient values for water and nanofluids for a dissipated heat of 115W.

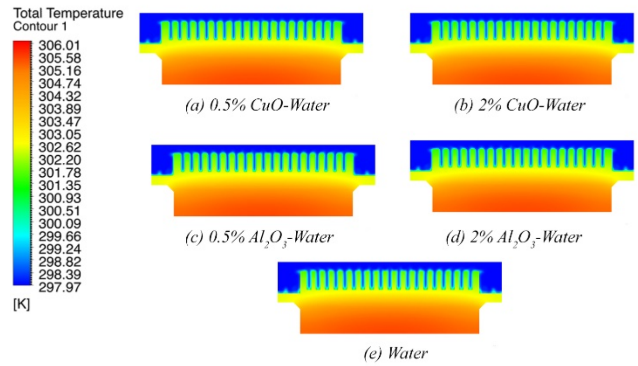

Fig.11 Temperature contours of heat sink used in liquid cooling in cross-section A-A

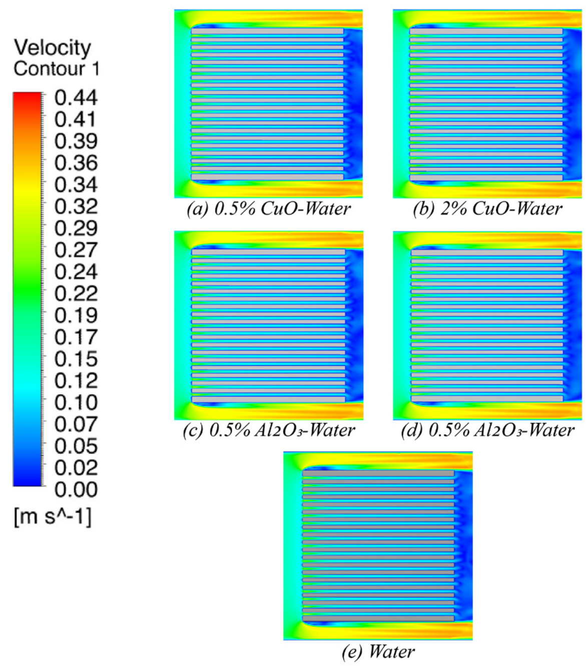

Fig.12 Velocity contours of heat sink used in liquid cooling in cross-section B-B

The temperature contours of the heat sink for various liquids in cross-section A-A are shown in Fig.11. From the temperature contours, the inlet fluid temperature is 298K. The fin temperature is within the range 300-302K. The temperature of the fluid adjacent to the fin walls is ranging from 299-300K. The CPU surface temperature is within 305-306K.

The velocity contours of the fluid flow across the micro-channel along the section B-B are shown in Fig.12. The inlet velocity is within the range of 0.10-0.18m/s. It also shows the flow separation behavior near the wall region. Stagnation point can be seen at the micro-channels' outlet.

4. Conclusion

In this paper, steady-state conjugate heat transfer analysis of different CPU cooling processes using CFD process were carried out. Ansys FLUENT 18.1 was used to carry out these simulations. The coolants used were air, water, 0.5%CuO-water nanofluid, 2% CuO-water nanofluid, 0.5% Al_2O_3-water nanofluid and 2% Al_2O_3-water nanofluid. Air had the worst heat transfer characteristics among them while 2% CuO-water nanofluid had the best, followed by 2% Al_2O_3-water nanofluid. The CPU surface temperature is found 321.11K for air cooling. For Reynolds number of 400, the maximum CPU surface temperature is found to be 308.83K for water and the minimum is found to be 308.53K for 2% CuO-water nanofluid. For Reynolds number of 1600, the maximum CPU surface temperature is found to be 304.81K for water and the minimum is found to be 304.59K for 2% CuO-water nanofluid. For Reynolds number of 400, the minimum local heat transfer coefficient is found to be 1384.84 w/m^2 for water and the maximum is found to be 1439.224 w/m^2 for 2% CuO-water nanofluid. For Reynolds number of 400, the minimum local heat transfer coefficient is found to be 1880.14 w/m^2 for water and the maximum is found to be 1949.74 w/m^2 for 2% CuO-water nanofluid. The liquid nanofluids were compared to water using various parameters and they consistently showed better heat transfer characteristics. The results show clear improvement in heat transfer characteristics when using nanofluids.

5. References

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Nomenclature

ρ : Density, kg/m^3
v : Velocity, m/s
C_p : Specific heat, J/kg.k
k : Thermal conductivity, W/m.k
μ : Kinematic viscosity, kg/m-s
D_h : Hydraulic diameter, m
Q : Mass flow rate, kg/s
$\dot{q}$: Dissipated heat, W
h : Heat transfer coefficient, $W/m^2.K$
Φ : Volume fraction, %