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Numerical Study of Chilled Ceiling with Different Nano Fluids

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***Abstract*:** Chilled ceiling system has benefits for providing comfort conditions and power saving. Mathematical and numerical analyses are presented. Three-dimensional and steady-state heat transfer are assumed. Temperatures distribution on the ceiling, floor, and heat transfer of the chilled ceiling are studied numerically by using the ANSYS FLUENT 18program for coolant of pure water and different nanofluids. The new correlation of the overall heat transfer coefficient is derivative. The effect of nanofluids and pure water velocity changed from(0.3 to 0.55)m\sec with constant inlet temperature and concentration of nanoparticles fluid on Reynolds number, Nusslt number, convection heat transfer coefficient, overall heat transfer coefficient, and cooling capacity of the chilled ceiling are analyzed. The different types of nanofluids are used: copper \water, and aluminum \ water. The numerical simulating is validated by the experiment's past studies and appeared good matching. The numerical and mathematical results concluded that the best rate of heat transfer of chilled ceiling can be noticed when using copper\water with a 0.5% concentration of copper particles and velocity of 0.55 m\sec. The cooling capacity of the chilled ceiling is influenced by the type of fluids so that the higher cooling capacity is presented by using copper\water with a 0.5% concentration of copper particles and velocity of 0.55 m\sec.

Key Word: Chilled Ceiling, Nanofluid, and Chilled Ceiling, Cooling Capacity, Mathematical Model, Nanofluid Type

I. Introduction

Radiant cooling systems(RCP) are pulling in increasingly more consideration due to enhancing thermal comfort conditions, saving energy, peaceful operation, and so on **[1]**. the popular radiant cooling system consists of tubes embedded in the ceiling, floor, or wall **[2]**. It includes flowing water through the neighboring structure surfaces and gives over half of the absolute sensible heat for building zone molding by radiation, and convection heat moves **[3]**.RCP presents the wide flexibility from where the division and installation comparison with other radiant system kinds, like capillary tube systems and, thermally active building systems**[4]**. Many studies have been achieved for improving the performance of chilled ceilings. Fisher and Pedersen **[5]** improved a correlation for mixed convection in the room, dimensioned 5.48 m × 3.65 m × 3.35 m in width, length, and height respectively, with changes in air per hour ventilation at 3–12. Awbi and Hatton **[6]** investigated the performance of chilled ceiling by proposing mixed convection heat transfer coefficient, both natural and forced convection impacts in a fully -insulated ambient chamber, 2.78 m × 2.78 m × 2.3 m in width, length, and height respectively, are used. Okamoto et al. etc **[7]** provided a calculation model for evaluating heat fluxes of ceiling radiant panels with the tube of meandering arrangement and spiral arrangement, utilizing tube density on panels and the difference in temperature between air room and supply water. This model is primarily utilized for panels that have small tube pitches and the difference in temperature of all surfaces can be neglected. Tye-Gingras and Gosselin **[8]** have concluded a semi-analytical method to the low thermal mass serpentine arrangement of radiant panels. Programming is needed in the calculation, due to several equations should be determined iteratively and numerically. Zhang et al. **[9]** presented experiments to determine the performance of metal ceiling has sloping fins. The heat transfer coefficient of radiation is nearly constant in all cases about 5.5W/(m^2.K). Xie et al. **[10]** studied non-uniform temperature and performance of capillary radiant cooling ceiling. Yu et al **[11]** analyzed the performance of metal panels with the serpentine arrangement of the tube. Lim et al **[12]** studied the performance of the thermoelectric radiant panel for heating numerically and experimentally. Shoky et al **[13]**presented an experimental and numerical study to find the profile of the temperature and velocity distribution. Also, studied the contaminant concentration in an occupied zone by using a corrugated ceiling radiant cooling plate (RCP) combined with Displacement Ventilation. Radzai et al **[14]** presented a review study for the various radiant cooling system such as the radiant cooling system with various water pipe configurations and compared the different designs of flow patterns. Also, investigated numerically the heat transfer of chilled ceiling and cooling characteristics. This paper aims to investigate numerically the performance of metal chilled ceilings with new kinds of fluid flowing through the tube of metal panels. The new fluids include Nanofluids such as copper oxide with water base fluid and aluminum oxide with water base fluid. Also derivation a new simplified formula to overall heat transfer coefficient of metal panels.

Nomenclature	
AUST	Area –weight average temperature of the uncontrolled surface in the room °C
Cp	Specific heat J/(K kg)
D	diameter of the tube

h	convection heat transfer coefficient(W/m2.K)
K	Thermal conductivity of the fluid(W\m.K)
Nu	Nusselt number
Pr	Prandtl Number
q_C	Convection heat flux ((W/m^2)
q_r	Radiation heat flux ((W/m^2)
Re	Reynolds number
T_a	Avarge room air Temperture (°C)
T	Temperture (°C)
U_o	Overall heat transfer coefficient between ceiling and room (W/(m^2 .°C)
W	Weight(g)
Ø	volume concentration
ρ	Density (kg\m^3)
μ	Viscosity (Pa.s)
Subscript	
bf	Base fluid
c	convection
f	fluid
h	Hydraulics
Nf	Nano fluid
Np	Nano particle
mp	Mean panel

II. Mathematical Model

A. Mathematical Model of Chilled Ceiling and Fluids Flow

The cooling capacity of the chilled ceiling equals the total heat flux that absorption by the chilled ceiling. Total heat flux (q_{tot}) represents by summation of radiation heat flux (q_r) and convection heat flux (q_c) [15]. Radiation heat flux (q_r) consists of short and long waves radiation. For this case study, there is no solar radiation, so q_r refers to longwave radiation heat that interchange between ceiling surface and inside surfaces of test zone.

Cooling capacity of chilled ceiling = $q_{tot} = q_r + q_c$ (1)

where

q_{tot} : Total heat flux (W/m^2)

q_r : Radiation heat flux ((W/m^2)

q_c: Convection heat flux (W/m^2)

The total heat flux absorption by the chilled ceiling can be written as Eq. (2) [16]

$$q_{tot}=U_o(T_a-T_{mp}) \quad (2)$$

Where

U_o: Overall heat transfer coefficient between ceiling and room (W/(m^2 .°C)

T_a: Average room air temperature (°C)

T_{mp}: Mean plate temperature(°C)

The radiation heat flux and convection heat flux can be expressed as Eq.(3)&(4) [17]

$$q_r = 5\times10^{-8} [(T_{mp}+273)^4-(AUST+273)^4] \quad (3)$$

$q_c=2.13(T_a - T_{mp})^{1.31}$ (4)

where

AUST: Area –weight average temperature of the uncontrolled surface in the room

Now , substitute Eq.(2),(3) and (4) in Eq.(1),

$$U_o(T_a-T_{mp}) = 5\times10^{-8}\,[(T_{mp}+273)^4-(AUST+273)^4] + 2.13(T_a - T_{mp})^{1.31} \quad (5)$$

The new expression of the Overall heat transfer coefficient from Eq.(5) can be seen as Eq.(6)

$$U_o=\frac{5\times10^{-8}\,[(T_{mp}+273)^4-(AUST+273)^4]}{(T_a - T_{mp})} +2.13(T_a - T_{mp})^{0.31} \quad (6)$$

For the flowing of the different fluids inside the tube, the forced convection heat transfer and turbulent flow are applied. So Nestle Number and the convection of heat transfer coefficient can be determined as following equations:

$$Nu=0.023(Re)^{4/5}\times Pr^{0.4} \quad (7)$$

$$h=\frac{Nu_D \times k_f}{D_h} \quad (8)$$

Where

h:convection heat transfer coefficient(W/m^2.K)

Nu: Nusselt number

Re: Reynolds Number

Pr: Prandtl Number

K_f : Thermal conductivity of the fluid(W\m.K)

D_h: The Hydraulics diameter of the tube (mm)

B. Mathematical Model of Nano Fluids

The most necessary properties of Nano fluid required for evaluating the cooling capacity of the chilled ceiling when used Nanofluids are density, thermal conductivity, specific heat, and viscosity. Thermo properties of Nanofluids are evaluated mathematically for all concentrations as following steps:

- The volume concentration of Nanoparticles needed for the preparation of Nanofluids is estimated utilizing the law of mixture as Eq.(9):[18]

$$\%\text{volume concentration } (\emptyset)=\frac{\left[\frac{WNano}{\rho Nano}\right]}{\left[\frac{WNano}{\rho Nano}+\frac{Wbf}{\rho bf}\right]} \quad (9)$$

Where:

W_{Np} : Weight of Nano particle (g)

W_{bf} : Weight of base fluid (g)

ρ_{Np} :Density of Nano particle (Kg/m^3)

ρ_{bf} :Density of base fluid (Kg/m^3)

- The base fluid, in this study, is water. The density of Nanofluids to all the volume concentrations in this investigation are estimated by using the following Eq.(10) [19] :

$$\rho_{Nf}=\emptyset\rho_{Np}+(1-\emptyset)\rho_{bf} \quad (10)$$

- The Nanofluids own unique specifications related to their thermal performances. Nanofluid's properties are various from the properties of basic heat transfer fluids. The nanoparticles offer a large surface area so that higher thermal conductivity is noticed in Nanofluids. The thermal conductivity of Nanofluid can be estimated from Eq.(11): [20]

$$k_{Nf}=k_{bf}\frac{[(k_{Np}+2k_{bf})-2\emptyset(k_{bf}-k_{Nf})]}{[(k_{Np}+2k_{bf})+\emptyset(k_{bf}-k_{Nf})]} \quad (11)$$

Where:

K_{Nf}: Thermal Conductivity of Nanofluid (W/m·K)

Table(1):The properties of fluid

K_{bf}: Thermal Cond

K_{Np}: Thermal Conductivity of Nanoparticle (W/m·K)

- The specific heat is the necessary property and has a substantial role in impacting the heat transfer rate of Nanofluids. For all volume concentrations of Nanoparticles in the base liquid, the specific heat can be estimated utilizing Eq.(12): [20]

$Cp_{Nf}=\emptyset Cp_{Np}+(1-\emptyset)Cp_{bf}$ (12)

Where :

Cp_{Nf} : Specific heat of Nanofluid J/(K kg)

Cp_{Np}: Specific heat of Nanofluid J/(K kg)

Cp_{bf} : Specific heat of base fluid J/(K kg)

5. A few experimental studies are concert on the Nanofluid viscosity and correlations are made to predict the Nanofluid viscosity in terms of volume concentration and base fluid density. In this study viscosity of Nanofluid can be estimated from the following Eq.(13): [20]

$$\mu_{Nf} = \mu_{bf}\left[\frac{1}{(1-\emptyset)^{2.5}}\right] \quad (13)$$

μ_{Nf} : Viscosity of Nanofluid (Pa.s)

μ_{bf} : Viscosity of base fluid (Pa.s)

The properties of fluids are utilized in this study can be shown in table(1)

Fluid	**Density (kg/m^3)**	**Thermal Conductivity of (W/m.K)**	**Specific heat of J/(K kg)**	**Viscosity (Pa.s)**
Water	1000	0.60	4180	8.91×10^{-4}
Copper oxide with water base fluid	6510	18	540	-
Aluminum oxide with water base	3970	40	765	-

III. Numerical Analysis

In this study, three different fluids, as coolants, are used to flow through the metal panel also, the room without a chilled ceiling is studied. ANSYS FLUENT18 **[21]** is utilized for simulating temperature and velocity distribution in the occupied zone and temperature distribution through the panels of the ceiling under different inlet temperatures and flow rates. Finite volume mode is utilized by chopping the zone into a considerable number of elements and using partial differential equations for all the elements with transferring them into the algebraic equation to resolve it. The first step of numerical simulation draws the geometry by Autocade2018 **[22]**. The geometry is the same for all cases, consisting of a room, panel ceiling, and heat sources. The room dimensions of 200 ×200× 200 cm in width, length, and height respectively. The panel ceiling includes a metal panel and tube. The metal panel is made from Aluminum, with dimensions of 200×200 cm in width and length respectively and 0.55mm thickness. While the tube is made from copper with inner and outer diameters of 11.7mm and 12.7mm respectively. The tube is arranged in a serpentine shape with a pitch of 20 cm. The three-quarter of the tube is immersed by the metal panel. The heat sources represent by distributing four boxes, cubic shape, dimensions of each box is 40 ×40× 40 cm in width, length, and height respectively. Figure(1) shows the details of geometry. The properties of the used material can be seen in the table(2).

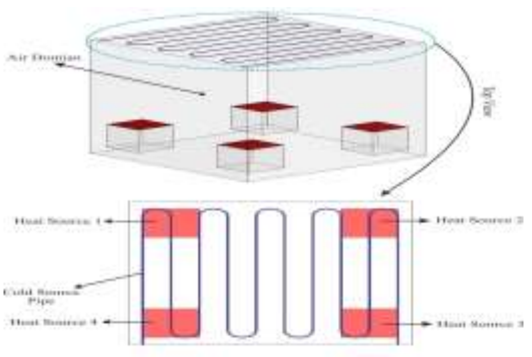
Table(2):The properties of material

Material	**Density (kg/m^3)**	**Thermal Conductivity of (W/m.K)**	**Specific heat of J/(K kg)**
copper	8940	401	390
Aluminum	2700	226	946

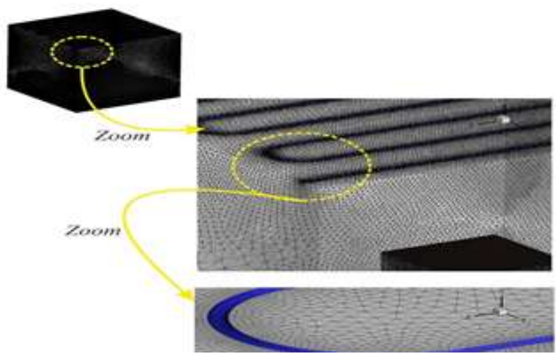
The second step of numerical simulation is generation mesh. It considers the basic technique for estimating the solution. A three-dimensional tetrahedral element is used. The cell number is5769299 with nodes is 1125060 utilized for three dimensions mesh. These types of mesh are utilized due to produce good mesh with high accuracy. The mesh of geometry and mesh type can be seen in figure(2). The total number of cells is a necessary indicator to present a good mesh. The numbers of cells are utilized for using chilled ceiling with different types of coolants fluids and without using chilled ceiling are the same. The boundary conditions for the flow and heat are specified for each section of the computational domain. The boundary conditions can be summarized in table(3)

Table(3):The boundary conditions description

Case number	Case description	Volume concentration %	The velocity of the supplied fluid (m/sec)	The temperature of the supplied fluid (°C)	Heat flux per each heater (W/m^2)
1	Without chilled ceiling	-	-	-	312.5
2	Chilled ceiling with coolant is water only	-	0.55-0.30	15	312.5
3	Chilled ceiling with coolant is copper oxide with water base fluid	0.5%	0.55-0.30	15	312.5
4	Chilled ceiling with coolant is Aluminum oxide with water base	0.5%	0.55-0.30	15	312.5



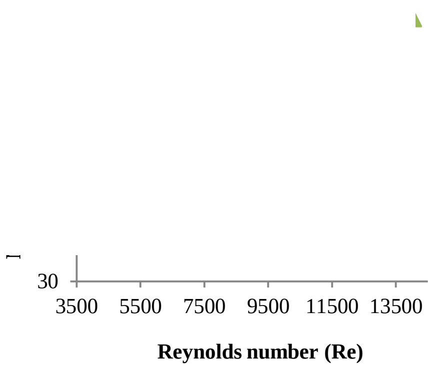
Figure(1):Describe the geometry of room



Figure(2): The geometry and type of mesh

IV. Validation

Validation of data is necessary to reliable the results. As part of numerical validation, the system is investigated numerically with pure water, turbulent states, and the Reynolds number domain of 6000–10000. Validation of the Nusselt number is made from the experimental results of Jassim and Ahmed **[23]** is appeared in Fig. 4. The figure shows that the numerical data obtained from the investigated is matches with Jassim and Ahmed study. It is also noted that the Nusselt number is directly proportional to the increase in the flow rate.



Figure(4): The validation of present study

V. Results and Discussion

Reynolds number is the optimum factor for describing the impact of fluid velocity, fluid flow rate, on the Features of the heat transfer. For different fluids, figure 5 appears the relationship between heat transfer coefficient and Reynolds number. It seems that by increasing the Reynolds number for different fluids, the heat transfer coefficient increases. The increase of heat transfer coefficient is related to the augment of fluids flow rate which causes the heat transfer rate to increase. Also, can be noticed that the copper\water (Nanofluid) has the higher heat transfer coefficient values. This is due to the higher thermal conductivity for the Nanofluid copper\water compared with aluminum\water and pure water. In addition to the effect of viscosity on the wall of tube decreases that causes to decrease the boundary layer thickness and force of shear stress on the wall of the tube causes to augment the heat transfer coefficient.

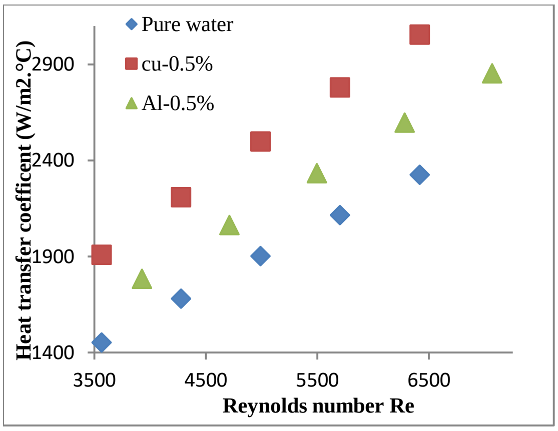
Figure 6 shows the Nusselt number in form of a Reynolds number. For all fluids, pure water and the two Nanofluids (copper and aluminum), it is noticed that the Nusselt number is in direct proportion with Reynolds number because of Nusselt number is a function of heat transfer coefficient so that the increase of heat transfer coefficient as Reynolds number increases leads to increase Nusselt number. However, the amount of Nu of Nanofluid is appeared to be higher than that of the pure water at a certain value of Re. This behavior can be related to the interaction between Nanoparticle with base fluid that leads to the breakdown of the layer of a boundary due to increasing the turbulence intensity.

Figure(7)describes the relationship of overall heat transfer coefficients (between the room and chilled ceiling) with increases of Reynolds number. For different fluids, pure water, and two Nanofluids, it is clear from figure 7 that the overall heat transfer coefficient increases as the Reynolds number increase. This is because depending on the overall heat transfer coefficient on convective heat transfer coefficient so that increases in Reynolds number cause higher overall heat transfer coefficient. Also, can be noticed that the higher overall heat transfer coefficient for copper\water comparison with pure water and aluminum\water. This is due to copper\water having a higher value of convection heat transfer coefficient and thermal conductivity.

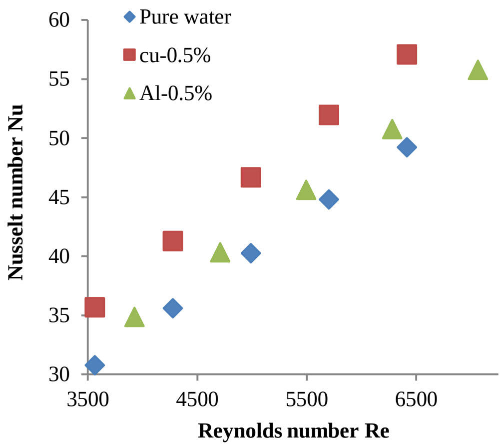
Figure(8)describes the relationship of overall heat transfer coefficients (between the room and chilled ceiling) with the difference between air temperature and mean panels temperature. For different fluids, pure water, and two Nanofluids, it is clear from figure 7 that the overall heat transfer coefficient decreases as the temperatures difference increase. This is because of decreasing in convection heat transfer rate since the air temperature does not approach the mean panel's temperature. Also, can be shown that the higher overall heat transfer coefficient for copper\water comparison with pure water and aluminum\water.

Figure(9)presents the relationship between the overall heat transfer coefficient and cooling capacity of chilled ceiling for different fluids (pure water, cooper\water, and aluminum \water). As clear from the figure (9), the cooling capacity increases as the overall heat transfer coefficient increases for all fluids. Also, can be noticed that the higher cooling capacity is obtained when using copper\water as a coolant because copper\water has the higher overall heat transfer coefficient.

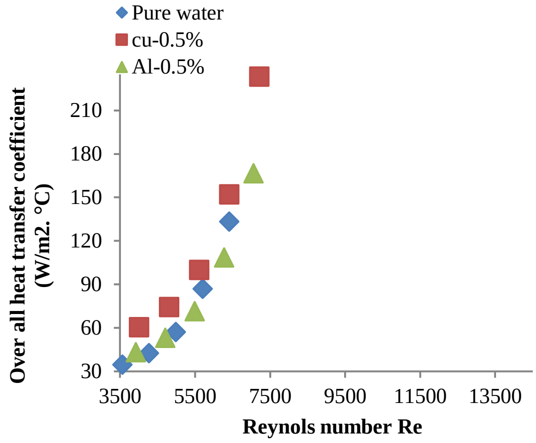
Figures (10), (11), (12), and (13) present the temperatures distribution on the ceiling and floor for cases without chilled ceiling, chilled ceiling with pure water, chilled ceiling with aluminum\water, and chilled ceiling with copper\water respectively. From figures(11),(12), and (13) can be noticed that the temperatures on the ceiling increase with the tube length increases this is referred to as increased heat transfer rate with increased length. Also, can be seen from these figures that the maximum temperature difference (temperature difference between outlet coolant temperature and inlet coolant temperature) when used cooper\water as a coolant. The temperature difference of (3,1.7and 1)°C for copper\ water, aluminum\water, and pure water respectively. That leads to the higher heat transfer rate of copper\water while the lower heat transfer rate can be noticed from the figure(10) because do not use chilled ceiling. Also, from figures(10) to (13) can be concluded that the temperature is distributed uniformly on the floor and the higher floor temperature can be seen from the figure (10) due to do not using chilled ceiling while the lower floor temperature can be seen from the figure(13) due to use chilled ceiling with Cu\water because Cu\water causes a higher rate of heat transfer.



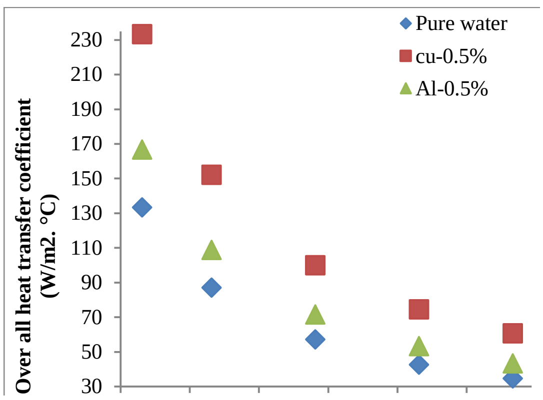
Figure(5): The variation of heat transfer coefficient with Reynolds number

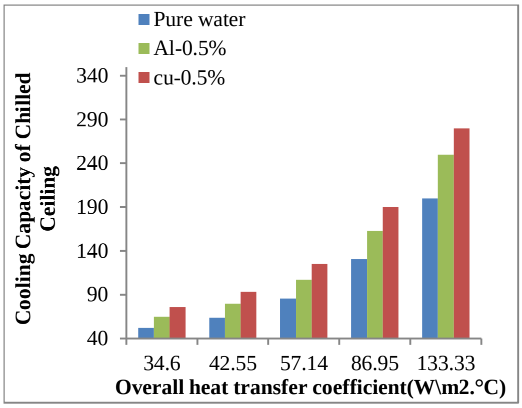


Figure(6): The variation of Nusselt number with Reynolds number



Figure(7): The variation of Overall heat transfer coefficient with Reynolds number





Figure(8): The variation of Overall heat transfer coefficient with difference temperatures between air and mean panels.

Figure(9): The variation of Overall heat transfer coefficient with Cooling capacity of chilled ceiling

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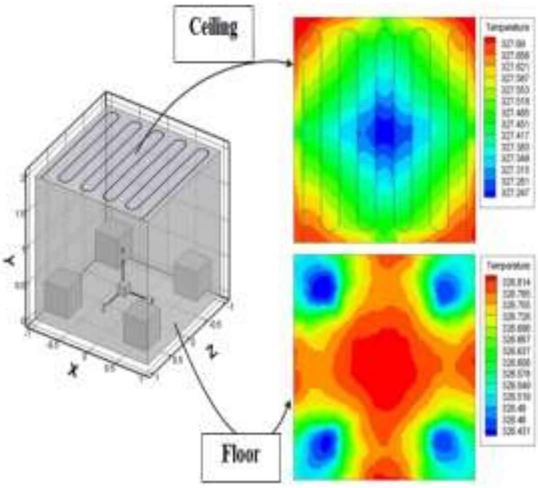

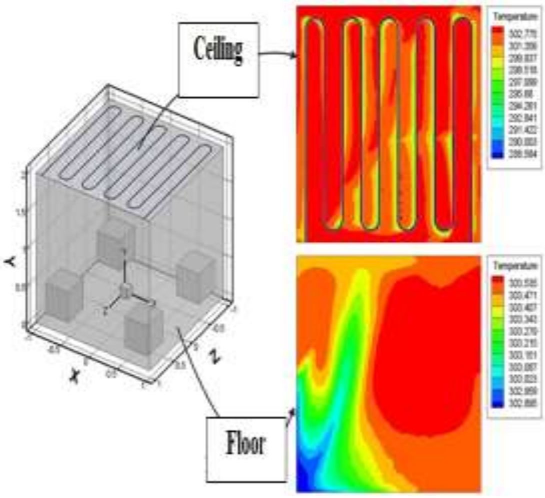

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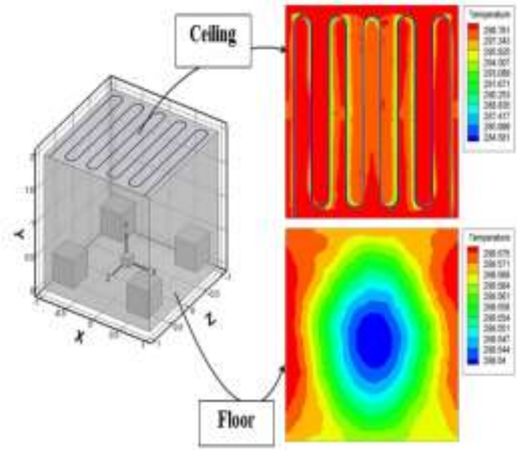
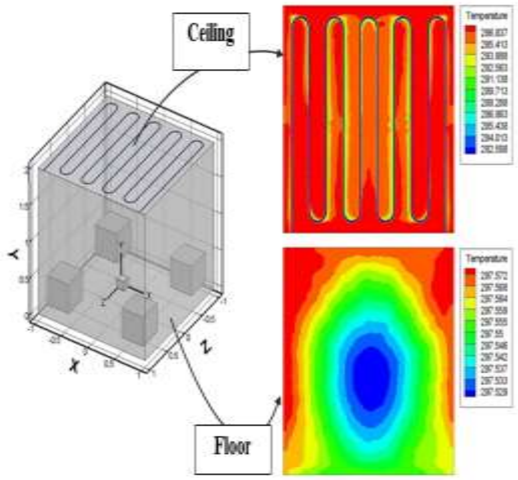


Figure(12): Temperatures distribution on ceiling and floor for Al-0.5% and water



Figure(13): Temperatures distribution on ceiling and floor for Cu-0.5% and water

VI. Conclusion

This study presents a simplified new correlation of the overall heat transfer coefficient between chilled ceiling and room. The cooling capacity of the chilled ceiling, Reynolds number, Nusselt number, temperatures distribution on ceiling and floor are studied numerically with three different fluids: pure water, copper \water, and aluminum \water and different velocity range of (0.3 to 0.55)m\s. The constant nanofluids concentrations of cu-0.5% and Al-0.5% are utilized. The numerical study is achieved by using ANSYS FLUENT18. The model has used consists of a room with dimensions of 200 ×200× 200 cm in width, length, and height respectively. The panel ceiling is made from metal panels and tubes with serpentine shapes. The inner and outer tube diameters of 11.7mm and 12.7mm respectively. The heat source is represented by four boxes, cubic shape, with dimensions of each box of 40 ×40× 40 cm in width, length, and height respectively. Each one produces 50W/m^2. The results show that for different fluids type, increasing the velocity of fluid from(0.3 to 0.55)m\sec causes an increase Reynolds number so that convection heat transfer coefficient increase from (1909.68 to 3056.12)W\$m^2$.° C ,from (1783.43 to 2854.14) W\$m^2$.° C and, from (1453.08 to 2854.14) W\$m^2$.° C for cu-0.5%\water, Al-0.5%\water and pure water respectively also Nusselt number increase from (35.66 to 57.07) , from (34.84 to 55.76) and, from (30.75 to 49.22) for cu-0.5%\water ,Al-0.5%\water and ,pure water respectively .The overall heat transfer increase from (60.55 to 233.33) W\m2.° C, from (43.25 to 166.66) W\$m^2$.° C ,and from(34.6 to 133.3) W\$m^2$.° C for cu-0.5%\water , Al- 0.5%\water and ,pure water respectively. From the above results can be concluded that the higher convection transfer coefficient, Nusselt number, and overall heat transfer coefficient for using cu-0.5%\water as a coolant. A higher cooling capacity is noticed when used cu-0.5%\water. At overall heat transfer coefficient is 34.7 W\$m^2$.° C, the cooling capacity are (75.68%,64.87% and 51.9%) for cu-0.5%\water ,Al-0.5%\water and ,pure water respectively.All fluids can be provided uniform temperature distribution on the ceiling and floor. But the best distribution of temperature can be noticed when used copper \water with a concentration of 0.5%

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