

The Experimental and Theoretical Study in Performance of Chilled Ceiling

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Abstract

The present study represents the experimental study for the performance of the chilled ceiling and its ability to achieve thermal conditions in occupied zones. The experimental study included the effect of different internal loads of (1600, 1300 and 1000) W and different supplied chilled water temperatures of (13.3, 14.2, 16.8 and 18)°C on the performance of chilled ceiling. The experimental results show that the cooling capacity of chilled ceiling increases as the temperature of supplied water decreases. For a decrease in the temperature of supplied chilled water by 33.5%, the cooling capacity of chilled ceiling is increased by 18.73%. This study presented a theoretical study of velocity and temperature distribution in occupied zones when using chilled ceiling.

1. Introduction

Chilled plates, a type of radiant chilled ceiling, are installed at typical heights from (2.5 to 8) m and can be installed on walls or floors. They cool only the plate surface. This type of system results in low air speed with an even temperature distribution in the occupied zone, thus providing very good comfort levels. It can provide an architecturally agreeable surface, into which a domain of services can be fitted. These plates achieved an extremely fast response of only a few minutes to alternating internal loads by metal plates because of low thermal inertia and lightweight construction, while the response of plaster board chilled ceiling to change internal load in space is about four to five times that of metal plates [1].

Tanabe et al., [2] investigated experimentally the effect of small air movement and humidity on comfortable conditions by using a radiant cooling system. The results show that, at higher humidity, the SET* (standard new effective temperature) was considered more suitable and a correct method to evaluate the thermal sensation vote of the whole body within ± 1 scale error of thermal sensation. Small air motion in the radiant cooling panels led to a sensation nearly one scale cooler than still air conditions at the same level of SET*.

Catalina et al., (2007), [3] examined experimentally the thermal performances of cooling ceilings and their effect on thermal comfort in a test room with an area of 9.6 m². The temperatures of all the exterior walls were controlled. The studied ceiling panels were equipped with capillary mats using polypropylene as material. Predicted Mean Vote (PMV) values have been calculated for different chilled ceiling surface temperatures to evaluate thermal comfort. The results indicate that the cooling ceiling could achieve indoor thermal comfort and good thermal performances in terms of specific cooling rate or vertical temperature asymmetry. The results obtained after the experiment showed that with a cooling ceiling the vertical temperature asymmetry is less than 1.1°C, which is an acceptable value that will not create discomfort in the occupancy zone.

Raghavan et al., (2017), [4] studied the potential of energy saving and cost benefit when using a slab-integrated radiant cooling

system. Their study was carried out at a green building in Malaysia with an installed radiant convective system. The performance of the cooling system was studied and estimated, and the energy saving by cooling radiant system was compared with the data obtained from the Building Energy Management System (BEMS) with evaluated energy consumption of conventional convective air system. The results show that the radiant slab system can lower the energy consumption by 34% compared with conventional variable air volume system, despite its higher initial cost. The payback period for the investment cost is about 2.5 years.

2. The Objective of the Main Work

The objective of this work can be summarized as follows:

- 1- Study the performance of chilled ceiling and its ability for reducing cooling load experimentally.
- 2- Study the potential of chilled ceiling to achieve thermal comfort conditions by using CBE tool.
- 3- Study the velocity and temperature distribution in occupied zones theoretically when using chilled ceiling.

3. Experimental Work

The chilled ceiling or chilled plate consists of corrugated metal plates (made of red copper metal) that are installed in a room with dimensions of 3m(H)x4m(W)x3m(L) located on the fourth floor on the surface of the Mechanical Engineering Department building, Al Mustansiriayah University, College of Engineering. Its location is at the south-east corner where both south and east walls are exposed to direct solar radiation while north and west walls are internal walls. The north wall is nearby conditioned space while the west wall is nearby unconditioned space. There are two windows; one of them has dimensions of 1.4m(W)x1.5m(H) on the south wall and another has dimensions of 1.85m(W) x 1.5 m (H) located on the east wall. Both windows have single glass with an iron frame. All four walls are 30 cm thick and consist of the following layers from inside to outside: Juss plaster 20mm, Cement plaster 20 mm,

Common Brick 240 mm , cement plaster 20mm . Figure (1) show the and diagramsketch of room.



Fig. 1: (a) The wall components

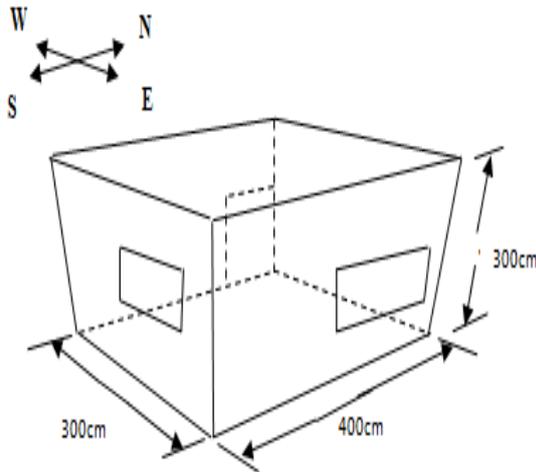


Fig. 1: (b) The details of Test Room

The chilled ceiling consist of corrugated metal plates, with copper tube is fitted inside it. A mold for the plate is made by pressing it by force at the same outer diameter of the tube(12.7mm) .The tube is fixed in the holes plate using lead welding applied at operating temperature of 250°C. The tube is fixed in the holes made inside the plate to increase the contact area between the tube and the plate in order to reduce the thermal resistance and increase the heat transfer between them . The plate is total area is cover about 54%of total area of the ceiling . Plate and pipes assembly made from red copper with high thermal conductivity of 404 W/m.°C [5],The dimension of each plate is 60cm(W)x60cm(L) and 150mm pitch manufactured according to ASHRAE standards [6]. The thickness of plate is 0.6mm . The remaining space of the area of the ceilingfilled with false plates .The back of each plate is covered with insulation made of glass wool which has a thermal conductivity of 0.04 W/m.°C, to prevent the heat gain to the plates from roof which is exposed to a direct solar radiation and to reduced the noise produced during the pass of water through the tubes. The copper tubes are fixed on corrugated panel a serpentine arrangement shape to increase the available time for heat transfer during water circulation and to enhance the heat transfer coefficients when compared with the straight parallel plate channel. [7]. The plate that made of red copper was painted from front side by black color to increase their ability to absorb the heat from the occupied zone . During experimental test the temperatures along the plate are measured using K-type thermocouple. Twenty seven thermocouples are fixed on the plates and the tubes distributed on three plates that are located at different position . Figure (2) illustrates the plate construction stages and the distribution thermocouples on the plates.



Fig. 2: The details of plates construction.

The plates assembly is installed at 2.7 m height of the test room by building up a frame of false ceiling. Figure (3) shows the finished ceiling photograph



Fig. 3: The Finishing Ceiling

The experimental tests can summarized in table (1)

Table 1: The Experimental Tests

No. of tests	Internal load (W)	Supplied chilled water temperature (°C)	Mean plate temperature (°C)
1	1600	13.3	16.5
		14.2	17
		16.8	20
		18	21.1
2	1300	13.3	16.4
		14.2	17.2
		16.8	19.8
		18	21
3	1000	13.3	16.1
		14.2	17
		16.8	19.5
		18	20.8

4. Mathematical Model

Analysis of chilled ceiling included:

- 1- Cooling capacity of chilled ceiling,
- 2- Number of required plates used in experimental work
- 3-Supplied mass flow rate of the chilled water to the chilled plates

Each items explained as following:

1- The Cooling capacity of chilled ceiling is determined by ability of plates to absorb heat from inside the room by radiation and convection as well as heat absorption by plates increase that means the plates capacity increase and near to remove cooling loads from zone. Assuming that the cooling load is equal to the electrical power of heat sources because the measurement were done in steady state conditions ,thus the heat gain are equal to cooling load, the capacity of chilled ceiling (cc) is given by the following equations:

$$\text{Cooling load} = Q \text{ heatgain in the space} = Q_{in} \quad (1)$$

$$Q \text{ Heat loss from space} = Q \text{ Heat absorption by plates} = Q_{out} \quad (2)$$

$$\text{since } Q_{in} = Q_{out} \text{ (1st law of thermodynamic)} \quad (3)$$

So,

$$\text{Cooling load} = Q \text{ Heat absorption} \quad (4)$$

$$Q \text{ Heat absorption} = Q \text{ radiation} + Q \text{ convection} \quad (5)$$

The equation of radiation is:

$$q_{r} = 5 \times 10^{-8} [(T_p + 273)^4 - (AUST + 273)^4] \quad (6)$$

AUST value can be determine as:

$$AUST = \frac{1}{A_{walls, total}} \sum_{i=1}^n A_{wall} T_{wall} \quad (7)$$

Depending on tests by Schruin et al .(1953) and simulation by Kalisperis (1985) based on a program developed by Kalisperis and summers (1985) they prove that if there is little or no outdoor exposure the AUST and air room are equal almost . This assumption is made in this research work .

For, analysis of heat transfer by convection. It defined as the heat transfer between the air and plate. Usually the heat transfer by convection is considered as natural convection. The convection heat transfer in plate depend mainly on temperature of plate surface and temperature of air stream layer directly below the plate because the fully developed stream begin usually (50 to 65mm) blow the plate. In this work the temperature is measured at 50mm below the plates, at 265 cm height. The convection heat transfer is determined by the following equation[9]:

$$q_c = h \times (T_p - T_{air}) \quad (8)$$

Where

$$h = 2.12 \times (T_p - T_{air})^{0.31} \quad (9)$$

To determine the required number of the plates ,assume an area of each plate is (60x60cm), then by using following equations[8]:

$$A_{plate} = \frac{\text{The maximum cooling load removed by CC(W)}}{(q_r + q_c)(W/m^2)} \quad (10)$$

$$N = \frac{A_{plates}}{A \text{ of one plate}} \quad (11)$$

The mass flow rate can be determined from the following equation:

$$Q(W) = m \cdot C_p \times (T_{win} - T_{wout}) \quad (12)$$

To improve the efficient of chilled ceiling for provide thermal comfort conditions ,PMV and PPD must be determine .In this work the PMV and PPD calculate using CBE tool. This tool produce by Building Energy Center for the calculations of thermal comfort according to the ASHREA standard 55 -2013 as shown in figure (4). At the left hand which represent the input date as illustrated in figure (4) that contain: air velocity , ,temperature of air and humidity in occupied zone ,mean radiant temperature , metabolic rate and clothing level. While at the right side give the results of PMV and PPD also tell you if system achieve comfortable conditions or not. This tool presented two methods of comfortable condition which are PMV method and adaptive

method. So firstly the selected method and then input the required data[9].

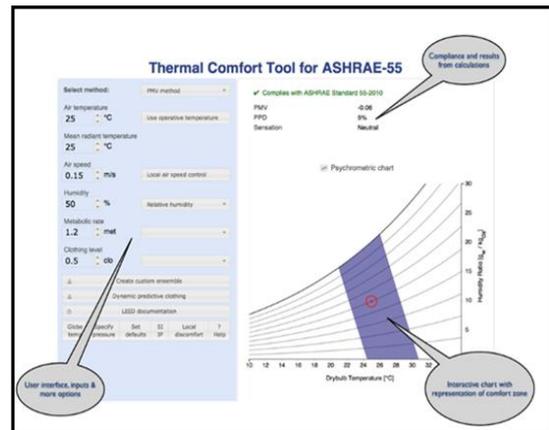


Fig. 4: The CBE tool

The required input parameters of CBE tool is temperatures, relative humidity and velocity of air in the room. These are obtained from experimental measurement, also metabolic rate , mean radiant temperature and clothing level. Since no device is available to measure the mean radiant temperature and its calculation consumption time, so in previous studies there was a try to avoid its calculation as possible. As a result in this study assume the mean radiant temperature is the same as the air temperature under indoor conditions [10].

5. The Results and Discussion

The effect of supply chilled water temperature on the performance of chilled ceiling is studied for different internal loads and constant mass flow rates of chilled water, as shown in figures (5) to (11).

Figure (5) shows the relationship between supplied chilled water temperature and mean plate temperature for different internal loads and constant supplied mass flow rate of chilled water. It can be noticed that for each internal load, as supplied chilled water temperature increases the mean plate temperature increases. The causes of increasing mean plate temperature with increase of supplied chilled water temperature. This illustrates that the internal load has a little impact on mean plate temperature for each supplied chilled water temperature due to constant mass flow rate of the supplied chilled water.

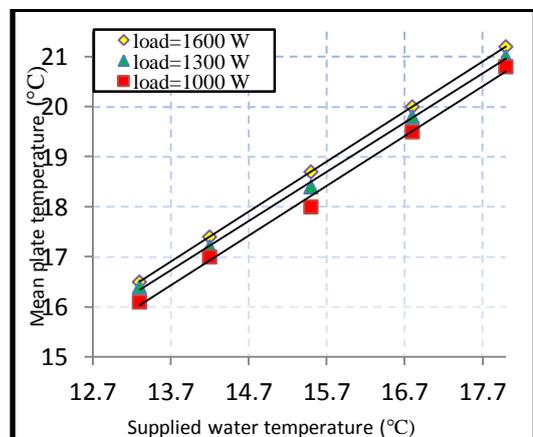


Fig. 5: The relationship between mean plate temperature and supplied chilled water temperature for different internal load

Figure (6) presents the relationship between heat transfer coefficient and supplied chilled water temperature for different internal loads. It can be noticed that for each internal load, the heat

transfer coefficient decreases as supplied temperature increases because of the decrease in the temperature difference with supplied chilled water temperature. Also it can be noticed, for each supplied water temperature, the heat transfer coefficient increase with increase internal load, due to increasing temperature difference with supplied chilled water temperature. For internal load increase from (1000 to 1600)W, the heat transfer coefficient increase from (4.61 to 4.77) W/m² respectively at supplied chilled water is 13.3°C.

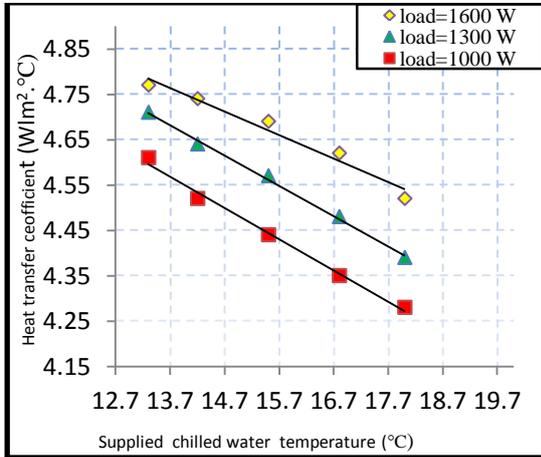


Fig. 6: The relationship between heat transfer coefficient and supplied chilled water temperature for different internal load

Figure (7) shows the relationship between average air room temperature (average at three different locations of heights, 10, 110, 170) cm and supplied chilled water temperature. It is clear that as supplied water temperature increases the average room air temperature increases for different internal loads, due to the increase of mean plate temperature with supplied chilled water temperature. At constant supplied temperature of chilled water, the average room air temperature increases with the increase in the internal load.

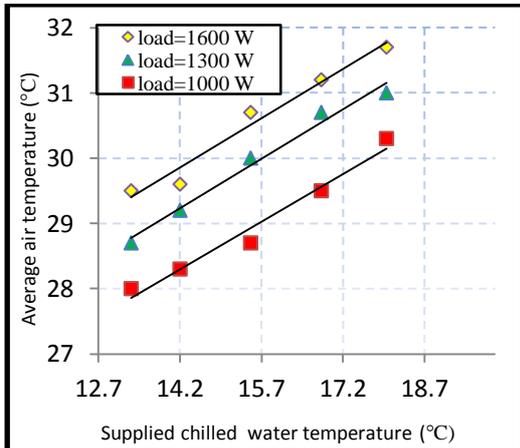


Fig. 7: The relationship between average air temperature and supplied chilled water temperature for different internal loads

Figure (8) describes the relationship between the cooling capacity and supplied water temperature for different internal loads. It can be noticed that for each internal load, the cooling capacity decreases with supplied chilled water temperature rise since convection and radiation heat flux decreases with increasing supplied chilled water temperature. For each supplied chilled water temperature, the cooling capacity increases with internal load increase, due to an increase in the convection and radiant heat flux with increasing internal load, for supplied chilled water temperature of 13.3°C, the cooling capacity increase from

(117.85 to 132.8)W/m² for internal loads increase from (1000 to 1600)W respectively.

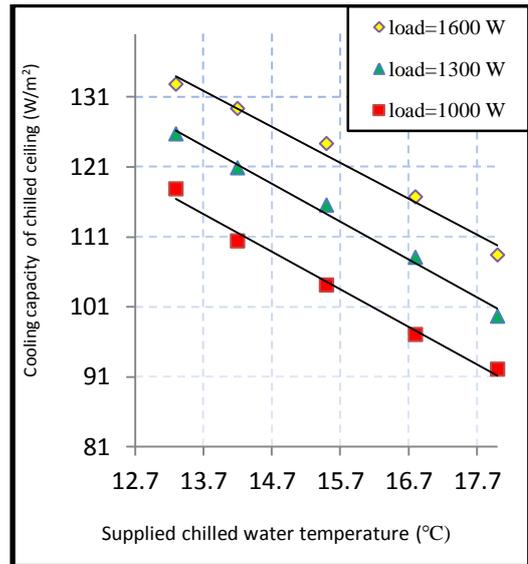


Fig. 8: The relationship between cooling capacity and supplied chilled water temperature for different internal loads

Figure (9) shows the relationship between PMV and supplied chilled water temperatures for different internal loads. It can be seen that as supplied chilled water increase, the PMV increases because of the increase in the average air temperature. For each supplied chilled water temperature the PMV increases as internal load increases since average air temperature increase as internal load increase. At supplied chilled water temperature of 13.3 °C, the PMV increases from (0.86to 1.3) for internal load increase from (1000 to 1600)W respectively.

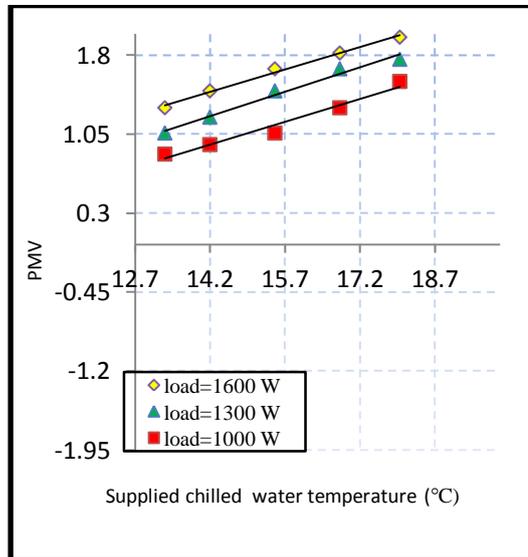


Fig. 9: The relationship between PMV and supplied chilled water temperature for different internal loads

Figure (10) shows the relationship between PPD and supplied chilled water temperature at different internal loads. It is clear that as supplied chilled water temperature increases the PPD increases for each internal load, due to an increase in the average air temperature. For each supplied water temperature, the PPD increase as internal load increase due to the rise in average air temperature with increase in internal load. At supplied water temperature is 13.3 °C, the PPD increases from (20 to 41)% for internal loads increase from (1000 to 1600)W respectively.

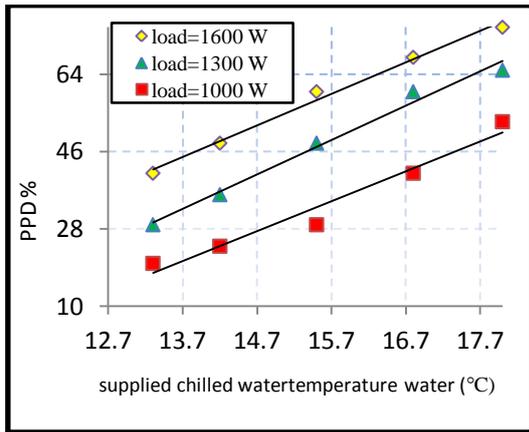


Fig. 10: The relationship between PPD and supplied chilled water temperature for different internal loads

Figure (11) shows the thermal conditions on comfortable chart using CBE tool for supplied temperature of chilled water is 16 °C ,that appeared the chilled ceiling with supplied air temperature cannot achievement thermal comfort conditions but it can reduce cooling load by 31.73% .

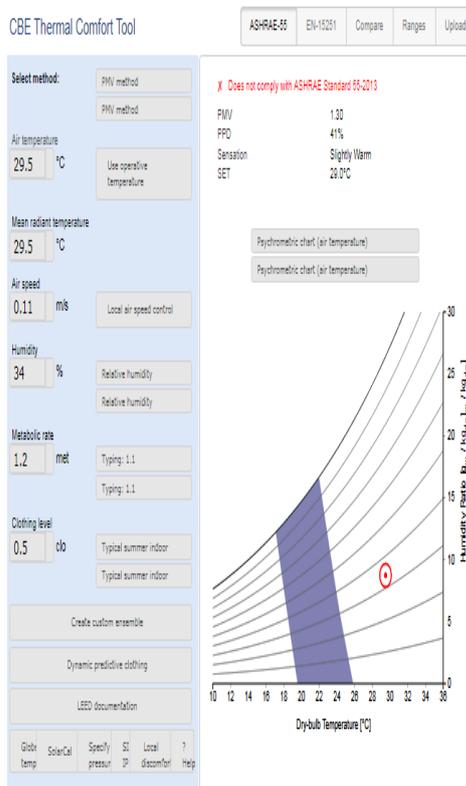


Fig. 11: The Thermal conditions using CBE tool

6. The Theoretical Study

In theoretical study of chilled ceiling used as a cooling system installed in a room with real dimensions of (4Wx3Lx3H)m .The study included the effect of using different mean plate temperatures and it effect on velocity and temperature distribution in occupied room by using Fluent 14.5 program. The different mean plate temperatures study is done with temperatures of (17 and 20)°C . The theoretical study is done with natural convection and radiation . The steady state conditions is assumed with constant temperature of the mean plate temperature. The internal load is 1600 W produced by using two heaters distributed in room. The dimension of geometry can see in figure (12)

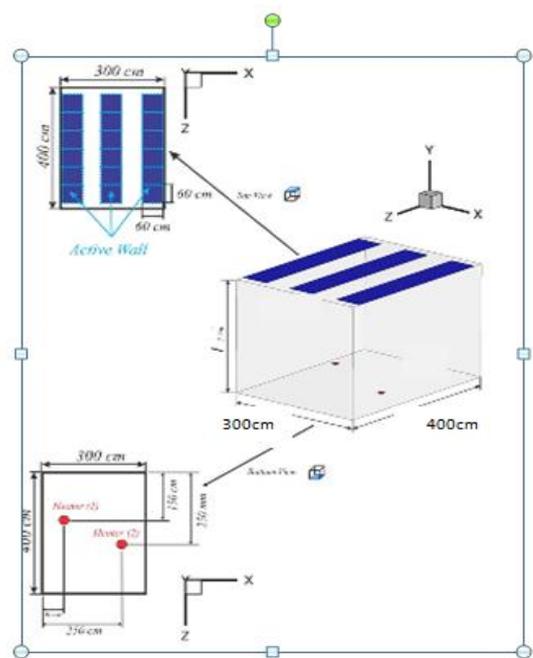


Fig. 12: The dimension geometry used in theoretical study

7. The Results and Discussion of Theoretical Study

Figure (13) shows the velocity vectors in (Y-Z)planes at different locations of X (100,0and-100) cm .It's clear that at X=-100 cm, the velocity increases through the heater and at a location where effected by the heating of the heater since the hot air is light ,the air moves up ward with an increase in its velocity. When the air reach near the ceiling and due to exchange of heat with cold ceiling the air becomes cooler and heavier and as result flows downward with a decrease in its velocity. The same behavior can be seen at other locations of X=0 and 100 cm.

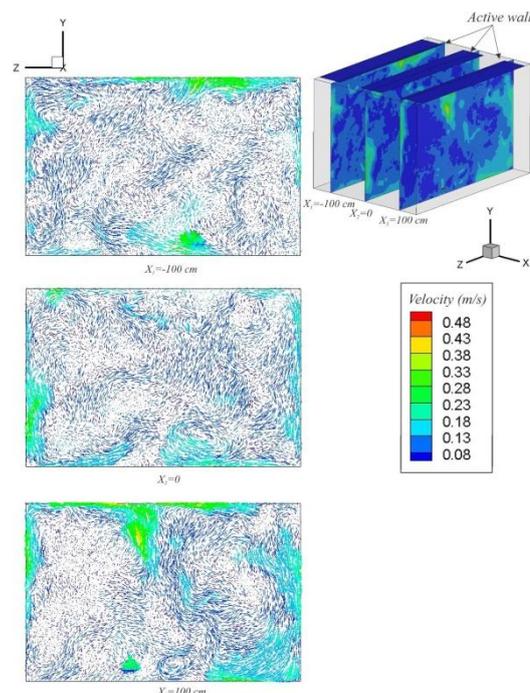


Fig. 13: The velocity vector at X direction for temperature ceiling is 17°C

Figure(14)shows the velocity vectors in the (X-Z) plane at different locations of Y(10,110,170 and 265) cm. At Y is 10cm ,it's clear that the velocity increases at areas located over and

near the heaters zone since the hot air is lighter. At Y is 110cm , the heat is distribution to the remain layer and the velocity increase more than that at Y of 10 cm and as a result the flow become more complex and the vortices is generated. When Y is 170cm ,the temperature of air increases leading to higher velocities the velocity and vortices appears clearly. At Y is 265 cm can notice that the vortices increases due to the increase in air velocity with height.

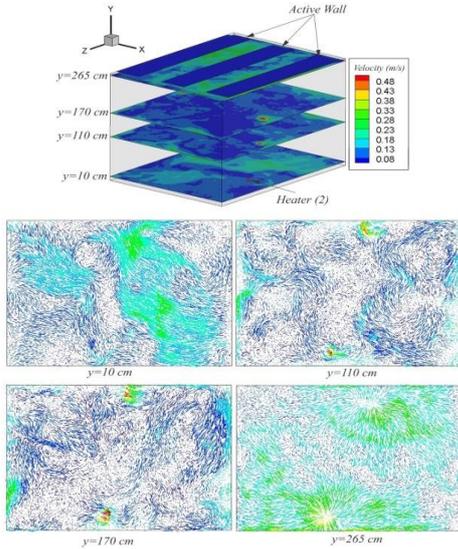


Fig. 14: The velocity vector at Y direction for temperature ceiling is 17°C

Figure (15) show the velocity vectors at (X-Y)plane located at different Z posting of (-50,0and 50) cm. At Z of -50 cm , notice that the air is moving upward due to include a buoyancy force .Also its clear that the air is very light within the heater zone and having relatively high velocity . When air reach to the ceiling the heat exchange occurs between hot air and the chilled ceiling and as a result the air cools and moves down ward since is become heavier . In the same manner notice at Z is 50cm .At Z is 0, the air moves upward since it is hot and after reach to the chilled ceiling and exchange the heat becomes heavier and flow down ward.

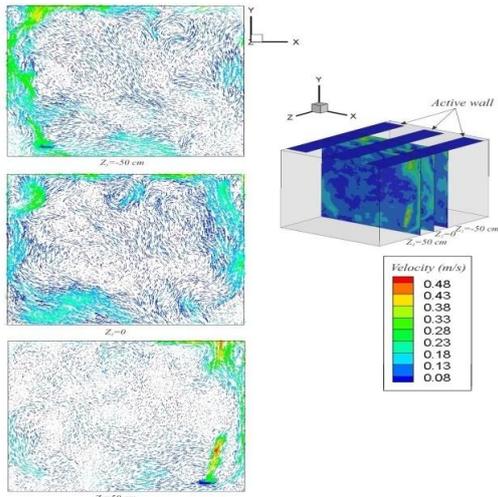


Fig. 15: The velocity vector at Z direction for temperature ceiling is 17°C

The same behavior can be seen at mean plate temperature of 20°C for velocity vectors at different planes locations in figures (16)to (18). From comparing between mean plate temperatures of (17 and 20)°C for different planes one can notice that as mean plate temperatures increases the air velocity increases because the cooling capacity of chilled ceiling decreases as mean plate temperatures increases and air becomes warmer and lighter that lead to increase in air velocity induced in the flow.

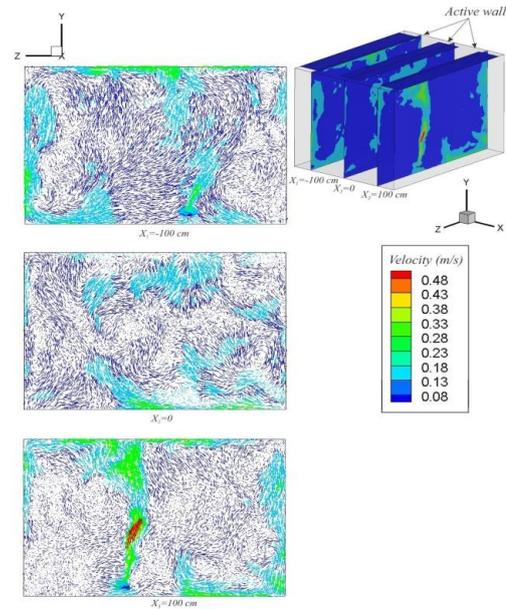


Fig. 16: The velocity vector at X direction for temperature ceiling is 20°C

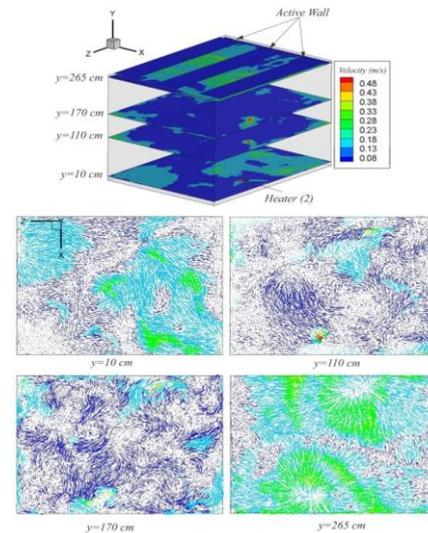


Fig. 17: The velocity vector at Y direction for temperature ceiling is 20°C

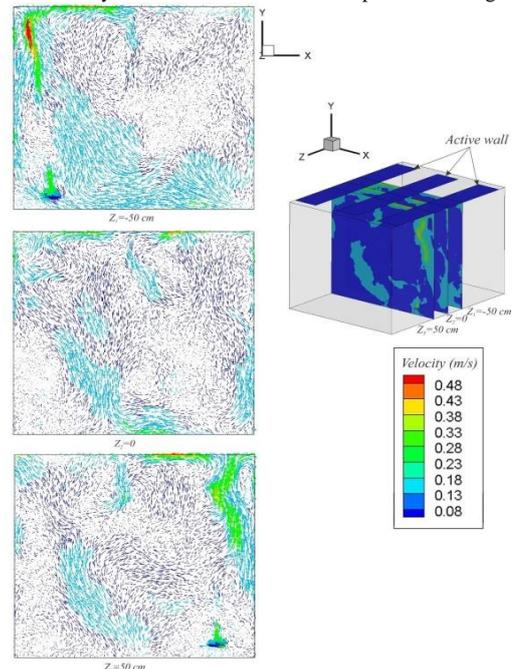


Fig. 18: The velocity vector at Z direction for temperature ceiling is 20°C

Figures (19) to(24) shows the temperature contours at (Y-Z),(X-Z)and (X-Y) planes for different mean plate temperatures studied .Figures (19)to (21) and from (22)to (24) represent the temperature contours for mean plate temperature of (17, and 20)°C respectively.

Figure (19) shows the temperature contours in (Y-Z)plane and at different locations of X (120,0and-120)cm .It's clear that at X of -120cm, the highest temperature is noticed near the heater (cleared by the red color) and at some location where effected by heating of the heater while the coldest temperature location can noticed at position far away from the heaters and lies near the ceiling .

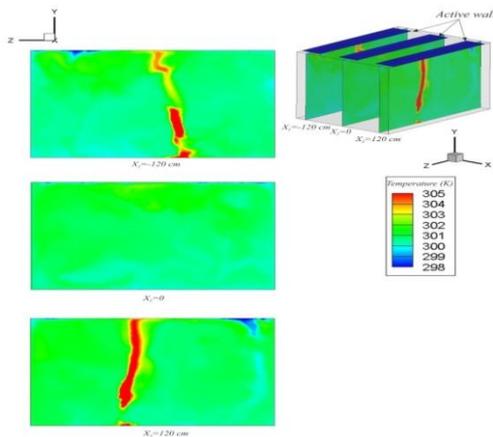


Fig. 19: The temperature contour at X direction for temperature ceiling is17°C

Figure(20)shows the temperature contours in (X-Z) plane at different locations of Y(10,110,170 and 265)cm. Generally noticed that the temperature increases with height .At Y is 10cm ,it's clear that the temperature is low except the locations near the heaters. At Y is 110cm , the heat is distribute to the remaining layer and the temperature increases more than that at Y of 10cm.When Y is 170cm ,the temperature of air increases to higher values and the highest temperature can be seen at Y of 265cm where the air becomes in contact with the chilled ceiling then the process of heat exchange take place and the air cools more and returns back downward.

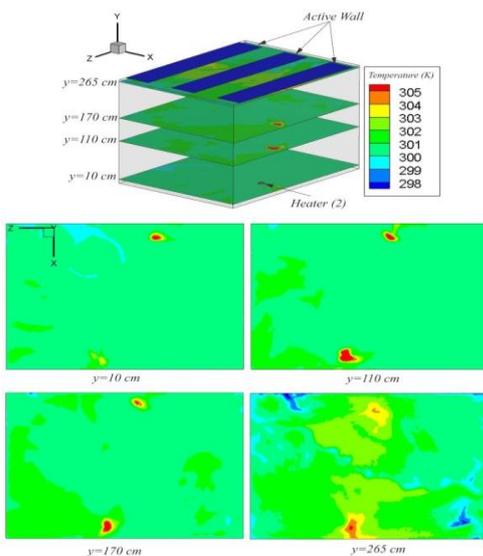


Fig. 20: The temperature contour at Y direction for temperature ceiling is17°C

Figure (21) shows the temperature contours at (X-Y)plane that located at different Z position of (-100,0and 100)cm . At Z -100cm , notice that the coolest air is located near the floor due to high

density . The warmer air rises upward due to lower density and the warmer air is located at a position affected by heating of the heaters. The same behavior noticed at Z is(100 and 0)cm

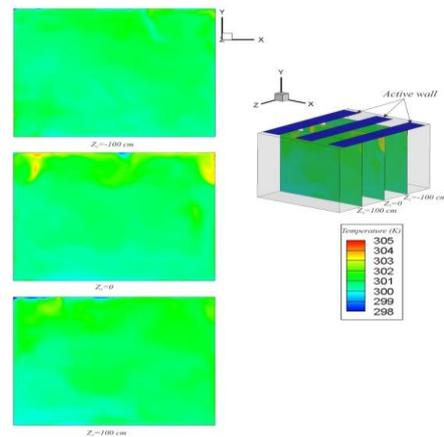


Fig. 21: The temperature contour at Z direction for temperature ceiling is17°C

In the same manner see is the mean plate temperature of 20°C and its temperature contours at different planes locations in figures (22)to (24). comparing between mean plate temperatures is (17 and 20)°C results for different planes notice that as mean plate temperatures increases the air temperature increases because the cooling capacity of chilled ceiling decreases as mean plate temperatures increases .

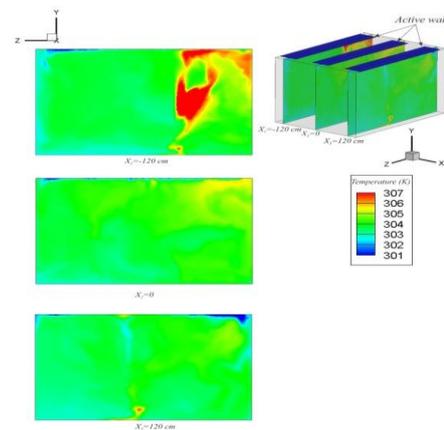


Fig. 22: The temperature contour at X direction for temperature ceiling is20°C

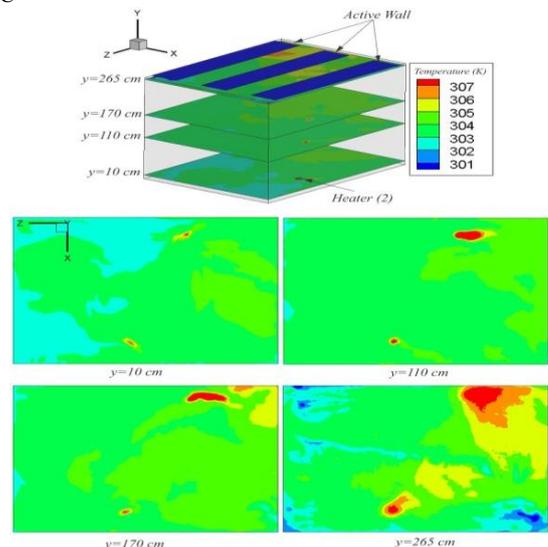


Fig. 23: The temperature contour at Y direction for temperature ceiling is20°C

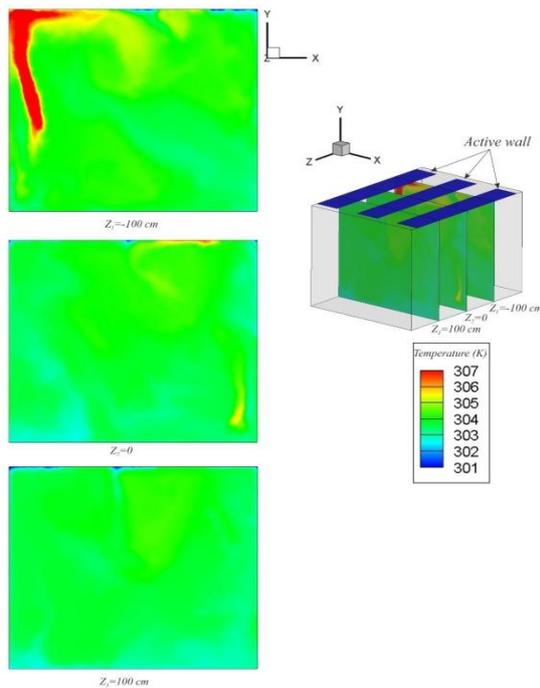


Fig. 24: The temperature contour at Z direction for temperature ceiling is 20°C

8. Conclusion

The mean plate temperature is important factor that effected on the performance of chilled ceiling .So the performance of chilled ceiling increases as mean plate temperature decrease . It's clear from figures that the thermal condition aren't achieved by chilled ceiling in Baghdad ,Iraq climate with 54% since the PMV and PPD lie out range limits according to the ASHRAE 55 standards. But it's can reduce cooling load . Chilled ceiling reduce cooling load by 31.73%. The theoretical results is given as a flow filed with velocity vectors and thermal behavior as temperature contours diagrams. The comparison between the theoretical and experimental results is done and good agreement is noticed maximum difference between the experimental and theoretical results isn't exceed 20 % .

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Nomenclature

L:Length , m
 W:Width ,m
 H:Hieght , m
 Q: Heat transfer , W
 qr:Radition heat flux W/m²
 h:Heat transfrf coefficnt (W/m².C)
 N:Number of plates
 qc: Convection heat flux W/m²
 Awall:Area of wall m²
 m' :Mass flow rater kg/s
 TWi :Temperature of supplied water to chilled plate (°C)
 TWO: Temperature of exit water from chilled plate (°C)
 Tp: Mean plate temperature (°C)

Subscripts

P:Plate
 r:Radtion
 C: Convection
 In: inlet
 Out: outlet
 W:Water

Abbreviations

SET: Standard Effective Temperature
 BEMS: Building Energy Management System
 AUST: Area-weighted average temperature of uncontrolled surface in room
 PMV: Predicated Mean Vote
 PPD: Percentage People Dissatisfied
 CC: Chilled Ceiling
 Cp: Specific Heat at constant Pressure
 ASHRAE: American Society For Heating, Refrigeration And Air Conditioning Engineers
 CBE: Center for the Built Environment