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Design and Analysis of Radiant Ceiling Cooling Panels for Classroom

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Abstract: In this study, radiant cooling panel is designed for a classroom. An arrangement is made such that the panels cover 70% of ceiling area. For study case a classroom is considered which need 27 such panels for covering 70% of area. The arrangement of panels, water flow rate, required temperature and amount of heat transfer taking place through panels is discussed in the paper. A cooling system is selected for maintaining the desired water temperature. Comparison is done between the cooling systems and the user can use any of them according to the requirements and cost. This system does not use any refrigerant hence it is environment friendly and can add a considerable solution to maintain temperature of a specific area. CFD analysis of the panel shows that adequate heat transfer takes place between panel and the room, this validates the design. When 15 ºC water is given as inlet to the panel, we get 22 ºC water as output at outlet of panel. In this paper, analysis is done for single panel same can be done for entire arrangement of panel structure.

I. INTRODUCTION

In order to provide the comfortable indoor environment, various heating and cooling systems condition the space through radiant and convective heat transfer. Radiant cooling systems use the surrounding surfaces as cooling sources, with radiant and convective heat transfer taking place. In general, a radiant cooling system is one in which radiant heat transfer contributes higher of the heat exchange within a conditioned environment. The more beneficial radiation exchange between the inhabitants and the radiant surfaces of a buildings. Radiant cooling allows the air temperature to be a little lower while maintaining comfort conditions, reducing heat losses from the building, which can be significant in mild climates. The radiant heating and cooling system can be applied in different ways 1. Radiant Cooling Panels, 2. Embedded surface system, 3. Thermally active building system. These systems contain tube arrangements, through which cold water flows. As the water flows along the tubes, heat exchange takes place due to which water gains some temperature. When it comes to radiant cooling systems, heat is removed from occupants through radiant heat transfer from cold surfaces, allowing the room air temperature to be maintained at a higher level than with conventional all-air systems. There are many different types of radiant heating and cooling systems, which may be classified based on the location of radiant surfaces, building structural integration, thermal medium, and so on. The radiant cooling system was classified as radiant ceiling cooling, radiant floor cooling systems and radiant wall cooling system based on the location of radiant surfaces. Because of their relatively large heat transfer surfaces, radiant cooling systems can be classified as low temperature heating or high temperature cooling systems, as they can function with water temperatures closer to the desired room temperature. The application of radiant floor cooling has been extended from western and northern European areas, where the outside air humidity is relatively low during the summer season, to regions where the humidity level is much higher, such as Thailand, the United States and China.

II. PROBLEM STATEMENT

AC systems play a vital role in providing human comfort in various climatic conditions. But refrigerants used in these systems cause harmful effects on the environment. Thus there is a need to find some alternative solutions. So we are designing a radiant ceiling cooling panel system which will provide desired effect by extracting radiant heat. Our problem statement is- "Design and analysis of Radiant Ceiling cooling panels for a classroom"

III. EXISTING TECHNIQUES

1) Beijing Tiptop Apartments The thermal properties of the building were designed to extend the time when the room temperature can remain in the range of 20°C - 26°C without heating or cooling, and only during periods of harsh weather will a hydronic system embedded in the concrete slab begin to operate. In winter and summer, supply water temperature are 28°C and 20°C, respectively, which are near to upper and lower levels of thermal comfort, resulting in a minor temperature difference between supply water and room. Building can function year round in a temperature range of 20°C to 26°C, and goal of internal comfort was met with simple system control.

2) The Qingdao Villa is situated in the Yangcheng neighbourhood of Qingdao, next to the Laoshan reservoir. Insulation on the outside of the external walls is 10-cm thick extruded polystyrene, and the roof is 15-cm thick extruded polystyrene. Radiant panels, an air conditioning system, a heat pump, and a pair of subsurface heat exchangers make up the HVAC system. As heating and cooling terminals, capillary mats were used. The capillary mats can be adhered to the ceiling or wall and covered by a layer of plaster with a thickness of 5–10 mm and a conductivity of 0.45 m/(WK), and the envelope housing the hydronic system has a consistent surface temperature because the pipe diameter is as small as 3.35 mm and the gap between the pipes is just 15 mm. The radiant panels handle building's sensible heating and cooling load, while a separate air conditioning system handles latent load created by interior heat gain and infiltration. Instead of using a heat pump, free cooling can be used directly through a plate-type exchanger when underground temperature approaches value required for radiant cooling. Similarly, when a lower cooling water temperature is required in summer, ground source heat pump will be activated. A complicated electronic control system is used to control the internal air temperature and humidity to avoid condensation on the surface of envelope enclosing hydronic system.

3) An office building in Shenzhen, China The structure was built as a factory and then transformed to an office building as an energy efficiency demonstration. The fan-coil-units (FCU) in the office area and capillary mats embedded in the floor in entry atrium are fed with chilled water at 18°C and handle all of sensible cooling load except occupant load; remaining cooling load is handled by a separate air conditioning system made up of many liquid dehumidifiers. A decorative element is hung in the middle of the atrium to block a portion of the transmitted solar heat that directly reaches the occupied zone, and exhaust air is vented through a window at the top of the atrium. A variable frequency magnetic levitation centrifugal chiller is used to enhance system performance, producing chilled water at 17°C with a rated COP of 8.35.

4) The comparison was conducted using a calibrated Energy Plus model of a typical office building in California. The case study building is a LEED platinum office building with a radiant heating and cooling system that uses evaporative cooling. At three levels, the EnergyPlus model was validated against field measurement data and building management system trending data from 2012.

a) The thermal response of the radiant slab

b) The monthly energy usage of HVAC components

c) Zone level hourly and annual thermal comfort conditions (air temperature). The comparison results show that the EnergyPlus model accurately captures the building's HVAC efficiency and thermal comfort condition.

- DOAS system.
- Floor, Ceiling, or Walls.
- The tubes can be embedded in the concrete or used as panels which can be hanged.

IV. SPECIFICATIONS OF MAJOR COMPONENTS

A. Specification of Classroom

1) Dimensions-

2) For Room- L= 11.39m =37.3687ft

W=6.6m =21.6535ft

h=3.8528m =12.6404ft

3) For Window- L=1.55m =5.08ft

W=1.85m =6.069ft

4) For Door- L=2.5m =8.202ft

W=1.3m =4.26ft

5) Lat. Deg N=18.3°F…………….. (HAVC sheet pdf)

6) U=0.86……….. (Table Transmission coefficient window, skylight, doors & glass block walls)

7) Student Occupancy- 60

B. Specification of Panel

1) Total no. of panels = 27
2) Total length of tube in each panel (L) = 21.6m
3) Diameter of copper tube = 12mm = 0.012m
4) Quantity of water in each panel= πr^2L= 2.44ltr
5) Total Quantity in all panels = 65.88ltr
6) Tank storage capacity = 200ltr
7) Diameter of copper tubes pressed into individual aluminium extrusions= 12mm
8) Length of panel run = 3600mm.
9) Width of the panel runs=600mm

C. Specifications of Thermo-electric Plate

1) TEC1-12706
2) T_h = 50°C
3) T_C = 14°C
4) Q_{max} = 50W
5) ΔT_{max} = 66°C
6) I_{max} = 6.4 amp
7) V_{max} = 14.4V
8) V = 12V
9) I = 5.8 A

All the standard components are assembled together in a proper sequence to form the setup.

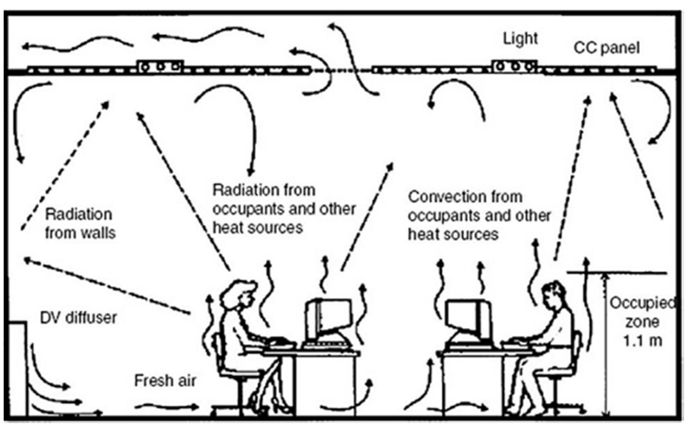

Fig. No 1: Setup for Combined chilled ceiling, displacement ventilation, and desiccant cooling system [1]

V. CALCULATION

A. Cooling Load Calculation

1) Thermal Condition

TABLE I: Thermal Condition

	DBT(°F)	WBT(°F)	RH(°F)	HR(°F)
Outside	104	76	28	91
Room	75	62.5	50	66
	ΔT=29	ΔT=13.5		ΔHR=25

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Where,

DBT= dry bulb temperature,

WBT= wet bulb temperature,

RH= relative humidity.

2) Transmission Value (U)

$U_{wall} = 0.39$
$U_{partition} = 0.38$
$U_{roof} = 0.2$
$U_{floor/ceiling} = 0.25$
$U_{glass(trans.)} = 1.13$
$U_{glass(radiation)} = 0.65$

3) Temperature Difference (ΔT)

a) Partition

1. AC to Non-AC =24°F
2. AC to AC =0°F

b) Floor

1. AC to Non-AC =24°F
2. AC to Ac =0°F

c) Ceiling

1. AC to Non-AC =24°F
2. AC to AC =0°F

d) Wall

Correction Factor = (10+9)/2 =9.5

N=4
S=8
E=10
W=14

TABLE II: Correction Factor

Wall	Direction (A)	Correction Factor for daily range (B)	ΔT(A+B) (°F)
Weight= 80lbs/ft	N=4	9.5	13.5
	S=8	9.5	17.5
	E=10	9.5	19.5
	W=14	9.5	23.5

e) Roof

Shaded=4 9.5 ΔT=13.5°F

Glass-

If glass is in wall= 29°F

If glass is in between AC/non-AC= 24°F

If glass is in between AC/AC= 0°F

f) Radiation through Glass

North= 23

South= 12

East= 12

West= 168

Total Internal Sensible Heat= $Q_{Light} + Q_{Equipment} + Q_{People}5 + Q_{Floor} + Q_{Ceiling} + Q_{Partition}$

= 16579.8113+ 2763.302+ 14700+ 4854.996+ 0+ 4854.996+ 8828.305

= 52581.4103 BTU/HR

= 15397.192 watt

g) Glass Radiation

North= 23
South= 12
East= 12
West= 168

External Sensible Heat= $(Q)_{Wall\ west} + (Q)_{Roof} + Q_{Glass\ Total}$

[$Q_{Glass\ Total} = Q_{GTES} + Q_{GREW}$

= 3932.4+ 936

= 4868.4 BTU/HR]

= 3009.9326+ 0+ 4868.4

= 7878.3326 BTU/HR

= 2306.9788 watt

h) External to Internal Sensible Heat

$Q_{OA} = 1.08 \times Ma \times CFM \times BF \times \Delta T$
Area CFM= 0.35 sq. ft
Consider,
$M_a \times CFM = 20$ per person
According to ASHRAE for classroom
$M_a \times CFM = 15$
Maximum CFM-

- According to people = No. of people×CFM per person
  = 1200 CFM
- According to Area = 809.166×0.35
  = 283.208 CFM
- According to Volume = Room Volume×NACPH
  [No. of Air change per hour(NACPH)= 4-6]
  = 970.992 CFM

By pass factor= 0.5 to 1
so for consider it is 0.75

$Q_{OA} = 1.08 \times BF \times Ma \times CFM \times \Delta T$
= 28188 BTU/HR
= 8254.1728 watt

i) Infiltration Air

Q_{IA}= Sensible Heat constant ×(CFM/feet)×Perimeter of door×ΔT
= 1.08×6×24.5×24
= 3810.24 BTU/HR

Total Sensible Heat = $(Q_{11}+Q_{eq}+Q_p+Q_f+Q_c+Q_{pa}) + (Q_w + Q_R + Q_g) + (Q_o + Q_i)$
= 92457.9829 BTU/HR
= 27074.08 watt

Total Latent Heat = $(Q_{LH})_{people} + (Q_{OA}) + (Q_{infiltration})$
= 12300+15300+2499
= 30099 BTU/HR
= 9570.4293 watt

j) Effective Room Sensible Heat

ERSH= Total Sensible Heat+ FOS ×(Total Sensible Heat)……….. [Consider, FOS= 10 to 15%]
= 106326.68 BTU/HR
= 31135.1918 watt

k) Effective Room Latent Heat

ERLH = Total Latent Heat + FOS (Total Latent Heat)……………. [Consider, FOS=2.5 to 5%]
= 31227.7125 BTU/HR
= 9144.279 watt

l) Effective Room Total Heat

ERTH = 106326.68 + 31227.7125
= 137554.3925 BTU/HR
= 40279.4707 watt

m) Load at Cooling coil

Contact factor (CF) = 1-BF
= 0.25

$Q_{coil\ sensible}$= 1.08×CF×Ma×CFM×ΔT
= 9396 BTU/HR
= 2751.391 watt

$Q_{coil\ latent}$ = 1.08×CF×Ma×CFM×ΔHR
= 5100 BTU/HR
= 1493.4114 watt

Total load at Cooling coil = 9396+5100
= 14496 BTU/HR
= 4244.802 watt

n) Grand Total Heat

GTH = Effective Room Total heat + Total load at Cooling coil
= 152050.3925 + FOS 1-3%
= 156804.6775BTU/HR

But, ITR = 12000BTU/HR
156804.6775= 13.06TR

o) Effective Sensible Heat Factor

$$ESHF = \frac{(ERSH)}{(ERSH+ERLH)}$$

= 0.773

p) Aperture Dew pt. Temperature

DBT = 75°F

Relative Humidity = 50%

Effective sensible heat factor = 0.719

ADPT = 46°F

Dehumidified Rise = CF×(Room temp- ADP)

= 0.25×(75-46)

= 7.25°F

$$\text{Dehumidified CFM} = \frac{(\text{ERSH})}{[(\text{Sensible heat constant})*\text{Dehumidified Rise}]}$$

= 13579.397 CFM

B. Radiant Heat Transfer

The radiant heat transfer is governed by the Stefan-Boltzmann Equation. For most buildings' enclosure cases encountered in practice, enclosure emittances is about 0.9 and view factor between ceiling and the balance of the enclosure is at least 0.87. Using these values, the altered Stefan-Boltzmann equation for Radiant Heat Transfer.

$$q_r = 0.15 \times 10 - 8[(t_p)^4 - (t_r)^4]$$

q_r = radiant cooling, $Btu/h.ft^2$ (W/m^2)

t_p = panel surface temperature, °R

t_r = room temperature

C. Convective Heat Transfer

Normal and forced convection combine to increase rate of heat transfer by convection. The cooled air in boundary layer just below panels gets replaced by warmer air in room, resulting in natural convection. Infiltration, human operation, and mechanical ventilation systems may all modify or even transform the natural process to the forced convection. The following equation gives the cooling convective heat transfer.

$$q_c = 0.31(t_p - t_r)^{0.31}(t_p - t_r)$$

q_c = cooling convective heat transfer, $Btu/h.ft^2$ (W/m^2)

t_p *and* t_r are in °*R* ………………….. (1°**R** − 491.67) × 5/9 = -272.6°**C**

Using these formulas, q_c and q_r for different combinations of t_p *and* t_r.

1. t_r = 30 °C = 545.67 °R *and* t_p = 15°C = 518.67 °R

   q_r = 24.43 ≈*25 Btu/h.ft²* = 77.07≈*78 w/m²*

   q_c= 23.25 ≈ 24 $Btu/h.ft^2$ = 75.71≈ 76 w/m^2

TABLE III: CRCP Heat Transfer

Panel Temperature (°C)	Room Temperature (°C)	$q_{radiation}$ (W/m2)	$q_{convection}$ (W/m2)
15	30	78	76
17	30	70	63
19	30	60	51
22	30	45	35
24	30	35	32
15	28	67	64
17	28	57	51
19	28	48	38
22	28	32	22
24	28	22	16

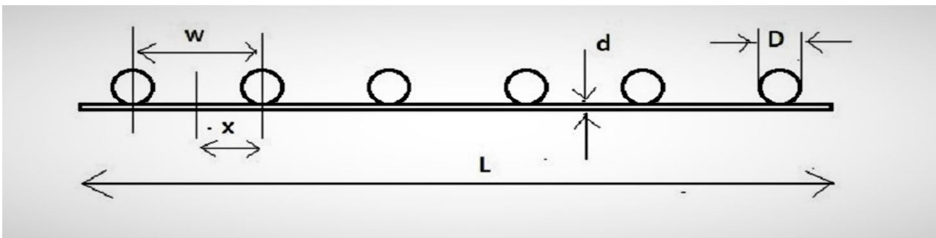


Fig. No 2: Cross section of a ceiling radiant cooling panel

tp = 19 ˚C   ta = 30 ˚C   qtotal = 111 W/m2   Cp, water = 4182J/kg ˚

1. To calculate overall heat transfer coefficient of panel using generalized co-relation**:**

$$q_{total} = UA(t_a - t_p)$$

from this eqn.

$$U = 10.091 \text{ W/m2 ˚C}$$

2. $\mu = (U/ k\delta)^{0.5} = 2.984$

3. $F = \{tanh\,[m(w - D)/2]\}/\,[m(w - D)/2] = 99.4\%$

4. $F' \simeq [D + (w - D)F]/w = 99.5\%$

5. $(t_{f,out} - t_a) / (t_{f,in} - t_a) = e^{(-UAF'/mCp)}$

substituting all the values in this equation

$$\frac{(t_{f,out}-19)}{15-19} = e^{\left(\frac{-10.091\times2.16\times0.995}{0.015\times4182}\right)}$$

we get, $t_{f,\,out} = 19.38\ ^{\circ}C$

7. $F_r = [mC_p\,(t_{f,out} - t_{f,in})]\ /\ \{A[-U(t_{f,in} - t_a)]\} = 85\%$
$m = 0.015\ kg/s$

8. $T_{p,mean} = t_{f,in} + \left\{\frac{mC_p(t_{f,out}-t_{f,in})}{AF_rU}\right\}(1 - F_r) = 17.4°C$

9. $q_{absorbed\ panel} = UA_{panel}(t_a - t_{p,mean}) = 278.532\ \text{W/m}^2$

10. $Q_{abs\ cold} = 86.679\ W$
No. of Chips = Heat absorbed by panel / heat absorbed by chip at cold side
= 3.213, *approximately* = 4

D. Calculations for Thermo-electric Peltier plate.

1) Seebeck Co-efficient(α):

The **Seebeck effect** is when electricity is created between a thermocouple when the ends are subjected to a temperature difference between them.

2) $\alpha = \frac{Vmax}{Th} = \frac{14.4}{(50+273)} = 0.046$ V/K

3) Electrical resistance (R):

$$R = \frac{Vmax}{Imax} \times \frac{Th - \Delta Tmax}{Th} = 1.79\ \Omega.$$

4) Thermal resistance of thermo-electric module (θ):

$$\theta = \frac{\Delta T\text{max}}{Vmax \times Imax} \times \frac{2Th}{(Th - \Delta Tmax)} = 1.8 \frac{K}{W}$$

5) Heat Transfer Rate (K):

$$K = \frac{\Delta T}{\theta} = \frac{(50-14)}{1.8} = 20\ W.$$

6) Amount of heat emitted on hot side (Q_{em}):

$$Q_{em} = \alpha \times I \times T_h - \frac{\Delta T}{\theta} + \frac{1}{2} \times I^2 \times R$$

Q_{em} = 96.2842 W.

7) Amount of heat absorbed on cold side(Q_{abs}):

$$Q_{abs} = \alpha \times I \times T_c - \frac{\Delta T}{\theta} + \frac{1}{2} \times I^2 \times R$$

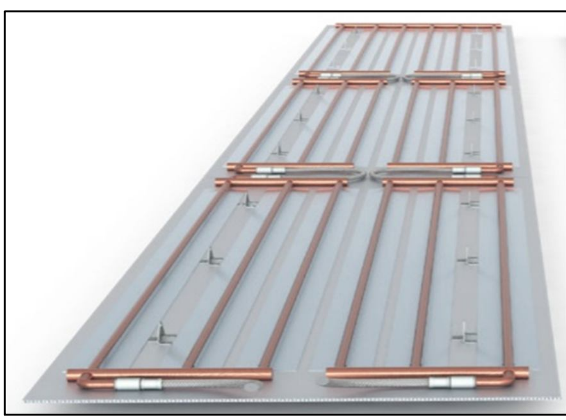
Q_{abs} = 86.679 W.

VI. CONSTRUCTION AND WORKING

1) Panel
2) Cooling system
3) Pump

A. Panel

Radiant cooling system consist of Aluminium panels suspended from the ceiling, through which chilled water is circulated. To be effective, the panels must be maintained at a temperature very near the dew point within the house, and the house must be kept dehumidified. In humid climates, simply opening a door could allow enough humidity into the home to allow condensation to occur. The panels cover the majority of the ceiling, resulting in high machine capital costs. To keep the home's humidity down, an auxiliary air-conditioning system would be needed in all but the most arid areas, adding to the capital cost



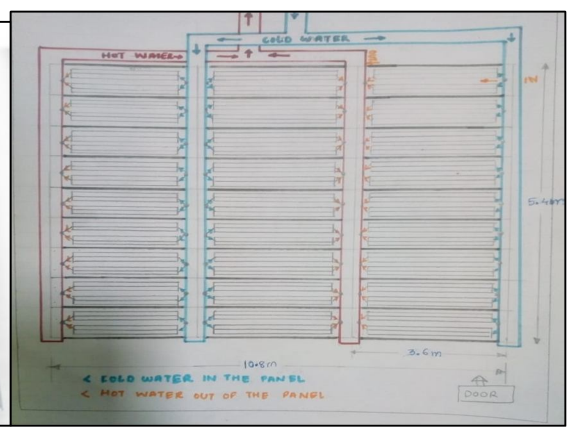


Fig. No 4: Panel [2]

Fig. No 5: Overall Panel Layout

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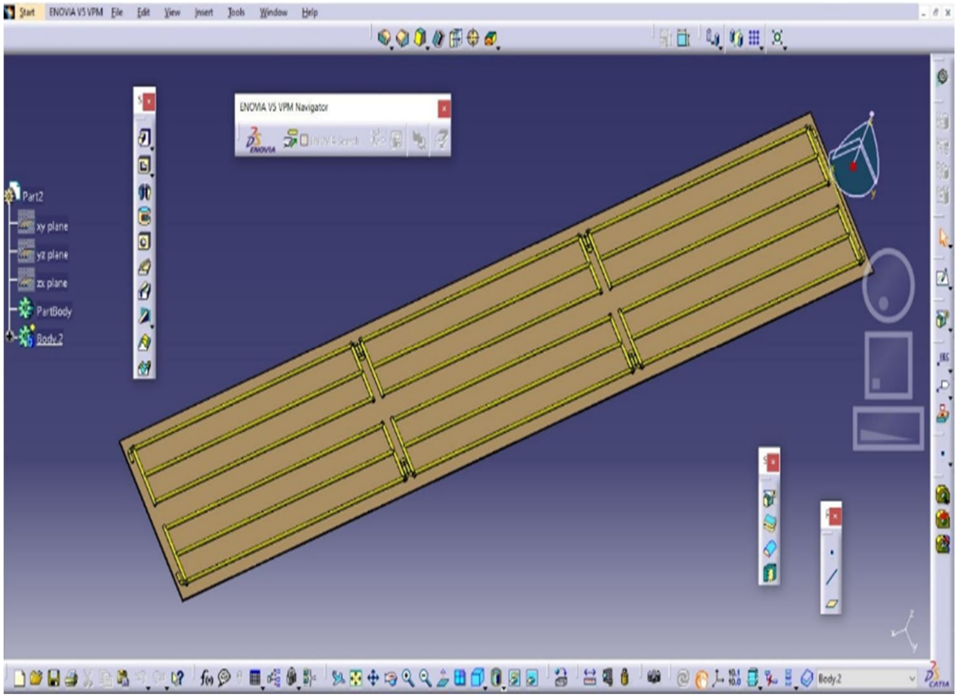

Fig. No 6: CATIA model of Panel

Cold water from cooling system enters the panel and flows through copper tubes fitted on panel. This cold water extracts the heat from panel and temperature water rises. This hot water is then collected in tank with help of pump through cooling system again circulated through panel and the cycle goes on.

B. Cooling Systems

Cooling system is used to cool water which is given as input to the panel. One can use any according to requirements:

1) *Thermo-electric Cooling:* The Peltier effect is used in thermoelectric cooling to create a heat flux at the junction of two different types of materials. A Peltier cooler, heater, or thermoelectric heat pump is a solid-state active heat pump that transfers heat from one side to the other while using electrical energy, depending on the current direction. In this system used for a classroom, collection of thermo-electric plates can be used to obtain a desired cooling effect. From the heat transfer rates it is concluded that 80 thermo electric plates will be required for the given classroom. Plates required may vary depending on number of occupants, electric devices present in the room, number of windows and doors present, amount of sunlight falling into the room etc. Cooling load of room is determined and accordingly the system can be designed for various applications.

a) Advantages

- Solid state design
- Compact and lightweight
- High reliability
- Rapid response time
- Localized cooling
- Precise temperature stability

b) Disadvantages

- The power consumption of a single TEC module is low. Combine them to form a thermopile, then cascade or parallel these thermopiles to create a high-power cooling system ranging from 1mW to 10KW.
- The temperature on the hot side should not exceed 60°C, or it will be damaged. When there is no heat sink, do not power the TEC modules for an extended period of time. Make sure TEC modules have enough heat dissipation devices.
- Condensation in case of humid climate.

2) *VCRS System:* One of the various refrigeration cycles, vapour-compression refrigeration, in which the refrigerant undergoes phase shifts, is the most extensively used method for air-conditioning buildings and automobiles. It's also found in home and commercial freezers, large-scale warehouses for chilled or frozen food and meat storage, refrigerated trucks and railroad carriages, and a variety of other applications. The modified system can be used both as a refrigerator and also as a water cooler. Therefore by using VCRS in radiant cooling system even reduce the utility bill of a small family. It consists of an inlet for the hot water and an exit for collecting the cold water. The cold water can be used instantly or it can be stored in a tank for later use.

a) Advantages

- When compared to an air refrigeration system, the size is modest for a given refrigeration capability.
- The amount of refrigerant circulated is insignificant. As a result, the operating costs are cheap.
- High performance coefficient.
- The temperature range that can be used is enormous.
- A regulating expansion valve can simply adjust the temperature of the evaporator.
- Phase change uses latent heat to achieve a high value of heat removal, whereas air refrigeration uses only sensible heat.
- It necessitates the use of a smaller evaporator.

b) Dis-advantages

- Initial investment is high, and the refrigerant is expensive.
- The refrigerant used is dangerous to the environment.
- It is necessary to guarantee that no refrigerant leaks occur.

C. AC Systems

An air conditioner is a device that cools a space by removing heat from it and transporting it to an outside area. The cool air can then be ventilated throughout the structure. The air conditioner is an important component of HVAC system, which focuses on improving comfort by regulating home temperature. Air conditioners are referred to as "split-systems" as they have an external element (the condenser) and an inside unit (the evaporator). These two technologies work together to cool and dehumidify an area indoors. This dehumidification occurs when warm air from within passes through a cold evaporator, where the heated air condenses and loses moisture in a same way that warm air does.

When compared water cooled systems give a better COP than air cooled systems.

1) Comparison Of Energy Consumption Of Thermo-Electric And Ac Systems

a) AC System

Step 1: Calculate area of room in feet square;

Area of classroom = 75.174 m^2 = 809.166 $feet^2$.

Step 2: Divide the space's square feet by 500.

$$\frac{809.166}{500} = 1.61833$$

Step 3: Multiply number from step 2 by 12000

1.61831.61833 × 12000 = 19419.98 Btu.

Step 4: Add 380Btu for every person in the room, if number is variable take an average:

$$380 \times 60 = 22{,}800\ Btu.$$

Step 5: Add 1000 Btu for each window

$$1000 \times 4 = 4000.$$

This space will need cooling of $(19419.98 + 22800 + 4000) = 46{,}219\frac{Btu}{hr}$.

= 3.85Ton of refrigeration.

This is approximately equal to 4Ton of refrigeration = 14.068 Kilowatt.

2) Thermo-electric System

Each thermo-electric device consumes 288 watt of power, in this application 27 such devices are used. Therefore, the total energy consumption is $(288 \times 27 = 7776\ watt)$.

Thus, we conclude that thermo-electric system requires less power than AC systems.

3) CFD Analysis

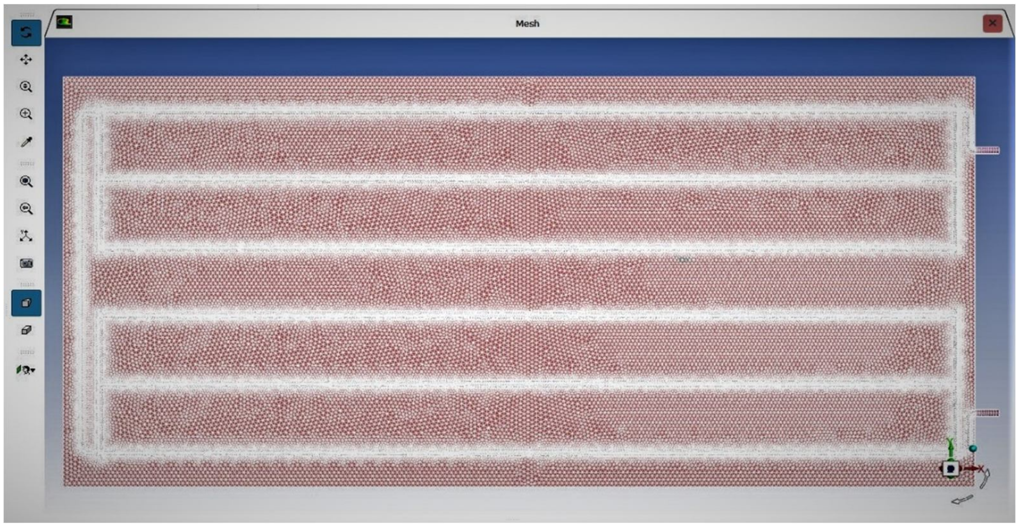

Fig. No 7: Panel Meshing

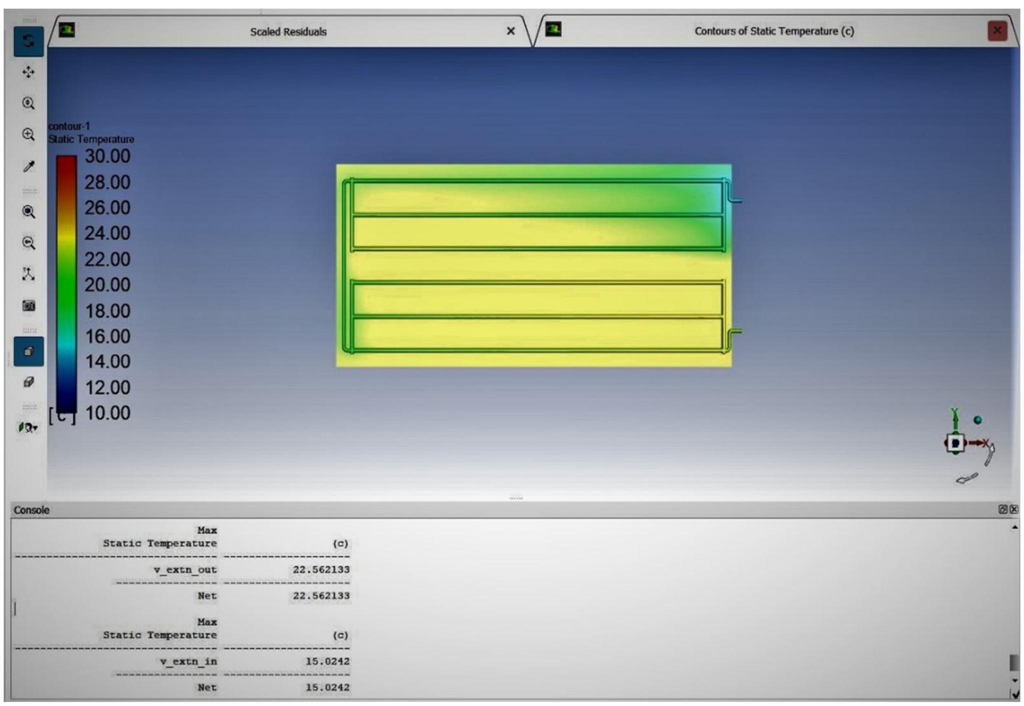

Fig. No 8: CFD analysis for Temperature distribution through panel

CFD analysis of panel shows that when we provide 15 ºC water as inlet to panel we get 22 ºC water at the outlet. This indicates that heat transfer takes place between panel and surrounding area of panel (classroom). Majority of heat transfer takes place through radiation and convection. Theoretical value of panel outlet temperature is 21 ºC which is very close to obtained CFD result. Hence, the design is validated.

VIII. CONCLUSION

A. The RHC system is deeply indebted to the development of related theory and practice, for example, comfort model, CFD analysis, energy simulation.

B. Conventional Radiant heating and cooling system have High thermal comfort, Reduced energy consumption, Quite operation and space saving.

C. In this paper, design and analysis of Radiant Ceiling Cooling panel is done. An arrangement of panels is done for a classroom application. From analytic calculations we get, Heat transfer value of radiation, conduction and convection. Heat load for classroom is calculated. A cooling system is used to maintain temperature of water at inlet of panels.

D. From comparison we conclude that Thermo- electric system improves the performance and can mitigate environmental pollution as it does not use refrigerants and it is concluded that adequate heat transfer takes place between the room and panel and desired cooling is obtained.

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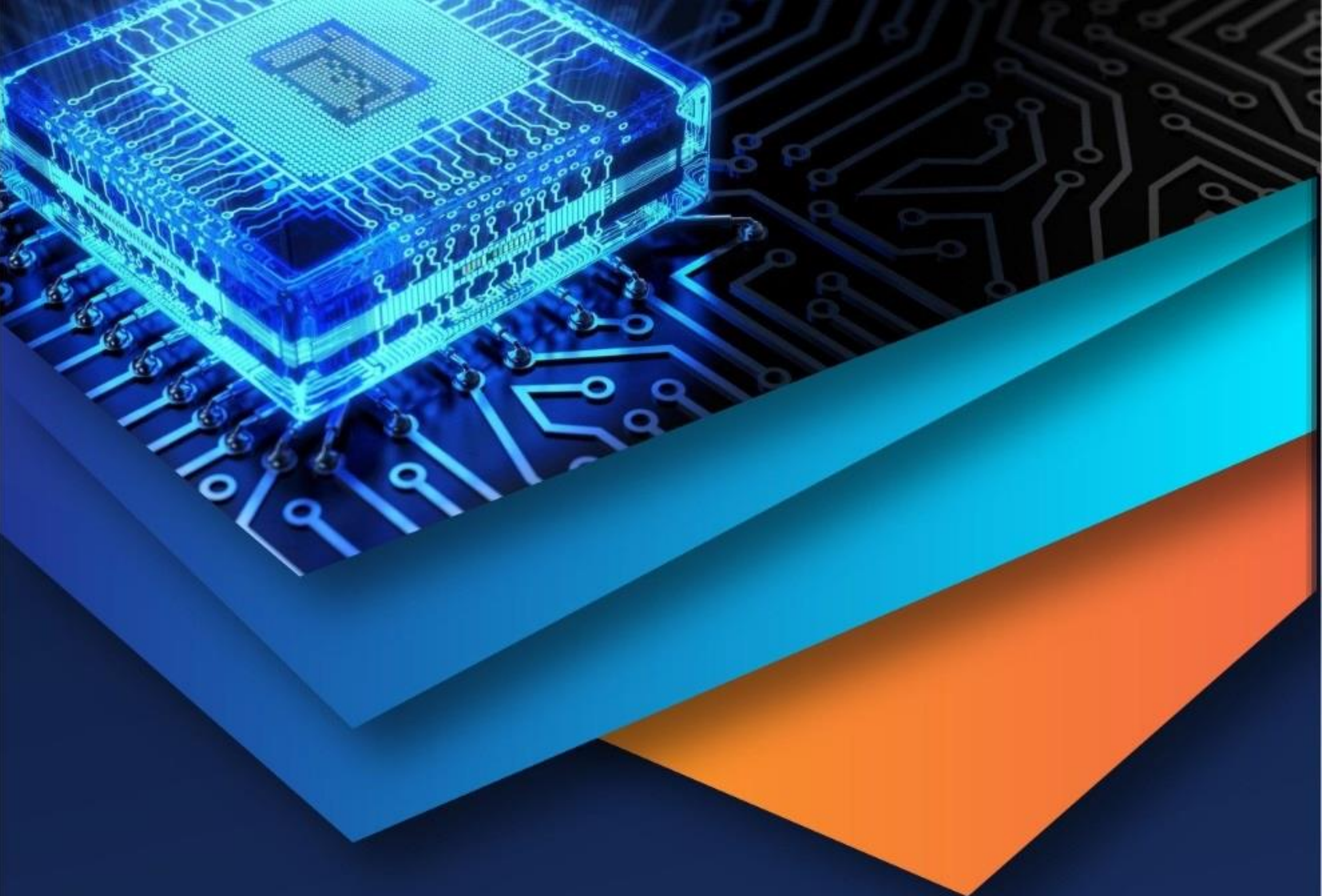

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