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ANALYSIS OF RADIANT COOLING IN CONCRETE SLABS WITH EMBEDDED PIPES

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Abstract— Radiation is an effective and proven way of heat transfer since ancient times; particularly radiant heating that has been in existence in Europe since several centuries. But radiant cooling is a relatively new application of radiation heat transfer and is being used widely in Europe and to some extent in the US since the last 15 – 20 years. Radiant cooling is highly efficient compared to regular air conditioning due to the high water temperatures used, minimized air system and also better quality of thermal comfort. This paper reviews about the results of the experimental analysis of area 4 sq. ft. and also the variation of temperature of the slab and room when different flow rates are maintained. The appreciable amount of heat was extracted from the slab and the room temperature was maintained at 32°C and the amount of average heat extracted was about 0.5-1 kW/m^2.

Index terms— Heat, power, radiation, radiant cooling, slab, water.

1 INTRODUCTION

RADIANT cooling system is a promising technique, which is suitable for independent control processes of temperature and humidity. The two main benefits of radiant cooling systems include the potential to save energy and improvement of indoor thermal comfort. Interests in radiant cooling systems have increased in recent years and there is no standardized method for radiant system design that is broadly accepted by the building industry. Design guidelines have provided the principles and methods of designing radiant cooling systems, the use of operative temperature for comfort control, and cooling capacity estimation. However, there seems to be no obvious source of guidance on how to apply the design principles to applications and on the selection of tools for analyzing performance and optimizing design. [1].

Radiant cooling cools a floor or ceiling by absorbing the heat radiated from the rest of the room. When the floor is cooled, it is often referred to as radiant floor cooling; cooling the ceiling is usually done in homes with radiant panels. Most radiant cooling applications have been based on aluminum 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. Structures built on concrete slabs are prime candidates for radiant cooling systems, and radiant ceiling/floor cooling takes advantage of the same principle using chilled water.

Radiant cooling systems typically use chilled water running in pipes in thermal contact with the surface. The circulating water only needs to be 2-4°C below the desired indoor air temperature. Heat is removed by the water flowing in the hydronic circuit once the heat from different sources in the space is absorbed by the actively cooled surface i.e., ceiling, floor or walls. Majority of the cooling process results from removing sensible heat through radiant exchange with people and objects and not air, occupant thermal comfort can be achieved with warmer interior air temperatures than with air based cooling systems. Combined with higher cooling capacity of water than air, and the having a cooled surface close to the desired indoor air temperature, radiant cooling systems offer significant reductions in cooling energy consumption [2].

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Radiant ceiling panel (RCP) and embedded surface system (ESS) are two water based radiant cooling systems. In ESS cooling from a slab can be delivered to a space from the floor or ceiling. Floor cooling is similar to floor heating that has been used in Europe since last few decades. However, delivering cooling from the ceiling has several advantages:

1. It is easier to leave ceilings exposed to a room than floors, increasing the effectiveness of thermal mass. Floors have furniture, coverings and furnishings that decrease the effectiveness of the system.
2. Greater convective heat exchange occurs through a chilled ceiling as warm air rises, leading to more air coming in contact with the cooled surface [3].

In RCP cooling panels are generally attached to ceilings, but can also be attached to walls. They are usually suspended from the ceiling, but can also be directly integrated with continuous dropped ceilings. Modular construction offers increased flexibility in terms of placement and integration with lighting or other electrical systems. Lower thermal mass compared to chilled slabs means they can't easily take advantage of passive cooling from thermal storage, but controls in panels can more quickly adjust to changes in outdoor temperature. Chilled panels are also better suited to buildings with spaces that have a greater variance in cooling loads. Perforated panels also offer better acoustical dampening than chilled slabs. Ceiling panels are also very suitable for retrofits as they can be attached to any ceiling. Chilled ceiling panels can be more easily integrated with ventilation supplied from the ceiling. Panels tend to cost more per unit of surface area than chilled slabs [3].

Now a days ESS is used more compared to RCP systems. The piping material used in ESS are usually copper but due to its high cost and difficulty in embedding it inside concrete, it has been replaced by the cross linked polythene (PEx) as it is cheaper and durable compared to copper piping [4].

2 Literature Review

Several authors discuss thermal comfort in spaces with a radiant cooling ceiling. A few papers published in conference proceedings and scientific journals describe computer modelling of the system with cooling ceiling. Some of the published papers are,

Takehito Imanari along with Toshiaki Omori and Kazuaki Bogaki described an experimental investigation of thermal comfort and the numerical simulation of energy consumption in 1999. The purpose of this study was to investigate various characteristics of radiant ceiling panel system and its applications [5].

Fariba Alamdari (1998) presents the room air distribution and thermal environment of combined displacement ventilation and cooled ceiling systems. A field flow model based on computational fluid dynamics (CFD) was used to simulate comparative environmental performance of displacement ventilation with and without cooling ceiling [6].

Guruprakash Shastry, Senior manager – Green Initiatives, Infosys reviews the radiant cooling system present in a building at Hyderabad Infosys Campus and states that the radiant cooling system consumed 33% less energy when compared to the conventional air-conditioning system for the period April 2011 - March 2012. The building has a total built-up area of about 24000 sq. m. distributed into east and west wings of 11600 sq. m. each and a central wing of about 800 sq. m. About 85% of the total building area is air-conditioned office area and the total occupancy of the building is about 2500. The most significant feature of the building is that it is split into two symmetric halves. One half is cooled by conventional (but very efficient) air conditioning and the other half by radiant cooling [7].

Bjarne W. Olesen reviews that for well-designed buildings these types of system are capable of providing a comfortable indoor climate both in summer and in winter in different climatic zones. Various control concepts and corresponding energy performance are presented. To remove latent heat, these systems may be combined with an air system. This air system can, however, be scaled down with the benefit of improved comfort (noise, draught) compared to full air-conditioning. An added benefit can be added by reducing building height. Finally, surface heating and cooling systems use water at a temperature close to room temperature. This increases the possibility of using renewable energy sources [8].

Lin Su et al.., reviews that Concrete ceiling panel cooling system had advantages of comfort and energy saving. This study presented heat transfer and cooling characteristics of the concrete ceiling radiant cooling panel. Two dimensional mathematical model of steady state heat transfer was developed by using finite difference method. Heat transfer in the concrete panel was numerically simulated. Temperatures of interior and surface of the concrete panel were obtained. According to calculated results, temperature distribution of the concrete panel was analyzed under the condition of different supply water temperatures and distances of tubes, and the numerical model was accurate enough by the experiment. Actual operation characteristics of concrete ceiling panel cooling system were analyzed according to measured data. The cooling capacity of the concrete panel was influenced by supply water temperature, distance of tubes and water flow rate [9].

Zhen Tian and James A. Love described that through integrated field measurements and building simulation with *Energy Plus*, it was found that the building energy performance could be improved by reducing conflicts between systems, especially simultaneous heating and cooling. Control strategies to coordinate air and radiant system operation are crucial to improve the overall building energy performance. Use of "low quality" cooling sources with radiant slab cooling was also considered [10].

Tomas Mikeska carried out theoretical investigations with a CFD model of the test room. The aim of the development of the CFD model was to allow for a deeper understanding of the diffuse ceiling inlet and wall radiant system and to facilitate efficient and economical optimization of the design taking into account various parameters. The results of the investigations presented show that a diffuse ceiling inlet can successfully ventilate and cool the room with a high density of occupants using supply air at an average temperature of 21°C. The resulting cooling power was 23 W/m² at a flow rate of 5.8 l/s·m² of floor area. The average air temperature in the test room was 24.5°C. The cooling power of 32 W/m² was available at a flow rate of 8.0 l/s·m² of floor area, which resulted in an average air temperature in the test room of 24°C. This creates a comfortable indoor environment without draughts. Sufficient mixing was obtained mainly as a result of the interaction of incoming air and heat sources situated in the test room. The diffuse ceiling inlet can therefore be considered a well-performing alternative to the traditional means of mechanical ventilation in spaces with a high density of occupants. The results also show that plastic capillary tubes integrated in a layer of high performance concrete can provide the energy needed for cooling between 29 W/m² and 59 W/m² of floor area with cooling water temperatures between 22°C and 18°C. This resulted in indoor air temperatures of 24.5°C and 22°C, respectively, and a draught-free indoor environment. The relatively high reaction speed of the designed system of radiant cooling was achieved as a result of the slim construction of high performance concrete. Measured values were used to validate a developed CFD model, with the aim of achieving a precise CFD model which can be used to evaluate indoor comfort numerically. The results show that transient calculations using Large Eddy Simulation turbulent models can give a good prediction of temperatures and air flow velocity magnitude in a room ventilated using a diffuse ceiling inlet. However, steady-state turbulent models needed to be applied to obtain adequate predictions in the rooms equipped with a wall radiant cooling system [11].

3 Experimental Setup

The experimental setup or model is based on the typical building. The slab of 4 sq. ft. area was pre-casted and then was placed on the room of 3 sq. ft. area with the wall thickness of 150mm. A window of area 150 x 150 mm² and a ventilation of area 200 x 70 mm² was provided for the room for continuous circulation of air inside the room.

Another slab was pre-casted along with the copper tubing of 3mm diameter embedded in it. This slab placed above the room. A 12.5 mm thick hollow box was prepared from Galvanized Iron sheets and inlet and outlet provisions for circulation of water was given in it. Also a solar water heater model was prepared of size 4 sq. ft. for further heating of water with a black glass on top of it.

The slab with copper tubing was placed on top of the room and then the box of GI sheet was placed on top of it. Also the arrangement for further heating of water was placed on top of the GI sheet box with an insulating layer in between them. The piping for inlet and outlet of water and the temperature sensors were placed at inlet to slab, inlet to GI sheet, outlet from slab, outlet from GI sheet, inside the room. Figure 1 shows the schematic block diagram of the setup. Figure 2 shows the slab with the copper tube embedded in it.

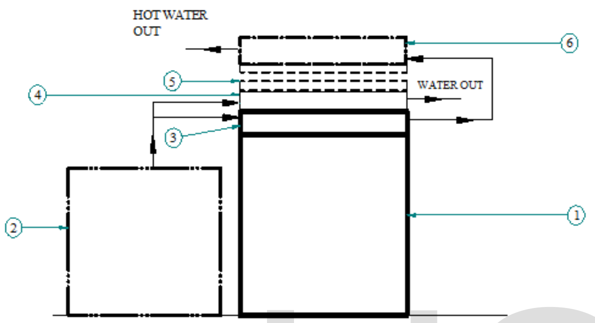

Fig. 1. Block diagram of the experimental setup

Table 1: List of components

Part No.	Part Name
1	Confined Space
2	Reservoir
3	Slab embedded with the piping
4	GI sheet box
5	Insulation
6	Solar water heater

3.1 Working

The water is supplied to the copper piping inside the slab and the GI sheet box simultaneously. Once the water starts flowing through the piping and the box it starts absorbing heat from the slab through conduction from both inner (piping) and outer (box) layers, thus reducing the temperature of the slab. Thus the room gives away the extra heat to the chilled slab by means of convection which in turn results in the temperature drop inside the room. The heated water from both piping and the box is then sent to the top most layer for further heating by solar radiation. This hot water can be then utilized for the domestic as well as power generation.

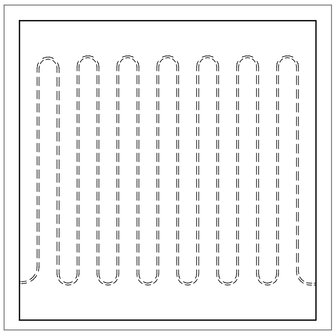

Fig. 2. Piping inside the slab

4 Methodology

The water is made to flow through the piping and then flow rate ($\dot{m}_1$ and $\dot{m}_2$) was measured separately at the outlet from slab and outlet from the GI sheet. Also the temperature was noted down at different inlets and outlets (T_1, T_2 and T_3). The water from both the outlets was then combined and supplied to the top most layer for further heating of water from solar radiation. From the obtained readings the amount of heat extracted from the slab (Q) is calculated using the Heat and Mass transfer formulae.

1. Heat extracted from the slab with respect to embedded tubes,

$$Q_1 = \dot{m}_1 C_P (T_2 - T_1) \text{ Watt……………. (1)}$$

Where,
Q_1= Heat extracted from the slab with respect to embedded tubes (W)
$\dot{m}_1$= Mass flow rate of water through the embedded tubes (kg/s)
C_P= Specific heat of water at avg. temp of T_1 and T_2 (J/kgK)
T_2= Outlet temperature of water from the tubing (K)
T_1= Inlet temperature of water in to the tubing (K)

2. Heat extracted from slab by GI sheet box,

$$Q_2 = \dot{m}_2 C_P (T_3 - T_1) \text{ Watt……………… (2)}$$

Where,
Q_2= Heat extracted from the slab by GI sheet box (W)
$\dot{m}_2$= Mass flow rate of water through the GI sheet box (kg/s)
C_P= Specific heat of water at avg. temp of T_1 and T_3 (J/kgK)
T_3= Outlet temperature of water from the tubing (K)
T_1= Inlet temperature of water in to the tubing (K)

3. Total amount of heat extracted from the slab,

$$Q_a = [(Q_1 + Q_2) / \text{Area of the slab}] \text{ W/m}^2\text{………. (3)}$$

5 Experimental Results

Experiment was carried out on the setup and results were obtained for four different cases. In all the four cases variation of the room temperature with respect to time was observed and noted. Also the heat extraction from the slab and by the solar radiation was calculated. This heat extraction from the slab also resulted in the reduction of room temperature. The results of the various cases are,

CASE 1: Slab without any flow of water.

In this case there was no flow of water inside the embedded tubes and the slab is kept open to the direct solar radiation. It is the same condition as that of the normal building. Here the room temperature will be almost equal to that of ambient temperature because there is no cooling process taking place. Also the slab temperatures will be high and they will radiate the heat absorbed from the sun into the room. Table 2 shows the temperature readings in case 1.

Table 2: Readings of Case 1.

Trial Timings	Room Temp. °C	Slab Temp. °C		Ambient Temp. °C
		Inner	Outer	
10:00	33	35.6	38.6	34
11:30	34.5	37	40.2	35
13:00	35.5	40.8	47.1	36
14:30	36	39.2	43.6	35
16:00	35	36.4	40.2	34

All the cases was studied with an average water temperature of 32°C. Each case was studied from 9.00AM to 4.30PM.

CASE 2: Slab with flow of water.

In Case2 water was passed only through embedded pipes and the temperature distribution was noted down. The room temperatures decreased as a result of heat extraction from the slab. The heat inside the room was then absorbed by the chilled slab. Here the cooling effect can be increased by decreasing the inlet water temperature. Table 3 shows that the room temperature can be maintained by varying the temperature of water as well as the flowrate of water. Average heat extracted was 0.131 kW/m². The room temperature was maintained at an average of 32°C.

Table3: Readings and heat extracted in Case 2.

Trial Timings	Room Temp. °C	Slab Temp. °C		Ambient Temp. °C	Mass flowrate of water $\dot{m}_1$ (kg/s)	Water temperature		Heat extracted with embedded tubes Q_1 (watt)	Total Heat extracted Q_a (kW/sq. m)
		Inner	Outer			Inlet to embedded tubes T_1 (°C)	Outlet from embedded tubes T_2 (°C)		
10:00	31	32.9	39.6	34	0.00259	31.5	35	37.874	0.102
11:30	32	34.3	41.5	35.5	0.00259	31.5	36	48.695	0.131
13:00	32.5	36.4	48	36	0.00259	32	37.5	59.516	0.160
14:30	32	35.8	45.6	36	0.00259	32.5	37.5	54.105	0.146
16:00	31.5	34.1	42.8	35	0.00259	31.5	35.5	43.284	0.116

CASE 3: Slab with water flow in addition with water flow inside GI box.

In case 3 along with embedded tubes, a GI box is placed directly above the slab and water is passed through it. This GI box extracts heat from the upper layer of the slab and also partially insulates the solar radiation falling on the slab. On the day of experimentation, the weather was slightly forecast. So the water temperature exiting the GI box was low and since there was lesser air movement in the atmosphere, the room temperature was slightly more than expected. If the air movement is good then the temperature of the room will reduce since some amount of heat is carried away by the air. The average heat extracted was 0.59 kW/m². This was due to the presence of the GI box. The Table 4 and Table 5 show various readings of case 3.

Table 4: Temperature readings of case 3.

Trial Timings	Room Temp. °C	Slab Temperature °C		Ambient Temp. °C	Mass flow rate of water		Inlet temp. of water T_1 (°C)	Outlet temp. of water	
		Inner	Outer		Embedded tubes $\dot{m}_1$ (kg/s)	GI box $\dot{m}_2$ (kg/s)		Embedded tubes T_2 (°C)	GI box T_3 (°C)
10:00	31.5	34.8	36.2	34	0.00259	0.021	31.5	35	33
11:30	32	34.8	36.4	34	0.00259	0.021	31.5	35	34
13:00	33	35.2	36.1	34.5	0.00259	0.021	32	35	34.5
14:30	32.5	35.6	36.5	35	0.00259	0.021	32	35	34.5
16:00	31.5	34.2	35.8	34	0.00259	0.021	31.5	34.5	33

Table 5: Heat extracted in case 3.

Heat Extracted with		Total Heat extracted Q_a (kW/sq. m)
Embedded tubes Q_1 (watt)	GI box Q_2 (watt)	
37.874	131.607	0.456
37.874	219.345	0.692
32.463	219.345	0.678
32.463	219.345	0.678
32.463	131.607	0.442

CASE 4: Slab with water flow along with water flow through GI box and solar water heater with insulation in between.

Compared to all the previous cases this one is the best suited case for cooling the room. The slab here is completely insulated from the solar radiation because of two layers present above the slab. Also there is an insulating layer between the solar water heater and GI box. The only heat entering the room will be through the walls and via air flow taking place between the room and environment. In order to cool the room the water temperature must be lower than that of ambient temperature.

The heat extraction here will be more since solar water heater is used in this case. The heat obtained in this case is at an average of 1 kW/m². Table 6 and Table 7shows different readings of case 4 and also imply that room temperature has notably lower compared to other cases. Also the water gets heated from solar radiation along with the heat extraction from the slab. Maximum temperature of water that can be obtained from the solar radiation is about 60°C (by using flat plate collector). This temperature can be furthermore increased up to 90°C by using parabolic mirrors or using black tubes. The temperature obtained can be utilized for domestic purposes as well as power generation.

Table 6: Temperature readings of case 4.

Trial Timings	Room Temp. °C	Slab Temp. °C		Ambient Temp. °C	Mass flow rate of water		Inlet temp. of water T_1 (°C)	Outlet temp. of water		Temp. of water heated by solar radiation T_4 (°C)
		Inner	Outer		Embedded tubes $\dot{m}_1$ (kg/s)	GI box $\dot{m}_2$ (kg/s)		Embedded tubes T_2 (°C)	GI box T_3 (°C)	
10:00	31	32.7	34.2	33.5	0.00259	0.021	31	33	33	52
11:30	31	33.1	34.6	34	0.00259	0.021	31.5	33	33	53.5
13:00	31.5	33.2	34.6	35	0.00259	0.021	31.5	33.5	34	55
14:30	31.5	33.5	35.2	35	0.00259	0.021	32	33	33.5	56
16:00	31	33	34.4	34.5	0.00259	0.021	31.5	32.5	33	54.5

Table 7: Heat extracted in case 4.

Heat Extracted with		Total Heat extracted Q_a (kW/sq. m)	Heat gained by water from solar radiation Q_o (kW/ sq. m)	Total heat gained by water Q (kW/ sq. m)
Embedded tubes Q_1 (watt)	GI box Q_2 (watt)			
21.642	175.476	0.530	0.553	1.084
16.232	131.607	0.398	0.597	0.995
21.642	219.345	0.649	0.626	1.275
10.821	131.607	0.383	0.670	1.053
10.821	131.607	0.383	0.641	1.024

5.1 Graphs

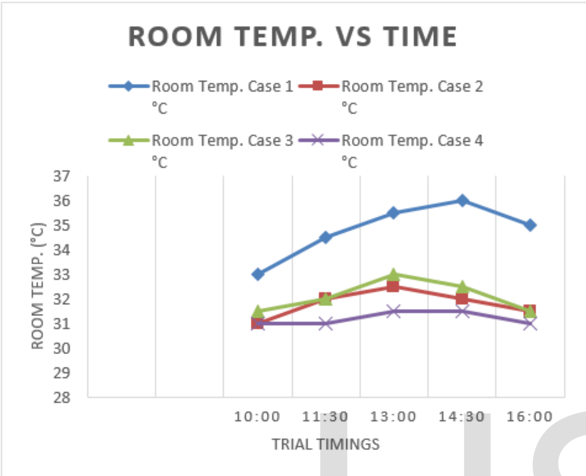

Fig. 3. Variation of Room Temperature Vs Time.

Figure 3 shows the variation of room temperature with time. From the graph it is noted that case 4 is most efficient compared to all cases. Also comparison of case 3 and case 2 cannot be done due to changes in weather but can be concluded that those two cases yield almost same results with higher heat extraction in case 3. The graph also implies that without any setup for cooling (case 1) the room temperature is same as that of the ambient temperature. This comparison tells that the room cooling has been done in all other cases.

6 Conclusion

Various experiments have been conducted using the radiant cooling technique using embedded copper tubes in the concrete slab. It has been noticed that there the water circulated in the embedded tubes had an increase of temperature of 2-5°C during the test. This increase in temperature leads to extraction of an average of 0.5-1kW/m² out of the concrete slab which would have otherwise caused in the increase of the room temperature. During the test the room temperature was constant at an average temperature of 32°C and the slab temperature was maintained at 34°C. This is a confirmation of the radiant cooling. The effectiveness of the radiant cooling system can be increased by using sub-cooled water.

The hot water obtained from the top layer can be used for domestic purposes if the surface area for heating is smaller i.e. in houses. If the surface area is large enough say industries then one can go for power generation. The current work can be extended to generate power to improve the overall performance of the radiant cooling system. Further CFD simulations can be performed to validate the test results and optimization of the flow parameters, the fluid properties can be performed to improve the performance of the radiant cooling systems [12].

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