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Energy Efficient HVAC System Designing and Simulation of Radiant Cooling System

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Abstract—The importance and want for energy efficiency in buildings is well understood. Also, the contribution of energy needed for HVAC (particularly for cooling in Indian context) in buildings ought to be the foremost important. One among the foremost energy efficient means of providing cooling in building with the utilization of Radiant cooling systems. Despite of being energy efficient and economical; the utilization of Radiant cooling has been restricted in India. However, currently there are few smart examples of such systems and there exists some expertise in designing and operating. Lack of careful understanding of system, lack of design and simulation capabilities, restricted data on integration with the building and remainder of the HVAC system, are a number of the most important barriers in scaling from radiant cooling systems installations in buildings.

Index Terms— Radiant Cooling System, Building Energy Simulation, Energy Saving, DOAS, EnergyPlus.

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1 INTRODUCTION

Radiant cooling is one of the cooling technologies used widely around the world in green buildings. However it is still rather new concept here in India. The product itself is simple and robust, but it sets some specific requirements for system design and operation.

This paper we will give the different perspectives to the topic: why client wants radiant cooling, what the designer should know about it, and what is critical during the installation and operation.
Design firms and owners are striving to meet HVAC loads with optimum comfort and minimal energy.

Radiant systems provide heating and cooling through pipes, most commonly filled with water, while ventilation and any humidity control requirements are efficiently met by a DOAS.

With space conditioning and ventilation responsible for 41-51% of the total energy load in conventional offices, leading design teams are turning to radiant systems that can cut this energy use in half. These savings come in large part because using water to move and remove heat in a building is inherently more efficient than using air. Water transfers thermal energy about 7 times more effectively than air.

2 NOMENCLATURE

DBT - Dry bulb temperature, DOAS – Dedicated Outdoor Air System, HVAC - Heating, Ventilation and Air Conditioning, IEQ -Indoor Environment Quality, RH - Relative Humidity, TABS - Thermally active building system, WBT - Wet bulb temperature.

3 MODES OF HEAT TRANSFER

(i) Conduction across surfaces

(ii) Convection between air and surfaces: Convection is heat transfer by mass motion of a fluid such as air or water when the heated fluid is caused to move away from the source of heat, carrying energy with it.

(iii) Radiation Exchange between Surfaces: Thermal radiation, process by which energy, in the form of electromagnetic radiation, is emitted by a heated surface in all directions and travels directly to its point of absorption at the speed of light. Thermal radiation exchange in buildings are in long wavelength infrared rays.

Heat Transfer Coefficients for radiant cooling systems:

- Typical radiative heat transfer coefficient hr~ 5.1 W/m2.K

- Typical natural convection heat transfer coefficient hc~ 2.8 - 5.8 W/m2.K.

- Combined heat transfer coefficient (hr+hc) ranges from~ 8-11 W/m2.K.

4 HUMAN BODY - HEAT GENERATION

Humans are exothermic heat generators

Degree of heat generation depends on activities we do like sitting, standing, walking etc.

(i) If Heat generated > heat loss, then we feel heating of body, sweat formation starts

(ii) If Heat generated < heat loss, then we feel cooling of the body, starts shivering

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(iii) If HEAT GENERATED = HEAT LOSS, known as thermal neutrality. It is also called as THERMAL COMFORT when the conditions are stable and agreeable.

5 HUMAN BODY – ENERGY BALANCE

Heat generated = M – W
Where
M = metabolic rate
W = rate of mechanical work accomplished
Heat loss = Qsk + Qres
Where
Qsk = rate of heat loss through skin
Qres = rate of heat loss through respiration
M – W = Qsk + Qres (neglecting body heat storage)
Heat loss from skin (Qsk) = Radiation + Convection + Evaporation + Conduction

6 COOLING OF THE HUMAN BODY – RADIATION HEAT TRANSFER DOMINATED

An adult male (naked), losses most of the heat through radiation (133 W) > Base metabolic rate (90 W) and hence the person will feel cold

7 FACTORS INFLUENCING THERMAL COMFORT

Personal Factors:

(a) Clothing
(b) Metabolic rate

Environmental Factors:

a) Mean radiant temperature: Weighted average of the temperatures of all the surfaces in direct line of sight of the body.
b) Air Movement: Average speed of the air to which the body is exposed.
c) Air temperature: Temperature of the air surrounding the body.
d) Air velocity: Average speed of the air to which the body is exposed.
e) Relative humidity: Amount of water vapor in a given space. The amount of moisture that air can hold is a function of the temperature.

- Evaporation will have effect when sweating happens.

- Sweating happens if heat generated is not lost by radiation and convection.

8 HUMAN BODY HEAT EXCHANGE

a) Maintaining lower indoor surface temperatures.

b) Enhance radiant heat exchange between human body and indoor surfaces –The central idea of radiative cooling.

OLD PRACTICES: HIGH THERMAL MASS BUILDINGS

- Uses thermal mass to keep the indoor surface temperatures at lower level.

NEW PRACTICES: RADIANT COOLING STRUCTURES

- Structure integrated cooling systems
- Panel cooling systems Supply of chilled water

9 RADIANT COOLING –BASICS

- An actively controlled surface is considered a "radiant system" if at least 50% of the design heat transfer is by thermal radiation (2004 ASHRAE Handbook).

- Radiant cooling is often part of a hybrid system that includes conditioning of ventilation air to address internal latent loads (humidity) from occupants and infiltration, plus sensible and latent loads associated with outside ventilation air.

With Radiant cooling, comfort conditions can be maintained with higher air temperature as compared to forced air cooling system.

NATURE OF OFFICE THERMAL LOADS –HUMANS AND EQUIPMENT

Humans Thermal Load [50 % radiative /50 % convective]

Equipment Thermal Loads: About 75% convective and ~25% radiative

ACTUAL OFFICE EQUIPMENT HEAT GAINS:

•Usually power consumption in office equipment is much less than the nameplate

•Real measured values to be used for large projects

•If not then oversizing and wrong ratio radiative/convective

Modelling of single zone system would reveal that that radiant cooling is more effective when the nature of thermal loads is radiant.

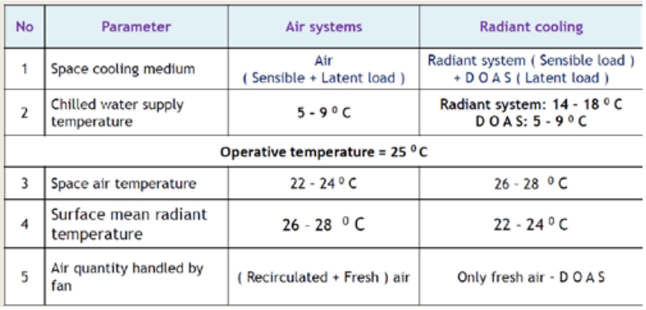
10 SUITABILITY & APPLICATIONS:

APPLICABLE:

(a) Anywhere sensible loads are more dominant than latent loads
(b) Where indoor humidity control is possible
(c) Laboratories
(d) Office buildings
(e) Educational facilities
(f) Healthcare facilities
(g) Government facilities

NOT APPLICABLE:

(a) •Where space sensible loads are not dominant
(b) •Where indoor humidity control is not possible
(c) –Kitchens
(d) –Bathrooms
(e) –Toilets
(f) Precaution to be taken to avoid condensation
(g) •Building air tightness (no infiltration) – positive air operation



No	Parameter	Air systems	Radiant cooling
1	Space cooling medium	Air (Sensible + Latent load)	Radiant system (Sensible load) + D O A S (Latent load)
2	Chilled water supply temperature	5 - 9 ⁰ C	Radiant system: 14 - 18 ⁰ C D O A S: 5 - 9 ⁰ C
Operative temperature = 25 ⁰ C			
3	Space air temperature	22 - 24 ⁰ C	26 - 28 ⁰ C
4	Surface mean radiant temperature	26 - 28 ⁰ C	22 - 24 ⁰ C
5	Air quantity handled by fan	(Recirculated + Fresh) air	Only fresh air - D O A S

Table-1: Conventional vs Radiant systems

11 TECHNOLOGY SNAPSHOT

• Cool or warm water is piped through panels, ceilings or floors to provide radiant thermal comfort to occupants.

• 100% of ventilation air is provided by a Dedicated Outside Air System (DOAS) which can include energy recovery.
• Pumping water is significantly more efficient than using fans to push air, so fan energy is significantly reduced with this system.
• Radiant system design avoids some common operational performance issues that plague standard forced-air systems such as simultaneous heating and cooling.
• Compatible with other lower energy cooling systems such as indirect evaporative cooling, ground or water source heat pumps, and high efficiency chillers.
• Air system is about 1/5th of a conventional air conditioned building resulting in lesser ducting and lower fan power
• Water is the main medium of heat transfer hence pumping energy much smaller compared to fan energy.
• Chilled water temperature in the radiant pipes is 60° F hence chillers run at high efficiency
• Perception of thermal comfort is higher compared to a conventional air conditioned building (better Mean Radiant Temperature)
• Lesser number of equipment's would result in lesser space required and lower cost.

12 CHILLED CEILING

Chilled ceilings are mounted within the ceiling to provide quiet, draft free cooling of the space below. Each unit is made up of a small bore chilled water pipe arranged in an S-shape and attached to the upper surface of a ceiling panel. Ceiling panels are typically of thin metallic construction but can simply be plasterboard. In some systems the chilled water pipes are embedded within the ceiling panel.

During operation, the panel is cooled through contact with the chilled-water pipework allowing it to cool the space through a combination of convective and radiant output (up to 40% radiant). An insulating mat is often placed above the chilled water pipework and panel to minimise uncontrolled cooling of the area above. It is up to the user to include any such insulation in the construction definition.

One advantage of chilled ceilings is that they can be placed in a shallow ceiling void enabling them to be used in buildings with low floor to ceiling heights. However, their limited cooling output makes them unsuitable for areas with moderate to high heat gains. The maximum capacity of chilled ceiling systems is in the order of 70 W/m2.

Chilled-ceiling systems require a separate ventilation system for fresh air supply.

Condensation of room air on and within the chilled ceiling can be avoided by shutting of chilled water flow based on room dew point temperature.

13 RADIANT COOLING MODELING

Demonstration of modeling of radiant cooling system in Design Builder. Design Builder is a Graphical User Interface (GUI) for simulation tool “EnergyPlus”.

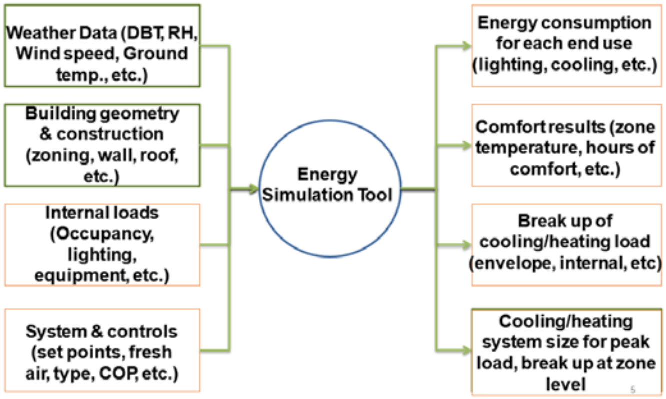


Figure 1: Inputs and outputs of a building simulation tool

14 BUILDING ENERGY SIMULATION PROCEDURE:

Step 1: Making Building Simulation Model

(a) Building envelope (walls, floors, ceilings, windows, glass etc.)

(b) Loads (Occupancy, Lighting and equipment etc.)

(c) Schedules

Step 2: HVAC modelling:

(a) Air loops,

(b) Chilled water loops

(c) Controls

Radiant slab modeling procedure:

(a) Building a model

(b) HVAC modeling (2 systems)
  (i) DOAS modelling
  (ii) Chilled slab/ceiling modeling.

(c) Run simulation

(d) Results analysis

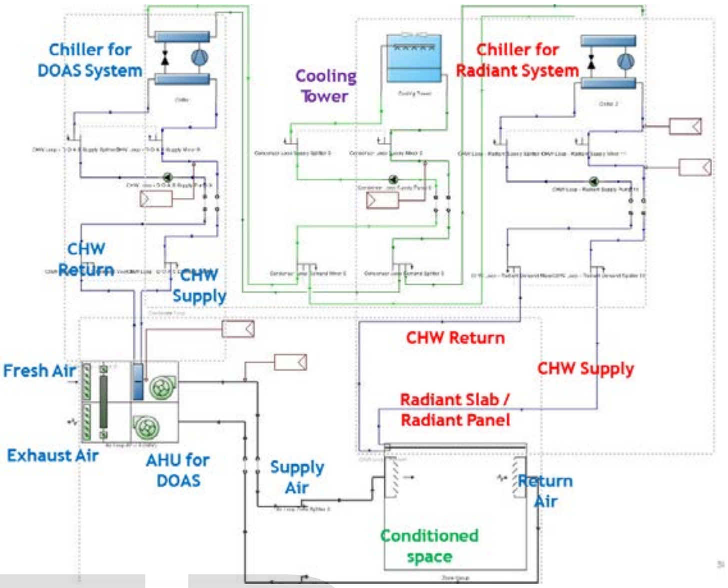


Fig 2: Schematic of Radiant slab cooling system modeling

15 OBJECTIVE: MODELING RADIANT SLAB COOLING SYSTEM

Step 1: Building a simulation model

Building envelope:

Wall: 230 mm brick (U value – 0.438 W/m2)
Roof: RCC 150 mm + XPS Insulation (U value – 0.409 W/m2)
Ground floor: RCC 150 + XPS insulation (U value – 0.409 W/m2)

Glazing:
Window to Wall ratio = 40 %
SHGC = 0.27
VLT = 0.49
Glass U Value = 1.5 W/m2-k

Internal loads: (8 am to 6 pm; Monday to Friday)
Occupancy = 0.65 people / m2
Equipment = 10 W / m2
Lighting = 15 W / m2
Ventilation rate = 3.8 liter / sec / person + 0.3 l/s-m2

- Area = 2375.27ft2

Floor to floor: 12 ft.
Project: Educational Facilities – Lecture

Day time operation
1 storey building (1 zone)

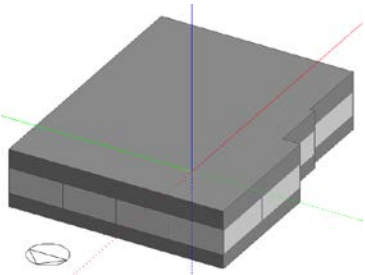


Fig 3: Layout of Educational Facilities- Lecture project

Step 2: Slab cooling modeling
Add zone group (1 zone)
Define set points: 24C; RH – 50%
Define fresh air rate (3.8 liter / sec / person + 0.3 l/s-m2)
Target 1 zone
Ground floor

16 DOAS SYSTEM MODELLING:

(a) Adding a generic Air loop
(b) Define supply air flow rates & Schedule. Design supply air flow rate (m3/s) : 1.4
(c) Recirculation should not be considered.
(d) Heat recovery (75% Sensible & Latent)
(e) In AHU Unit cooling coil & Scheduling is added.
(f) At zone level air distribution unit is added to the zones and extract unit is added to the zones
(g) Connect the air loop to the zones
(h) Chiller to be added and define chilled water loop schedule
(i) Connect chilled water loop to cooling coil
(j) Connect cooling tower to the chiller

17 RADIANT COOLING SYSTEM CLASSIFICATION & BASICS OF SLAB COOLING

RADIANT COOLING SYSTEMS -CLASSIFICATION

BASED ON SYSTEM INTEGRATION.

(A) Structure integrated systems (Slab, Wall), TABS:

(i) Better coupling with the thermal mass of the building structure.

(ii) Lower cost per unit area of active surface

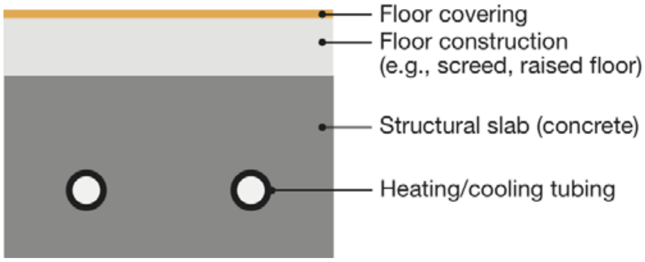


Fig.4: Layout of Structure integrated systems

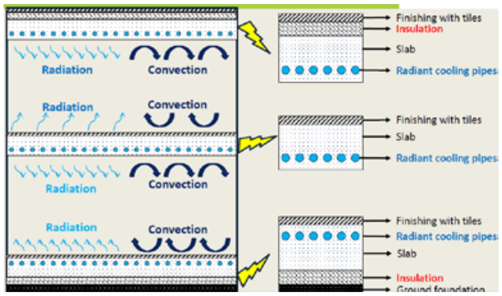


Fig.5: Layout of Structure integrated slab cooling systems

(B) Panel cooling systems (Ceiling suspended, Wall mounted)

(i) Zoning and installation flexibility.

(ii) Better responsiveness and control

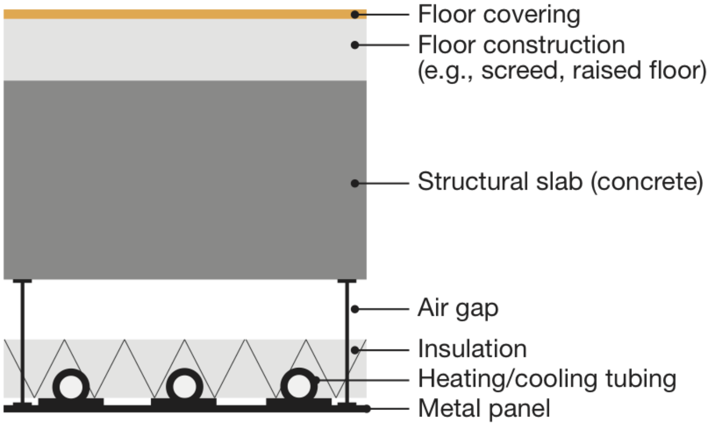


Fig.6: Layout of Panel cooling systems

(C) Embedded surface system

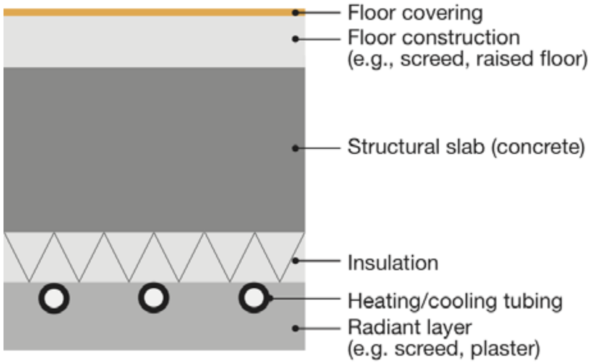


Fig.7: Layout of Embedded surface systems

18 RADIANT SYSTEM MODELLING:

Add chilled ceiling at zone level.
Define parameters for chilled ceiling

(i) Tube dia., circuit length limited to 100 m,
(ii) Zone control operative temperature
(iii) Add cooling set point schedule
(iv) Dew point offset (20C)
(v) Define operation schedule
(vi) Add chilled water plant loop
(vii) Define chilled water loop schedule.
(viii) Chiller selection

No	Chiller	Load share
1	**DOAS**	**37%**
2	**Radiant**	**63%**

TABLE 1: DOAS & Radiant System Load share

19 SIMULATION RESULTS: KEY PARAMETERS TO BE CHECKED

(i) Comfort (Set points for temperature & RH)

(ii) Ventilation rates

(iii) Slab surface temperature

(iv) Inside dew point temperature

19 ENERGY BENEFITS

(i) Chiller energy savings

(ii) Fan energy savings as there is no recirculation of indoor space air

20 OTHER BENEFITS

(A) Better IEQ
  (i) Less noise due to less draft
  (ii) Even temperature distribution

(B) Space savings per floor (reduction in mechanical room space).

(C) Less floor to floor height (no change in ceiling to floor height), implies reduction in building wall material usage

21 SPECIAL CONSIDERATIONS FOR RADIANT SLAB

(i) •Radiant pipes to be kept under a pressure of 3 –4 kg/cm2 always during installation.

(ii) •Manifolds to be preferably at the peripheral area

(iii) •Two separate controls for peripheral area near glass and work station area

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