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Investigations on cooling parameters of conventional HVAC system & peltier module cooled hydronic radiant system

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Abstract

In hot and humid environments, the desire for effective cooling has been a fundamental human need throughout history. In the current era of escalating living costs and declining air conditioner prices due to market competition, there's a concurrent rise in global warming. To counter this, there's a pressing need for an environmentally friendly cooling system. This proposal suggests the development and evaluation of a cost-effective radiant cooling system.

During the design phase, factors like sensible and latent heat loads, humidity, temperature changes, air infiltration, room size, and wall/window orientation are crucial. Utilizing ASHRAE guidelines, a hydronic system was integrated into the design. Post-fabrication, a theoretical air conditioning rig was statistically calculated. A comparative analysis was conducted to assess human comfort during both summer and monsoon seasons, alongside operational costs for each system.

The implemented low-cost radiant cooling system aims to surpass the eco-friendliness of traditional air conditioners. By meticulously considering various parameters during the design phase, including those outlined in ASHRAE guidelines, the system seeks to provide an optimal balance between efficiency and environmental sustainability. This research delves into contrasting the performance of conventional HVAC systems with a low-cost radiant cooling system utilizing Peltier modules. The comparison of human comfort and operational costs during different seasons serves as a metric for evaluating its performance. This approach not only addresses the immediate need for efficient cooling but also aligns with the imperative of mitigating the environmental impact of conventional air conditioning technologies.

Keywords: HVAC, humid environments, energy conservation, cooling parameters, peltier module

Introduction

Because of the growing concern for energy conservation and the growing need for thermal comfort, cooling systems that give better human comfort, are eco-friendly, and consume less electricity are essential. Moving water is more efficient than moving air due to physical and thermal qualities. Water can transport 3,400 times the energy that air can in the same volume. This feature is employed to its greatest advantage in a radiant cooling system. This is the fundamental principle at work in radiant cooling. There is a flow of cold water via pipes placed in the MDF walls and cools the whole wall, resulting in a wall surface temperature of roughly 20 degrees Celsius. Cooling is performed inside a room when a cool panel absorbs the heat (radiation) created by humans, computers, lights, and other equipment exposed to the panel. To maintain a healthy interior climate and to manage the moisture content of the air inside the office area, fresh air is provided via an air system. In other words, the chilled walls handle the sensible heat load, while the Dedicated Outdoor Air System (DOAS) addresses the latent heat load. The varied heat loads during work are considered:

- Solar heat gains via glass wall and roof solar and transmission heat gain.
- Heat gain transmission excluding walls and roof.
- Infiltration Heat Gain.
- Sensible Internal Heat Gain.
- Room Latent Heat.

Importance of this R&D in the proposed region in terms of societal benefit

- Energy conservation improved thermal comfort.
- More architectural freedom Lower operating and maintenance expenses.
- More efficient ventilation management.
- Global warming mitigation.
- There are no toxic chemicals in the system, making it environmentally friendly.

The use of a liquid heat-transfer medium in heating and cooling systems is known as hydronic. Water, glycol, or mineral oil are common working fluids. Steam and hot water radiators are two of the oldest and most prevalent forms. The different types of Radiant systems are: Chilled Slabs, Panels, and TABS.

Background and Literature Review

According to research undertaken by the Lawrence Berkeley National Laboratory, radiant cooling energy savings vary with climate, but on average in the United States, savings are in the region of 30% when compared to traditional systems. Cool, humid places might save 17%, whereas hot, arid regions could save 42% [11].

Infosys Bangalore built a 250 m^2 data centre wherein the designers aimed for a PUE (Power Use Effectiveness) of 1.12 which is an improvement over the current value of PUE 1.37. They managed to achieve PUE of 1.37 at < 50% load. This was the first project in India to maintain high server hall temperatures (~27 °C) to enable warm-water cooling to avoid compressor use and thus lower cooling energy cost. A high efficiency cooling plant yields a PUE of 1.18, however the plant only runs during occupied office hours requiring the use of a small, relatively inefficient, air-cooled chiller to serve the data centre during "off" hours. The air-cooled chiller takes the operation to a PUE of 1.4. The combined operation in all modes performs at a 1.33 PUE. We have observed from current literature that a large portion of the energy savings can also be ascribed to a lower amount of energy necessary to pump water rather than disperse air using fans. Radiant cooling may move some cooling to off-peak night-time hours by linking the system with building mass [12].

From Kan Shindo, Jun Shinoda's, A comparative study of the whole life carbon of a radiant system and an all-air system in a non-residential building, the whole life carbon was 10.1 kg CO2-eq/m^2/year and 9.0 kgCO2-eq/ m^2/year for the all-air system and TABS, respectively. Compared to the all-air system, TABS reduced annual total primary energy use by 34% and whole life carbon by 11%. The percentages of operational carbon to whole life carbon were 29% and 18% for the VAV system and TABS, respectively. The implementation of the TABS contributed to the reduction of operational carbon (-1.29 kgCO2-eq/ m^2/year) and a slight increase in embodied carbon (+0.21 kgCO2-eq/ m^2/year) compared to the VAV system [13].

In a report by the National Renewable Energy Laboratory that evaluated strategies to achieve 50% energy savings in large office buildings, the equipment and construction cost of a radiant system with DOAS for the 90.1 prototype low-rise large office building was estimated to be \$22.1/ft^2 and the baseline VAV system cost was \$18.6/ft^2. (Leach, Lobato, Hirsch, Pless, & Torcellini, 2010). In the radiant design, the radiant slab and its associated hydronic system cost was \$10.89/ft^2 [14]. In the study 'Comparison of Construction and Energy Costs for Radiant vs. VAV Systems in The California Bay Area' by Jingjuan Dove Feng, Hwakong Cheng, radiant HVAC design has a total cost of \$38.9/ft^2compared to \$29.9/$ft^2$for the VAV design, representing a \$9.0/ft^2premium for the radiant design. The analysis is based on a typical floor layout that is representative of open plan office spaces with a total floor area around 112,000 ft^2. Though there are some sheet metal cost savings for the radiant design due to smaller ducts, the savings due not outweigh the increased piping costs. The total installed cost for sheet metal is \$4.5/ ft^2 for the radiant design, compared to \$7.9/ $ft^2$for the VAV design. As much of the cost premium for the radiant design is associated with piping labour, the premium is more pronounced in the San Francisco Bay area with its high labour rates at about \$120/hr. For the estimated national average labour rate of \$85/hr. the premium for radiant is \$6.8/ ft^2, compared to the VAV system. The high installed cost for the radiant equipment is partly a reflection of the current radiant manufacturers' pricing strategies and the contractors' bidding practices. The radiant market is relatively small and immature in the United States. Radiant system costs are likely to decrease due to economies of scale as the market grows and as uncertainties decrease as the design and construction industry gains more experience [15].

Model Design

The first phase of the design process must state the dimensions of the model to be cooled. The model dimensions, thus, must be decided upon. A model that is compact so as to reduce hassle of fabrication and expense, but standardized to understand the results of the radiant cooling system was desired. The model dimensions, in line with above considerations were decided upon as follows:

Length (L): 1.5 ft.
Breadth (B): 1.5 ft.
Height (H): 1 ft.
Volume area: Length x Breadth x Height = 2.25 ft^3

Computer Assisted Drawings or CADs of the model were created to check for feasibility, ease of assembly, panel construction feasibility and the integration of the slabs together. With chilled slab system selected as the type of radiant cooling system, the model to be created was designed to emulate the form of a slab. The slabs were thus designed as two separate walls with pipes running through its centre, forming the base of a chilled slab radiant cooling system. The CAD must also encompass and portray the feasibility of the pipe turns, a general number of pipes congregated onto a single wall and their continuation to the other wall, the location of the sump tank and its reach from the model.

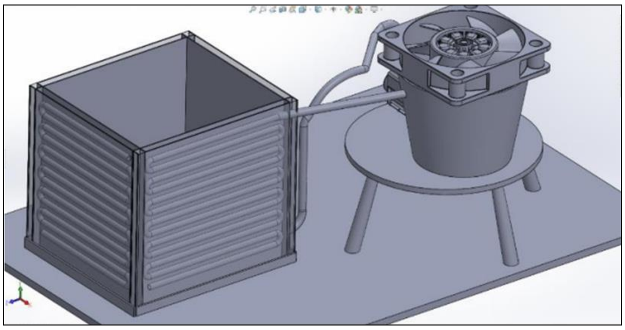

Fig 1: Model CAD

The model inner walls must be conducive to heat, while the outer walls must insulate heat, to ensure proper radiant cooling without significant losses. The following materials were shortlisted from a plethora of materials and were rated by team members based on thermal conductivity, availability, price, and machinability.

Table 1: Material Selection

Material	Thermal Conductivity (W/m K)	Availability	Price	Machinability
Wood	0.15	High	Low	Low
PLA	0.16	Moderate	High	High
Bricks	[ASHRAE]	High	Low	Low
Carbon Fiber	10	Low	High	Low
Plaster of Paris (PoP)	0.18	High	Low	Moderate

With the above constraints in mind, wood was selected as the material for the inner and outer walls of the model.

Cooling Load Calculations

In general, the cooling load for any system, conventional or radiant is divided into two types.

- Sensible Load.
- Latent Load.

Environmental Parameters

The following parameters were recorded for Mumbai during the months of February and March.

Table 2: Outside air conditions for the months of February & March

Wet bulb temperature (°C)	Dry bulb temperature (°C)	Humidity (%)
29.3	30.1	54
28.4	29.1	48
29.1	30	61
29.5	30.2	65
30	32	70
31.2	32.5	75

Sensible Heat Load: Due to the simplicity of the model and no external heat sources, only solar heat gain and infiltration heat are included in heat load calculations:

Solar heat gain from walls and roofs

$Q_s = U \times A \times (dT)$ [i]

Where,

Qs - Solar heat gain

U - Overall heat transfer coefficient = Thermal conductivity of Wood = 0.15 W/m K

A_w - Area of walls = 1.5 ft. x 1 ft. = 0.139 m^2

Al - Area of ceiling/floor = 1.5 x 1.5 ft2 = 0.2090318 m^2

DT - Temperature difference between outside and room conditions = 5 °C

Thus,

Total solar heat gained = 0.57 W

Latent Heat

While the latent heat load was added as a factor, radiant cooling systems traditionally do not deal with latent heat loads. With the load as small as 0.0001 W, a ventilation system that could manage the same, without interfering in the cooling procedure was unable to be found.

Apparatus Dew Point Temperature

Room sensible heat factor = Total sensible heat load/total heat load.

$$= \frac{0.57}{0.5701} = 0.9974$$

On the psychometric chart, the apparatus dew point temperature was found to be 13 °C. Therefore, to avoid wall condensation, the radiant cooling slab temperature must be kept above 13 °C.

Loop Design

Loop design is another important parameter of the radiant cooling system. Loop design helps determine the number of loops to be had on a single slab of the model. Area ratio of radiant panels to total surfaces should be kept within 0.15 to 0.38 when the radiant surface temperature is 20 °C or below (ASHRAE Handbook).

Thus, loop design was conducted as follows:

The model dimensions are 1.5 ft. x 1.5 ft. x 1 ft. = 46cm x 46 cm x 30cm

Therefore, wall dimensions = 46cm x 30 cm.

Considering bends on either side of the straight tubes, equivalent radiant area was calculated.

Radiant Area = 22 cm x 35 cm = 770 cm^2 …. (Margin was taken as 4 cm x 5.5 cm)

From above constraint,

Required Radiant Area = 0.15 * 770 = 115.5 cm^2

Pipe Diameter (d) = 6 mm = 0.6 cm…….Smallest Diameter of copper pipe available)

Single copper pipe area = 0.6*30 = 18 cm^2

Therefore,

Minimum number of loops required on each wall = 115.5/18 = 6.338

Thus, the number of loops on the panel are kept as 7. The final wall before the sump tank has only six loops for operational ease. If inconsistencies are observed during the testing phase, the number of loops will be increased to 7.

Model Assembly

Before the fabrication or assembly of the model, panels, or the system altogether, a list of objects required for the successful operation of the system must be made.

Auxiliary Components

The following auxiliary components are selected for the Model:

1. Centrifugal Pump
2. Water Storage Device
3. Temperature Gun
4. Thermostat

Final Assembly

Fig 2: Final Model Assembly

Testing

Testing the radiant cooling system was carried out using the following procedure.

Set up the pump to the power supply, attach the entry pipe to the pump outlet and exit pipe into the water storage device. Quickly fill the water storage device with 3.5 liters of cold water, place the pump into the water storage device and turn the pump ON for a period of one cycle i.e., 30 seconds only. Once the system tubing is filled with cold water, turn the pump off. After about 10 minutes turn the pump ON to cycle out the warm water in the tubing. After 30 minutes empty the water storage tank and fill it again with 3.5 liters of fresh cold water. Repeat steps 5,6,7 until desired temperature is obtained.

Observations

Fig 3: Observations

Water Temperature	Room Temperature	Time	Time period	Amount of Water	
15	29.6	11:00 AM	0	3.5 litres	
16.5	28.8	11:10 AM	10	3.5 litres	
17.3	28.5	11:20 AM	20	3.5 litres	
18.6	27.9	11:30 AM	30	3.5 litres	
19.1	27.7	11:45 AM	45	3.5 litres	
20.4	27.5	12:00AM	60	3.5 litres	
					Water Change
15	26.9	12:15 PM	75	3.5 litres	
17	26.4	12:30 PM	90	3.5 litres	
19	26.1	12:45 PM	105	3.5 litres	
21	25.7	1:00 PM	120	3.5 litres	
					Water Change)
15	25.4	13:10	130	3.5 litres	
15.8	25	13:20	140	3.5 litres	
17	24.9	13:25	145	3.5 litres	
18	24.8	13:40	160	3.5 litres	
Water Temperature	Room Temperature	Time	Time period	Amount of Water	
14.5	29.6	12:10 PM	0	3.5 litres	
15.8	28.8	12:20 PM	10	3.5 litres	
17.3	28.5	12:30 PM	20	3.5 litres	
18.6	26.9	12:40 PM	30	3.5 litres	
					Water Change
15	26.9	12:45 PM	35	3.5 litres	
17	26.4	12:55 PM	45	3.5 litres	
19	26.1	1:05 PM	55	3.5 litres	
21	25.4	1:15 PM	65	3.5 litres	
					Water Change
15	25.2	1:35 PM	75	3.5 litres	
15.8	25	1:45 PM	85	3.5 litres	
17	24.9	1:55 PM	95	3.5 litres	
18	24.8	2:05 PM	105	3.5 litres	

$$\text{EER} = \frac{\text{Cooling Capacity in BTU/hr}}{\text{Input Power consumed}}$$

Results

Power Consumption of Radiant

Power consumed by the radiant cooling model can be divided into 2 subcategories.

- Power consumed by the pump.
- Power consumed by the cooler.

Power consumed by pump

Power consumed by pump $[P_1]$ = Number of hours × Capacity of appliance

$$= \frac{3}{60} \text{ x } 55 = 2.75 \text{ W-hr.}$$

Power consumed by the cooler

Actual power consumed [P2] = 300 x 7/20 = 105 W-hour

$[P_{radiant}] = P_1 + P_2 = 105 + 1.833$

$\mathbf{P_{radiant} = 107.25}$ **W-hour**

Power Consumed by HVAC

Power consumed $[P_{HVAC}]$ = TOR required = 0.145 = 509.943 W = 1738.907 BTU/hour

Now, considering a 5-star rated AC, its Energy Efficiency Ratio (EER) is 3.5 and above. The formula for EER is as follows:

$$\mathrm{EER} = \frac{\text{Cooling Capacity in BTU/hr}}{\text{Input Power consumed}}$$

The highest EER possible is 14 with the help of current technology. The most excellent energy efficiency ratios in today's times are around 12.
Thus, considering EER = 12
Therefore, for our model,

$$\text{Power consumed } [P_{HVAC}] = \frac{1738.907908}{12}$$

P_{HVAC} = 144.9 W-hour
Therefore,
P_{HVAC} = 144.9 W-hour

Comparison between radiant and HVAC
Percentage Saving in power
Percentage Power saving in radiant cooling model =

$$\frac{Phvac - Pradiant}{Phvac} = \frac{144.9-107.25}{144.9} \times 100 \approx 26\%$$

Ease of assembly and handling
The simplistic model that we have designed stands as a baseline that bigger radiant cooling models can also be built with relative ease. An HVAC system needs to be installed individually in each house and requires the assistance of an expert. However, with chilled slab radiant cooling system, the system is built from the ground up along with the building walls. Other than maintenance, there is no need for technical installation or assistance from a skilled technician for the same. For minor leakages, a common plumber may also repair it. Thus, from the perspective of an end user, the radiant cooling model is easier to assemble, handle and maintain.

Cost Effectiveness
While copper is expensive on its own, the entire radiant model costs significantly less than an AC. It does not use any expensive components, using readily and widely available devices like a water cooler, centrifugal pump, etc. The installation and maintenance cost are also lower than that of a conventional HVAC system.

Human Comfort
Radiant cooling is also widely providing in comfort. While the latent heat of the model could not be removed, a general application of a DOAS or ventilation system lowers the latent heat of the system as well. From Peter Simmonds, Practical Applications of radiant heating and cooling to maintain comfort conditions, it is proven that radiant cooling and heating systems provide better thermal comfort than HVAC VAV systems.

Conclusion

We successfully designed an efficient and cost-effective radiant cooling system, with the help of available and inexpensive components. The design phase included multiple factors including gaining a basic understanding of refrigeration cycles, learning the bare minimum about radiant cooling systems, gaining a superficial knowledge of plumbing, wiring and assembly. The main objective of the project was to ensure the scope of the project in the green energy sector. With an advantageous power saving of 26% over a conventional HVAC system, the value which is widely accepted to be around 30 ~ 50% in hot conditions, the radiant cooling model designed has successfully completed the objective set at the beginning. During the fabrication and assembly phase, it was observed that the radiant cooling system was much easier to install than a conventional HVAC system. Further, it reduces the cost of operation though the investment required may be more at the start. Radiant cooling models also have superior human comfort levels than a conventional HVAC system, this being especially true in arid conditions. In humid climates, with the addition of a DOAS or AHU, the humidity can be easily mitigated. The temperature of the model was kept around 24 to 25 °C which is the range of human comfort. This is difficult to do in a conventional HVAC system, which requires the usage of electronic control systems to emulate the same. During the testing phase, after many test runs, we were able to optimize the operation time of the pump to suitably deliver desired temperatures while keeping the power consumption to a minimum. With a host of innovative technologies and operational solutions, this study demonstrates that achieving ambitious efficiency targets for large scale industry based radiant cooling setups is possible, even in a tropical climate. Such precedents set in the industry opens possibilities to examine, emulate, and where warranted, to improve upon. Thus, the radiant cooling system and its scope and relevance in the green energy sector was found out.

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