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Detailed Characterization of Novel Radiant Floor Heating and Cooling Systems

S. Shukla, R. Daneshazarian, A. Mwesigye, SB. Dworkin
Mechanical and Industrial Engineering Department
Ryerson University
Toronto, Canada

J. Swift
Grip Metal Manufacturing
NUCAP Industries Inc.
Scarborough, Canada

***Abstract*—**Traditional radiant floor heating systems consist of a heat source- hot water pipes or electrical heating wires, embedded in concrete and other building materials. Radiant floor cooling systems typically use water close to room temperature. Both systems have the potential to offer benefits to homeowners as compared to the widely adopted forced air and hot water radiator systems. They exhibit quiet operation, minimal airborne dust production, and furniture space savings. Also, they optimize thermal comfort and result in energy savings of 15-30%. However, these floor heating systems are more expensive than conventional alternatives, and there is still potential for improved heat transfer efficiency with novel design improvements. Floor cooling systems are also limited by factors such as acceptable floor temperature, dew point temperature, and responsiveness of the floor to fluctuations in thermal load. Recently, a retrofittable radiant panel configuration has been proposed by the industry partner as a component in floor heating systems, comprising a metal plate with small spikes that can be pressed into cement board or wood. The spikes can serve two purposes; they can bind materials together reducing manufacturing costs and improve heat transfer. The behavior of this configuration was simulated for different materials for the metal plate, spike dimensions, and varying spacing between the spikes. Two scenarios for this configuration were considered: radiant floor heating in an office environment and radiant floor cooling in a basketball court. The optimal configuration comprises an aluminum sheet with an enhanced surface consisting of a series of spikes, increasing surface area and penetrating surrounding material, with spike length of 0.09 in (2.3 mm). It yields approximately 60% energy reduction and heat transfer enhancement compared to a no-spike metal plate configuration. The outcome of this research is fundamental understanding leading to an optimized design of a cost-effective and energy-efficient floor-heating and floor-cooling system that can be easily installed in new or retrofitted buildings. By significantly improving radiant floor heating systems, more and more traditional natural gas heating can be offset, leading to reduced greenhouse gas emissions.

Keywords- Metal Plate with Spikes; Radiant Floor Heating and Cooling; Energy Efficiency; Thermal Comfort; Computer Simulation; Economic Optimization

I. INTRODUCTION

A. Background

1) Energy Use in Buildings: According to the International Energy Agency (IEA), building sector is responsible for 36% of total energy consumption and this contributes to 40% of total CO_2 emissions. Over the next 40 years, the building sector will grow by nearly 230 billion square meters which is equivalent to adding the floor area of Japan's landmass to the planet every year until 2060 [1]. Hence, there has been a spark of interest globally to reduce the energy consumption of commercial & industrial buildings and residential housing. The combination of strategies such as improving efficiency of heating, ventilation, and air conditioning (HVAC) equipment and reducing the thermal demand of the house by improving envelope conditions, better control, and introducing renewable energy technologies could yield significant reduction of greenhouse gas emissions (GHG). The potential for GHG emission, CO_2 primarily, is presented in Fig.1.

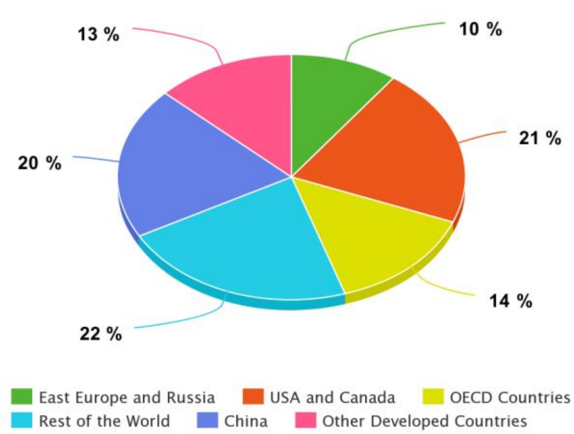

Figure 1. Potential CO_2 reductions from the building sector [1]

According to a survey of commercial and institutional energy use, commercial and institutional buildings in Canada represent 26% of the total energy consumption [2]. As presented in Figure 2, 65% of the energy consumed in the buildings sector is dedicated to space heating and thus the highest GHG intensity- greenhouse gas emissions per unit floor area (m^2)- is seen for space heating equipment as well.

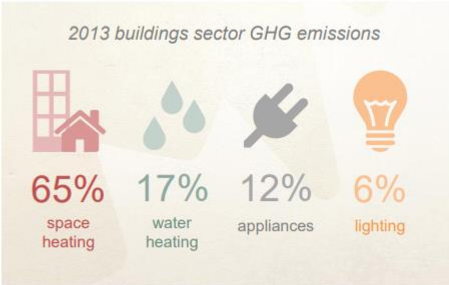

Figure 2. Breakdown of building sector GHG emissions [3]

At 41.6% of the total energy consumption of buildings in Canada, Ontario's building sector consumes the highest amount of energy and this is because buildings, commercial and institutional, account for 35.6% of buildings in Canada [4]. According to the National Energy Board (NEB), the GHG emission factor for electricity and natural gas in Ontario is 40 g CO_2 per kWh electricity generation and 1860 g CO_2 per m^3 of natural gas burned [5]. By significantly improving radiant floor heating systems, more and more traditional natural gas heating can be offset, leading to reduced GHG emissions. Since buildings are the biggest consumer of energy in Canada, it is important that space heating systems used in buildings operate in a more economical and sustainable way. This research is in line with Canada's Climate Change Action Plan (CCCAP) and the short-term goal of reducing GHG emissions by 15% below 1990 levels by the year 2020 [6].

2) Radiant Floor Heating and Cooling Systems: The Romans pioneered floor-heating systems; evident from ancient sites known as "hypocausts", the floors were heated by directing exhaust gases from wood fires under raised floors [7]. In early 20th century, when building envelopes were not as airtight as they are now, radiant floor systems were not adopted as much in cold climate countries such as Canada. To compensate for harsh cold climatic conditions, floors had to be heated to uncomfortably high temperatures and thus there was little to no effort made in navigating nuances of space heating systems. However, since the energy crisis of the 1970s, there has been increased focus on implementing buildings code that foster 'energy-efficient' building envelopes such that those pertaining to minimizing transmission and ventilation heat losses [7].

Radiant floor heating and cooling systems have the potential to offer more benefits to homeowners than the widely adopted forced-air convection system. State-of-the-art systems comprise hot water pipes embedded in concrete underneath wood, with a floor surface temperature between 19°C and 29°C [7–9]. They are integral to the sustainable energy market as they function well with geothermal, or efficient heat pump systems. They exhibit quiet operation, minimal airborne dust production, furniture space savings, and simultaneously optimize comfort and energy savings [10,11].

Ideal heating curve starts at the lowest temperature at the head and increases towards the feet [11]. Radiant floor systems follow the same pattern. This demonstrates enhancement in thermal comfort conditions and it is shown in Fig. 3.

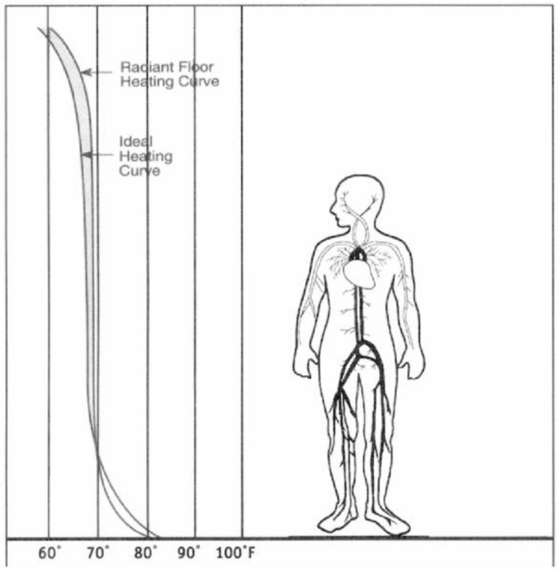

Figure 3. Ideal heating curve and radiant floor heating curve [11]

Radiant floor cooling systems emerged later than floor heating systems, having first been introduced in dry climates of Europe in the mid-20th century. They were first employed in the Copenhagen Opera House where outdoor conditions are relatively dry and cool and the floor cooling system's sole purpose is to remove solar heat gain by circulating water at 15-18°C [12].

The main challenge of radiant floor systems, however, is that they are expensive to construct and install. Furthermore, due to the insulating characteristics of many floor materials (e.g. wood), there is potential to improve energy transfer with advanced system design. Also, they cannot be easily retrofitted and the tendency of concrete to hold heat makes them less responsive to fluctuations in thermal loads [13].

Since their introduction, a number of studies have considered different variations of radiant floor heating and cooling systems. The next section details a review of related studies.

B. *Literature Review*

Different variations of radiant floor heating systems can be found in the literature. Izquierdo and Agustin-Camacho considered micro photovoltaic-heat pump systems in conjunction with radiant floor heating systems [14]. Zhou and He assessed thermal performance of a radiant floor heating system with different heat storage materials [15]. Most of well-researched radiant floor heating systems fall in the following categories: heavy- pipes laid out in the concrete layer of the construction or lightweight- pipes placed in aluminum foil [16]. Also, numerous studies have been performed to demonstrate thermal comfort achieved by radiant floor systems; they show that the temperature distribution is uniform and maintains thermal comfort conditions prescribed by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) [16–18].

Radiant floor cooling systems have been an economically viable option for large space buildings such as airports, convention centers, atria, and entrance halls [20]. This is primarily because, as identified through experimental analyses of multiple studies, the indoor thermal environment in these spaces possess high-intensity solar radiation and high temperature internal wall surfaces [20, 21]. For large space buildings whose envelopes are mainly composed of glass facades and skylights, floor cooling is an effective means of removing sensible heat because of direct absorption of solar radiation and long wave radiant heat exchange with a building envelope [20]. Research conducted at Lawrence Berkeley National Laboratory concluded that radiant panel cooling used less than 5% of the otherwise necessary fan energy to remove a given amount of indoor sensible heat [23]. Also, on average, it has the potential of saving 30% of the overall cooling energy in applications across a range of representative climates in North America [22, 23].

There has been little to no research performed on retrofitted radiant floor panel configurations that optimize thermal comfort and save energy, all while operating within 19°C to 29°C floor surface temperature ranges and minimizing the risk of condensation [7]. This study is novel and aims to accomplish an economically viable and energy-efficient radiant floor configuration that maintains thermal comfort standards. It incorporates metal sheeting [25] with small strong spikes (0.76 mm to 2.41 mm long), that can both decrease construction costs through mechanical adhesion, and increase conductivity through the floor. The physical model of this proposed design is discussed in the following section.

II. PHYSICAL MODEL

A schematic two-dimensional representation of the proposed radiant panel is depicted in Fig. 4. The heat source can be an electrical heating element or hot/cold water through a network of pipes.

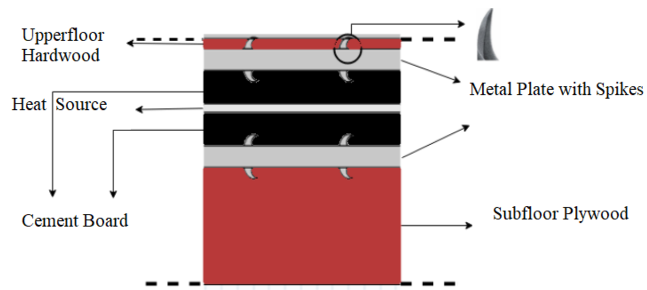

Figure 4. Radiant panel layout

A three-dimensional representation of the panel layout and spike variations for the metal plate are shown in Fig. 5 and Fig. 6, respectively.

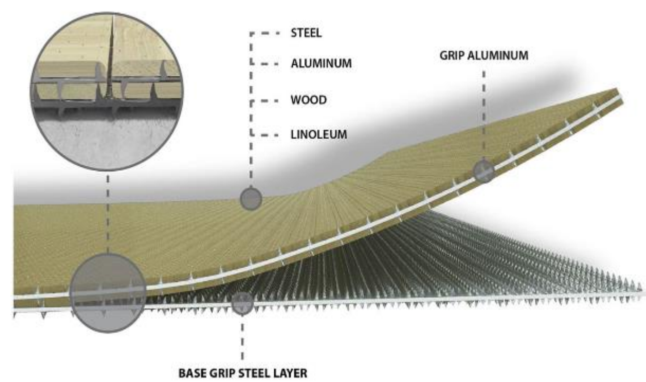

Figure 5. Three-dimensional panel layout [25]

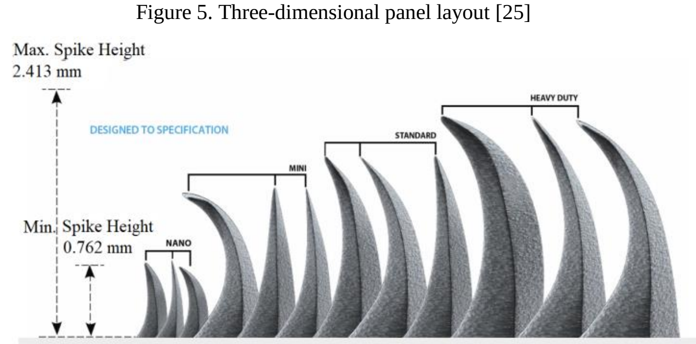

Figure 6. Spike variations for metal plate [26]

For the metal plate with spikes, two material alloys were considered: aluminum alloy 5052 H38 and carbon steel 1010 full hardness (H85-95).

Thermophysical properties of each layer in the panel layout presented in Fig. 4 are shown in Table I. Here, the panel layout and the materials used were the same for the radiant floor heating and the radiant floor cooling applications.

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Table I. Thermophysical properties of each layer in radiant panel [26]

Layer	Material	Density (kg/m^3)	Thermal Conductivity (W/m.K)	Heat Capacity (J/ kg. K)
Extended Surface	Aluminum 5052 H38	2680	138	880
	Carbon Steel 1010	7870	49.8	450
Upper Floor	Hardwood	720	0.16	1255
Subfloor	Plywood	540	0.1154	1210
Concrete Board	Cement	1920	0.58	1006

III. METHODOLOGY

The investigation of the enhanced heat transfer surface started with creating a computational heat transfer model in COMSOL [26]. Detailed conductive heat transfer within the enhanced floor panel, along with convective and radiative heat transfer between the panel and a conditioned interior space, were characterized numerically. The model was used systematically to parametrically quantify surface configurations (varying spike spacing and length), as there were multiple versions available for integration. Newly proposed design modifications were then assessed by performing simulations and comparing the predicted power consumption needed to maintain room temperature. The radiant floor heating system was simulated for an office-building environment. The radiant floor cooling system was simulated for an indoor gymnasium-based basketball court.

A. *Computational Domain*

For the heat transfer simulation, two orthogonal cross sections have been considered; parallel to the heat source and perpendicular to the heat source. The lengths of the spikes are 2.29 mm (0.09'') and 1.52 mm (0.06'') based on ease of manufacturability. The dimensions of the various layers are given in Fig. 7. Here, the length of the subfloor is the same as spike length. Moreover, the heat source is a hot/cold water pipe.

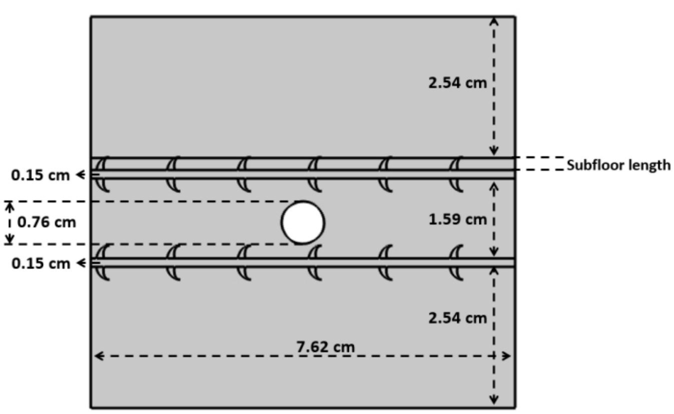


Figure 7. Dimensions of the radiant panel (perpendicular to the heat source)

B. *Mesh Independency*

The mesh independency analysis is carried out to find the optimum number of nodes for the simulation. As presented in Fig. 8, the optimum number is 27409 which is based on the time to achieve to the set point temperature of 22°C and 24°C for radiant floor heating and radiant floor cooling respectively. All the simulation results presented in subsequent sections will have achieved at least 27409 nodes with the use of a triangular mesh.

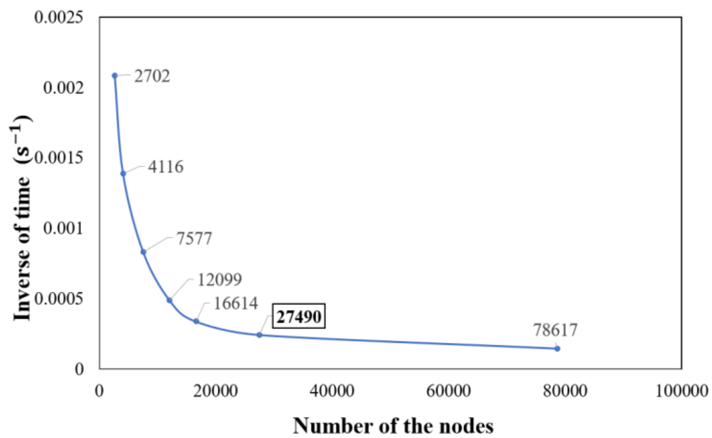


Figure 8. Mesh independency for the optimum number of nodes

C. *Boundary Conditions*

1) Radiant Floor Heating: For the radiant floor heating application, the initial temperature of the entire panel and air layer, topmost layer of thickness 2.54 cm on Fig. 7, were assumed to be 10ºC. The left and right side of the panel layout had a periodic condition applied to it and thus both sides of the wall were maintained at the same temperatures. In accordance with ASHRAE Standard 55-1992, 30% relative humidity was considered representing typical indoor environment conditions for a winter season [8].

2) Radiant Floor Cooling: In accordance with ASHRAE standard 55-1992, 50% relative humidity was considered representing typical indoor environment conditions for the summer season [8]. An initial condition of 27ºC was used representing a typical indoor temperature on a sunny day in the summer. Also, a periodic condition was used for both sides of the model.

D. *Solution Procedure*

1) Radiant Floor Heating: Here, different nuances of the panel layouts: different spike variations (spacing, length and fitting with the upper layer) and material for metal plate, were first modelled. Through a careful review of these simulation results, an optimal configuration was determined and then the effect of having more than two metal plate with spikes were studied.

2) Radiant Floor Cooling: For the radiant floor cooling application, two different simulations were run. Similar to the radiant floor heating application, the first of the simulations was run to quantify efficacy of enhanced metal plate with spikes and to understand how spike spacing, and material properties would influence heat distribution. Once optimal panel dimensions and metal plate material were determined, a radiant floor cooling application in basketball court was simulated.

For the radiant floor cooling application in a basketball court, it was important to understand three heat transfer mechanisms of cooling: conduction through the floor, evaporative cooling of sweat from the basketball player, and radiation due to the temperature difference between the floor and the player's body. Using Fanger's scale and considering an active metabolism of a basketball player, a body temperature of 38ºC was used [9]. A typical indoor basketball court height of 17' was used, along with a basketball player height of 6' similar to a study in [20]. The model including the human body is shown in Fig. 9. At this stage in the project, only the influence of evaporative cooling has been studied and hence the model was simplified to a sphere at 38ºC and 400W/m^2 metabolic rate [21].

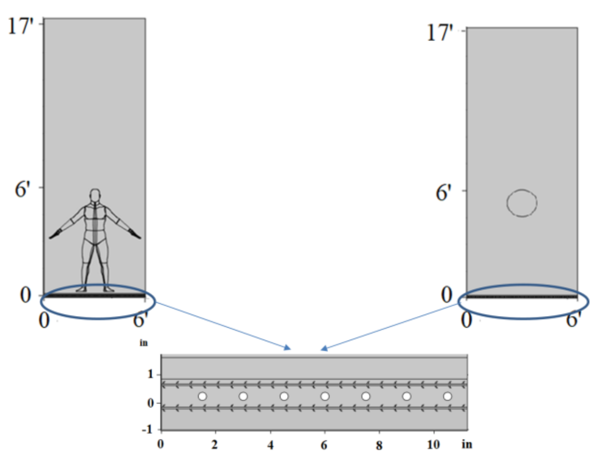


Figure 9. Basketball court radiant floor cooling application: left to right shows the transition to the simplified model and the bottom image shows a detailed view of array of an array of cold water pipes embedded in a radiant panel configuration

IV. Results and Discussion

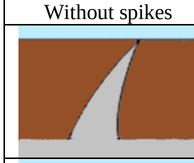
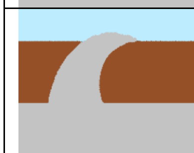
A. Radiant Floor Heating

Initial simulations were performed to observe the impact of spike protrusion, the material of the metal plate with spikes, and spike length. The results obtained for each of these variations are summarized in Table II. Table II shows the amount of time it takes to heat the floor from 10°C, the initial condition, to 22°C, the setpoint temperature for four scenarios; a metal plate that is not enhanced with small spikes, a spike barely touching the upper floor plywood, a spike nailed down to the upper floor plywood, and a spike under the plywood.

Energy reduction shown in Table II was calculated using (1). E_f and E_{nf} denote energy consumption for the metal plate with spikes configuration and the metal plate without spikes — just a flat metal plate configuration.

$$\text{Energy Reduced (\%)} = \frac{E_f - E_{nf}}{E_{nf}} \text{ x } 100 \qquad (1)$$

Table II. Optimization of metal plate with spikes

Scenario	Plate Material	Spike Length (in)	Setpoint Time (min)	Energy Reduction (%)
Without spikes	-	-	68	-
	Al	0.06	34	50
	C	0.09	39	43
	Al	0.06	30	56
	C	0.09	36	47
	Al	0.06	28	59
	C	0.09	33	51
	Al	**0.09**	**25**	**63**
	C	0.09	31	54
	Al	0.06	46	32
	C	0.09	52	23

It can be seen from Table II that an aluminum metal plate with spikes with 0.09'' spike length is the optimal configuration.

For the optimal configuration, the temperature distributions across the air layer were simulated. Using an electrial heating element as heat source, temperature distributions after the air layer has reached the setpoint temperature were plotted as shown in Fig. 10 and Fig. 11, respectively. These results were plotted for a heat source emitting 10 W/ ft^2, which is the minimum amount of power used for radiant floor heating in industry [14-16].

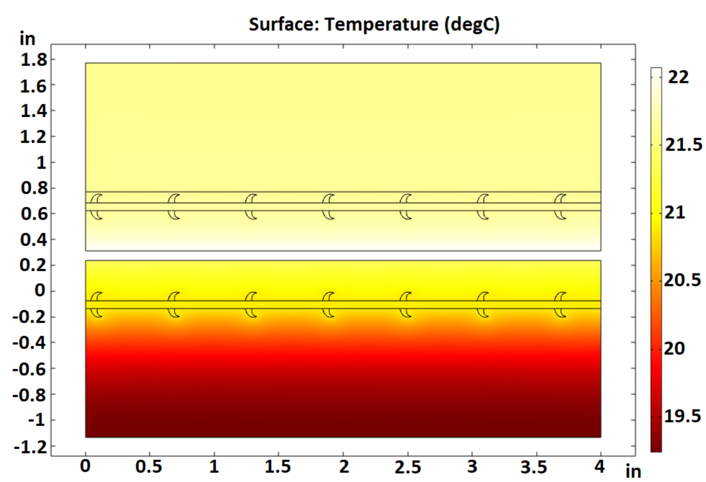


Figure 10. Temperature distribution parallel to the heat source

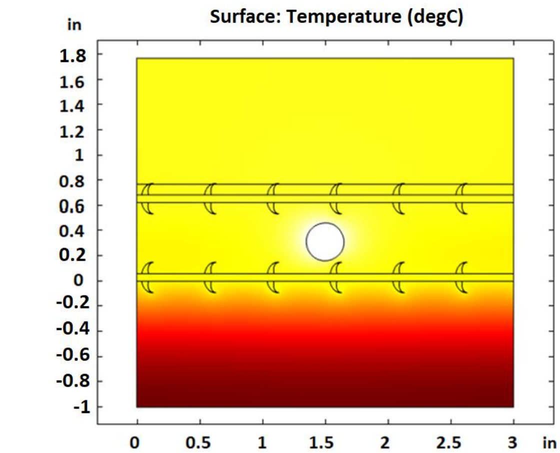


Figure 11. Temperature distribution perpendicular to the heat source

As can be seen from Fig. 10 and Fig. 11, parallel and perpendicular to the heat source, both, yield uniform temperature distributions and reach the 22°C setpoint temperature in under 28 minutes, as opposed to the without-spikes configuration which takes 68 minutes to reach the setpoint temperature.

In addition, the effect of having extra metal plate with spikes layers was observed. Consistent with expectations, the addition of extra layers resulted in extra time needed to reach the setpoint temperature. This can be explained from the fact that having an extra metal plate with spikes sandwiched in between concrete boards adds thermal mass to the system. This effect is illustrated in Fig. 12 and Fig. 13 for two different heat sources; a resistive element, and hot water pipes, respectively.

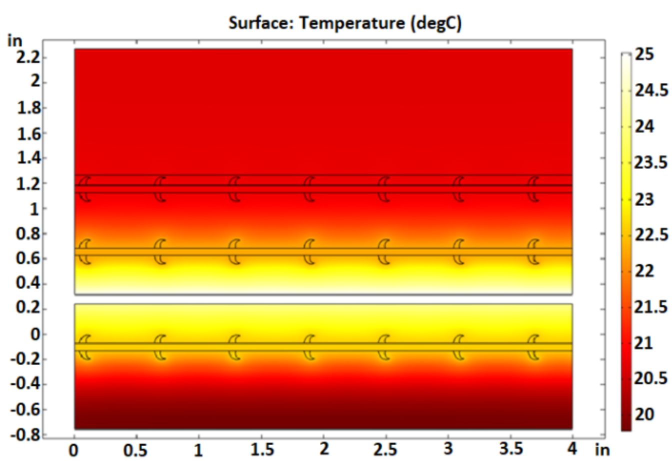


Figure 12. Temperature distribution associated with the addition of an extra plate with spikes (parallel to the heat source)

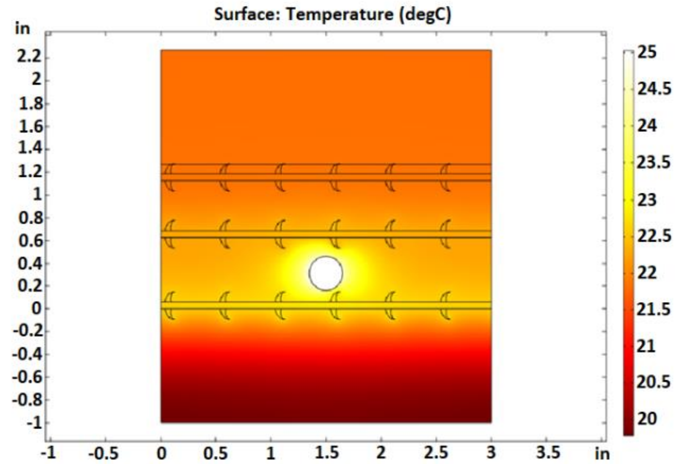


Figure 13. Temperature distribution associated with the addition of an extra d plate with spikes (perpendicular to the heat source)

Here, surface temperatures for all configurations were in the 'comfortable range' of 19°C to 29°C which is recommended by ASHRAE and some European standards [9-11].

B. Radiant Floor Cooling

For the radiant floor cooling application in the basketball court, only the spike-under-the-surface scenario was considered. This is in line with construction methods of floors of basketball courts [20]. Hence, the optimal configuration had to be iteratively simulated only for different materials for metal plate with spikes. Consistent with a radiant floor heating layout, only two material candidates were considered: aluminum alloy and carbon steel. Since water of 15°C-18°C is to be used to cool the floor, an air to water heat pump was assumed to be used to supply water to the pipes. Table III shows the amount of time it takes to cool the air layer from the 30°C, initial condition to 24°C, cooling setpoint temperature for a coefficient of performance (COP) of the heat pump of 3, and under various cooling load scenarios. Similar to prior results for the radiant floor heating layout, it was determined that using an aluminum plate with small spikes yields the most efficient configuration.

Also, temperature distributions for the air layer were uniform and floor surface temperatures were not lower than the design dew point temperature of 16°C, or lower than 19°C, which are the ASHRAE and European standards' recommendations for lowest floor surface temperature for radiant floor cooling systems [8-10].

Table III. Optimization of Metal plate with spikes

Cooling Load (W)	**Power Consumption of Heat Pump (W)**	**Cooldown Time- Al[a] (min)**	**Cooldown Time- C[a] (min)**
20	7	45	53
30	10	35	39
50	17	26	28
100	33	17	19

a. Al-Aluminum and C- Carbon Steel

Next, the optimal radiant panel configuration was simulated for an indoor basketball court environment. As mentioned earlier, only evaporative cooling has been accounted for at this stage in the project. A moist air transport module was added and 25 CFM/person flow rate was used, in accordance with ASHRAE Standard 62-1999 [7, 8]. An air velocity of 0.1 m/s was used. As mentioned in [20], this is most commonly used in large space buildings. The initial condition and temperature distribution once the setpoint temperature is reached are shown in Fig. 14.

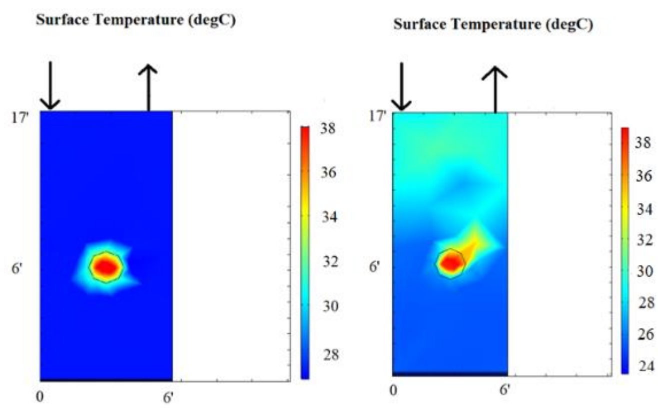


Figure 14. Evaporative cooling through a radiant floor. The image on the left represents the intiail condition of a sphere starting at 38°C. The image on the right is a screen capture once the setpoint temperature of 24°C has been reached.

V. FUTURE WORK AND CONCLUSION

This novel study aimed at configuring the optimal radiant panel layout composed of a metal plate with spikes and flooring materials rendering it retrofittable and energy-efficient. Using an aluminum metal plate with 0.09''spikes nailed down to upper floor hardwood yielded an energy reduction of 63% compared to the base case scenario. Preliminary calculations show that such retrofittable systems have potential to save upto 30% energy in space heating and space cooling systems. It was observed that the addition of extra layers of a metal plate with spikes adds extra thermal mass to the system. A potential pathway of interest may also be to consider off-peak electricity during the night to start heating up the floor and carry out economic projections for its use in office buildings. For radiant floor cooling system, the influence of radiation and conduction still needs to be investigated and the work is in progress. The optimal layout does not lead to condensation and is expected to yield greater thermal comfort for basketball players.

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