Design and Modelling of a Passive Cooling System for Typical Residential Houses in Pakistan

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A thesis submitted to the National University of Sciences and Technology, Islamabad,

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DEDICATION

Dedicated to my mother, wife, daughter and son whose tremendous support, cooperation and love led me to this wonderful accomplishment.

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LIST OF SYMBOLS, ABBREVIATIONS AND ACRONYMS

PCM	Phase Change Material
IDECs	Indirect evaporative coolers
EC	Evaporative Cooling
PECW	Passive Evaporative Cooling Wall
CAD	Computer Aided Design
sq. ft	Square feet
Kph	Kilometers per hour
EES	Engineering Equation Solver
W	Watt
%	Percentage
°C	Degree Centigrade
TERP	Thermoelectric radiant panel
TEM	Thermoelectric modules
PEX	Cross linked Polyethylene
W m-1 K-1	Thermal Conductivity (Weber per meter kelvin)
Btu/h. ft °F)	Thermal Conductivity in Imperial System
Kt	Thermal conductivity of pipe material
Do	Pipe outer diameter
Di	Pipe inner diameter
Kp	Thermal conductivity of concrete
Xp	Embedded depth
M	Pipe spacing

Rc	Floors cover specific resistance
in.	Inch
M	Meter
Ft	Feet
m3s-1	volumetric flow rate (cubic meters per second)
GPM	Gallons per minute
m^3	Cubic Meter
ft^3	Cubic Feet
Btu/kWh	Thermal Efficiency
BTU	British Thermal Unit
kW	Kilowatt
SEER	Seasonal Energy Efficiency Ratio
q” surf	Heat flux from surface
q” conv	Heat flux of convection
q” rad	Heat flux of radiation
Ts	Panel Surface Temperature
Ta	Air Temperature
$\dot{m}w$	Mass flow rate of water
cw	Specific heat capacity of water
Tout	Temperature of water leaving the hydronic loop
Tin	Temperature of water entering the hydronic loop
Usw	Overall coefficient of heat transfer from surface to water
Asw	Area for heat transfer from surface to water
NTU	Number of transfer units

TABS	Thermally activated building systems
Ru	Resistance per unit area
Rt	Thermal resistance of the wall
Rs	Thermal resistance between the pipes
Rp	Thermal resistance of panel body
Rc	Thermal resistance of active panel surface
π	Pie
K	Thermal conductivity
T	Time
Ln	Natural Log
ΔT	Temperature difference
Wm-2	Watts per meter squared
Am	Ante Meridiam
Pm	Post Meridiam
Seek	Sustainability, Energy, Efficiency and knowledge

ABSTRACT

Various research projects are increasingly focused on achieving net-zero operations by minimizing building energy consumption. This study evaluates the performance of two low-cost ground-source cooling systems for residential homes in Karachi, which can work alongside existing air-air split air-conditioning units without requiring extensive modification. The first system, a ground-source direct radiant floor cooling system for a four-story home, utilizes cold water from an underground concrete storage tank to supply the radiant floor system covering half of the top floor. The water then flows up to an overhead storage tank, integrating with the building's water supply. Measurements using an infrared thermometer from 1 PM to 5 PM over several days and a mathematical model based on Engineering Equation Solver (EES) estimated the cooling capacity and potential energy savings. Results indicated maintaining an air temperature of 25°C provided an average cooling capacity of 12 Wm-2, saving 319 W of electricity with minimal additional pumping power. The second system, a ground-source evaporative roof cooling system for a three-story home, involves installing terracotta tiles on half of the roof with a perforated PVC piping system above them. Cold water from the underground tank supplies an overhead storage tank, which connects to the PVC pipes. Six K-type thermocouple sensors and thermal imaging measured temperature differences, showing the roof with terracotta tiles was 10°C to 15°C cooler than the roof without tiles during peak sun hours, and the ceiling covered with tiles was 4°C to 7°C cooler than the ceiling without tiles. Temperature readings were taken thrice an hour from 11:30 AM to 3:30 PM, supported by data such as ambient temperature, relative humidity and windspeed from www.timeanddate.com. Both systems demonstrated significant energy savings and improved indoor thermal comfort. Further insights can be obtained by developing detailed models of building load and heat transfer in the underground tank and validating the results experimentally.

Keywords: Radiant Cooling, Hydronic System, Evaporative Cooling System, Modelling, Terracotta tiles, Ground-source evaporative roof cooling, Residential home, Karachi, Perforated PVC piping system, Underground concrete storage tank, K-type thermocouple sensors, Thermal imaging, Roof temperature reduction, Indoor thermal comfort, Cost-effective cooling, Energy savings, Hot climates, Heat transfer, Experimental validation.

CHAPTER 1: INTRODUCTION

This research has been done in two parts, part one consists of the mathematical model of a hydronic radiant floor cooling system which is a simple and cost-effective hydronic cooling scheme was simulated for a residential complex located in Karachi, Pakistan. The proposed setup utilizes an underground water storage tank instead of a conventional heat pump to provide a source of cold water. Temperature readings of the underground tank and the air in the top floor of the building under consideration were taken with the aid of an infrared thermometer. A mathematical model was developed using Engineering Equation Solver (EES) to compute the cooling capacity of the system and its potential energy-conservation benefits. The subsequent section elaborates the methodology used for the study. Part two consists of an evaporative roof cooling system which is done experimentally on a two-storey residential building. Terracotta tiles are installed on the roof of the building and a perforated PVC piping system is laid on top of them from the overhead tank to provide the tiles with water. Temperatures are monitored for six days using a digital thermometer and six K type sensors placed on the roof and ceiling and a thermal imaging IR gun. Further data like ambient temperature, wind speed and relative humidity is collected from the website www.timeanddate.com.

1.1 History of Hydronic Floor Cooling System:

1.1.1 Introduction

Hydronic floor cooling systems, a subtype of radiant cooling systems, are designed to regulate indoor temperatures through the use of water-cooled surfaces embedded in the floors. These systems have gained attention for their energy efficiency and ability to provide consistent cooling. This essay explores the development, working principles, and historical milestones of hydronic floor cooling systems.

1.1.2 What Are Hydronic Floor Cooling Systems?

Hydronic floor cooling systems use water as a heat transfer medium to cool indoor spaces. Pipes are installed beneath the floor surface, and chilled water circulates through these pipes, absorbing heat from the room above. The cooled floor surface then radiates coolness into the room, providing a comfortable and even temperature distribution. These systems are particularly effective in regions with high cooling demands and are often used in residential, commercial, and industrial buildings.

1.1.3 How Do They Work?

The operation of hydronic floor cooling systems involves several key components:

Chilled Water Source: A central chiller or a geothermal system provides the chilled water.

Distribution System: A network of pipes, usually made from materials like PEX (cross-linked polyethylene), is installed beneath the floor surface.

Control System: Thermostats and sensors regulate the flow of chilled water to maintain the desired room temperature.

Heat Exchange: As the chilled water circulates through the pipes, it absorbs heat from the room, which is then carried away and expelled by the chiller or into the ground in the case of geothermal systems.

1.1.4 Development and Historical Milestones

The concept of radiant heating and cooling dates back to ancient civilizations, where the Romans used hypocaust systems for heating. However, the modern hydronic floor cooling systems evolved significantly in the 20th century.

Early 20th Century: The initial development of hydronic systems began with radiant heating applications. Engineers and architects experimented with various methods to integrate water-based heating into building designs.

Mid-20th Century: The oil crisis in the 1970s spurred interest in energy-efficient building technologies. Researchers and engineers started exploring the use of hydronic systems for cooling purposes. Early prototypes were developed, primarily in Europe and North America, where the focus was on reducing energy consumption.

Late 20th Century: Technological advancements in materials and control systems led to the refinement of hydronic cooling systems. The introduction of durable and flexible piping materials like PEX and improved insulation techniques made these systems more viable and efficient.

21st Century: The push for sustainable and green building practices has accelerated the adoption of hydronic floor cooling systems. Innovations in renewable energy sources, such as geothermal and solar, have been integrated with hydronic systems to further enhance their efficiency and reduce carbon footprints. Today, these systems are widely recognized for their potential to provide comfortable indoor environments while minimizing energy usage.

1.2 Literature Review on Hydronic Systems:

The need for efficient and sustainable cooling and heating systems has increased with the rise in global temperatures. Radiant systems have been gaining popularity as a sustainable and energy-efficient solution for cooling and heating buildings [1]. Radiant floor heating systems have gained widespread adoption in various regions across the globe. For instance, nearly all residential buildings in Korea and 85% of rural houses in northern China feature this heating technology [2], [3]. In Denmark, Germany and Austria between 30% to 50% of residential buildings that are newly constructed incorporate radiant floor heating systems [2]. Furthermore, when integrated with a ventilation system capable of managing latent load, the radiant cooling system has demonstrated successful implementation in hot and humid climates, such as China, India, Thailand, Singapore, and other similar regions [2], [4]. However, very few new buildings in Pakistan have radiant systems [5]. One of the possible barriers to wide-scale adoption is the excessive cost of additional equipment such as pumps, chillers, and heat exchangers.

To reduce costs associated with radiant cooling systems, various researchers have focused on incorporating renewable energy sources and exploring alternative technologies [6]. Feng et. al [7] and Hassan & Abdelaziz [8] suggest incorporating a small chiller powered by solar panels to cool the water circulating through the channels, resulting in quicker and more efficient cooling. Additionally, Luo et al. [9] proposed a thermoelectric radiant panel

(TERP) system, which utilized thermoelectric modules (TEM) instead of conventional water pipes as a heat source. This method provides a more reliable and simplified system control, along with reduced initial and operational expenses, making it an attractive option for cost-conscious projects. However, most of these systems are even more complex than simple radiant cooling systems which discourages adoption.

Mokhtari and Ghasempour [10] proposed an active radiative cooling system for a single-family home located in the hot, semi-arid climate of Iran. The system uses a hydronic cooling system inside the house and rooftop panels to provide cooling. Results of the feasibility study showed that the storage tank and number of panels directly affect the system's performance, while there is an optimum value for the water flow rate. Larger storage tanks and higher water flow rates resulted in a larger cooling energy. However, the system components are not readily available off the shelf, and further studies and tests are required to establish the system's performance and long-term reliability. Other researchers, such as Srivastava et al. [11] have explored incorporating more typical and reliable equipment, such as cooling towers, as sources for Radiant Cooling systems. A study conducted by Mokhtari [12] introduces the concept of the Cooling Station, a passive urban cooling system providing radiant cooling to people through rooftop radiative cooling panels. The simulations conducted by Timothy [13] show that hydronic radiant cooling with an evaporative supply water source and dedicated outside air system can achieve significant energy savings (54% to 71%) compared to conventional VAV systems.

Moreover, [14], [15] has discussed the advantages of hydronic radiant floor heating which include the efficient use of space and that cleaning is not required. Also, the system does not produce noise, cause drafts or use ducts. The system has uniform temperature distribution and is a low-temperature heating system.

1.3 History of Usage of Terracotta tiles:

1.3.1 Introduction

Terracotta tiles, known for their durability and aesthetic appeal, have been used in construction for centuries. Beyond their traditional role in roofing, they have gained prominence for their cooling properties, particularly in hot climates. This essay explores the history, working principles, and key milestones in the use of terracotta tiles for roof cooling.

1.3.2 What Are Terracotta Tiles?

Terracotta tiles are ceramic tiles made from natural clay that is molded and baked at high temperatures. The word "terracotta" comes from the Italian words for "baked earth," reflecting the material's earthy origins. These tiles are renowned for their reddish-brown color, which can vary depending on the clay used and the firing process. Historically, terracotta tiles have been used for roofing, flooring, and decorative purposes.

1.3.3 How Do They Work for Roof Cooling?

Terracotta tiles help in cooling roofs through several mechanisms:

Thermal Mass: The dense nature of terracotta allows it to absorb heat during the day and release it slowly at night, moderating temperature fluctuations.

Evaporative Cooling: When water is applied to the surface of terracotta tiles, it evaporates, absorbing heat and cooling the tiles. This principle is similar to the way sweat cools the human body.

Reflectivity: The natural color and finish of terracotta tiles reflect a portion of solar radiation, reducing the amount of heat absorbed by the roof.

1.3.4 Development and Historical Milestones

The use of terracotta tiles dates back to ancient civilizations, with significant developments over the centuries:

Ancient Civilizations: The earliest use of terracotta tiles can be traced to ancient Greece and Rome. The Greeks are credited with developing the fired clay roofing tile, which was later adopted and refined by the Romans. These early tiles were valued for their durability and fire resistance.

Middle Ages: During the Middle Ages, terracotta tiles became widespread in Europe, particularly in the Mediterranean region. Their ability to keep buildings cool in hot climates made them a popular roofing material.

Colonial Period: The Spanish and Portuguese colonists brought terracotta roofing tiles to the Americas, where they were used extensively in regions like California and the southwestern United States. These tiles were well-suited to the warm climates and added a distinct architectural style.

20th Century: Advances in manufacturing processes allowed for more uniform and durable terracotta tiles. During this period, the environmental benefits of terracotta tiles began to be recognized, particularly in terms of their cooling properties.

21st Century: With the growing emphasis on sustainable building practices, terracotta tiles have gained renewed interest for their natural cooling abilities. Modern applications include using terracotta tiles in conjunction with water-based cooling systems, enhancing their evaporative cooling effect.

1.3.5 Key Examples

Traditional Mediterranean Architecture: Many buildings in the Mediterranean region, such as those in Spain, Italy, and Greece, have long utilized terracotta tiles for their cooling properties.

Modern Sustainable Buildings: In recent years, terracotta tiles have been incorporated into green building designs. For example, the California Academy of Sciences in San Francisco uses a combination of terracotta tiles and other sustainable materials to achieve energy efficiency.

The use of terracotta tiles for roof cooling is a practice deeply rooted in history, with origins in ancient civilizations. Their thermal mass, evaporative cooling, and reflective properties make them an effective and sustainable roofing material. As the demand for energy-efficient and environmentally friendly building solutions grows, terracotta tiles continue to be a valuable component in modern construction.

1.4 Literature Review on Evaporative Cooling System:

The need for an efficient and low-cost cooling system is becoming a necessity as due to global warming the earth’s temperature increases every year. Therefore, research is conducted on low-cost evaporative cooling systems which utilize no electricity and generate free cooling. Terracotta tiles are used in this experiment which are porous, and some research has been carried out on its various types by using a 3D printing technique and to compare them on the basis of porosity which affects evaporative cooling effect[16]. A comprehensive review of evaporative cooling (EC) technology for building air-conditioning highlights its environmental friendliness and effectiveness. Amer's study emphasizes the high effectiveness and energy savings of indirect evaporative coolers (IDECs), particularly those using the Maisotsenko-cycle (M-cycle) based dew-point IEC system, despite their complexity and high initial costs[17]. Bhushan’s review underscores the potential of EC technology in achieving zero energy cost cooling with minimal environmental impact and low initial cost, calling for further research to advance the technology[18]. Xudong’s review of IEC technology highlights its potential to replace conventional air conditioning by offering enhanced performance and energy efficiency, achieving wet-bulb effectiveness over 90% and energy efficiency ratios up to 80%. Various heat exchanger designs and materials, including cellulose fiber, aluminum, and ceramic, are used, and IEC systems are often combined with other cooling methods like DEC, mechanical vapor compression, and desiccants[19].

Recent research in evaporative cooling technology has introduced several advancements and models to improve efficiency and performance. Fisenko developed a mathematical model for natural draft cooling towers, focusing on the cooling effects of falling droplets and water films, which accurately predicts performance and improves efficiency under specific conditions[20]. Zongwei proposed a "combined air conditioner" integrating evaporative cooling, heat pipes, and vapor compression refrigeration, showing significant energy savings, particularly in cold, dry regions, with a 27.40% increase in the cooling coefficient of performance (COP) compared to conventional units[21]. L. Zhang introduced a simulation method in EnergyPlus to assess the impact of rainfall-induced evaporation on building cooling in subtropical China, demonstrating that evaporation from porous roof tiles can significantly reduce roof temperatures and cooling loads. This method showed potential cooling load savings of up to 14.8% during summer, emphasizing the need to consider evaporation in simulations to avoid overestimating cooling loads[22].

Anna Laura's research on cool roof solutions and high-reflectance coatings for buildings focuses on optimizing infrared reflectance for clay tiles used in Mediterranean regions, maintaining their traditional appearance suitable for historical areas. Her experimental and numerical analyses show these coatings can reflect up to 75% of solar radiation, significantly reducing attic temperatures and improving thermal comfort. Testing revealed that high-reflective coatings increased solar reflectance by over 20%, with the darkest coatings reducing surface temperatures by about 4°C. Light red and darker coatings provided substantial cooling benefits, with energy savings of 33% in Palermo and 30% in Rome, and minimal winter penalties[23], [24]. Evaluating a 16th-century building in central Italy, innovative cool clay tiles improved energy efficiency, reducing summer overheating by 30% and saving up to 51% in cooling energy with less than a 2% heating penalty[25]. Extending these findings to historic districts suggested significant energy and CO2 emission reductions. Dynamic simulations and field monitoring of a residential village in Italy showed these tiles saved 141 tons of CO2 per year by reducing cooling energy needs and offset an additional 772 tons of CO2 per year due to increased albedo, highlighting the significant energy and environmental benefits of cool roofs[26].

Lei Zhang's research on evaporative cooling using porous materials has shown significant findings. In his study on porous face bricks, Zhang found that these bricks quickly absorb water, reaching 6.87% moisture content in 30 seconds, with optimal cooling achieved at 3.1% moisture content. Excess watering beyond this level does not enhance cooling, highlighting the importance of maintaining this critical moisture level for efficient cooling and water conservation[27]. Additionally, Zhang developed a new simulation method in EnergyPlus to assess rainfall-induced evaporation on building cooling in subtropical China. This method, incorporating an evaporative cooling module (ECM), accurately predicted temperature reductions and cooling load savings, showing that porous roof tiles could lower external and internal temperatures by up to 6.4°C and 3.2°C, respectively, and reduce cooling loads by up to 14.8% during summer. Ignoring evaporation in simulations could lead to a significant overestimation of cooling loads[28].

Yu Zhang's research on porous clay tiles (PCT) for evaporative cooling demonstrated their high-water absorption and retention, significantly enhancing cooling performance. Testing PCT in a wind tunnel, simulating Guangzhou's summer weather, showed that external surface temperatures could drop by up to 11°C, and internal heat flux could be reduced by 67.7%, by converting 80% of absorbed shortwave radiation into latent heat. Wet porous tiles absorbed about 80% of shortwave radiation, lowering external surface temperatures by 5°C and reducing internal heat flow by 65.5%. The thermal resistance of wet tiles was comparable to a 10-mm-thick polystyrene foam board, effectively doubling the insulation compared to dry tiles. These findings highlight PCT's potential to mitigate urban heat islands and reduce building energy consumption. Future research will explore the relationship between the microstructure and macroscopic properties of PCT and the effects of different climate conditions on its cooling performance[29].

Mukesh's research investigates the use of terracotta blocks to replace concrete below the neutral axis in structures, which reduces dead load and project costs while supporting eco-friendly practices. The study incorporates fly ash, quarry dust, and stone chips into concrete, enhancing strength and reducing greenhouse emissions[30]. Abdullah's experimental study in Seiyun city, Yemen, evaluated the cooling performance of various wetted media—clay plates, clay with jute fiber, and clay with wood wool—in a bio-inspired cooling design within a wind tower. Results showed clay with jute fiber achieved the highest cooling efficiency at 85.2%, followed by clay with wood wool and clay alone. Increasing design height and wood wool pads improved cooling efficiency but also increased air pressure drop[31]. Wanphen's tests on roofing materials—pebbles, silica sand, volcanic ash, and siliceous shale—revealed that siliceous shale was effective in vapor absorption, volcanic ash in water absorption, and large particles in drying rate. Porous materials with high vapor absorption and evaporation, including reflective ones, were found to be effective in mitigating urban heat and reducing energy use for cooling[32].

Juliet’s research examines how pavements’ heat conditions are influenced by solar radiation, revealing that dark materials like asphalt absorb more heat than lighter ones like concrete, with asphalt reaching the highest temperatures and terracotta the lowest. Sprinkling water on pavements, particularly asphalt, can help reduce surface temperatures and mitigate heat release into the environment[33]. Bundit's study explores the effectiveness of a solar chimney and roof water spraying as passive cooling systems in hot, humid conditions, finding that while the solar chimney alone reduced room temperatures by 1.0-3.5°C, its performance was enhanced by combining it with water spraying, which lowered temperatures by 2.0-6.2°C. This combination proved most effective during high solar radiation periods[34]. Samuel's experiments on concrete and terracotta tile roofing under wind-driven firebrand showers found that flat terracotta tiles, with their interlocking design, performed better by trapping firebrands and preventing them from reaching the sarking, suggesting the use of continuous firebrand-resistant underlayment as a mitigation strategy[35].

Chelliah's experiment compared various phase change materials (PCMs) incorporated into terracotta tiles, evaluating their performance and cost-effectiveness to determine the optimal material for cooling[36]. Jiang He explored a passive evaporative cooling wall (PECW) using porous ceramics with high water absorption, finding that ceramic pipes maintained wet surfaces, reducing temperatures below outdoor air temperature and achieving a maximum cooling efficiency of 0.7 under sunny, windy conditions. The pipes remained wet for a year with clean city water, with ongoing experiments using rainwater[37]. Elisa's research on clay tile roofs in hot climates demonstrated that their ventilated air layer, through natural and forced convection, effectively reduces roof temperatures. The study assessed over 30 clay products, revealing that they often met or exceeded solar reflectivity standards, and found that ventilated clay tiles significantly lowered peak temperatures and improved indoor comfort compared to an unventilated copper roof, thus mitigating urban heat island effects and enhancing indoor comfort[38]

CHAPTER 2: METHODOLOGY

2.1 Hydronic Radiant Floor Cooling System:

2.1.1 Modeling Parameters

For the study, the top floor of a four-story residential building (ground plus three floors) was chosen. The specific floor being studied currently uses air-to-air split air-conditioners only during extreme heat, and when not in use (as was the case in March when temperatures were being recorded), ventilation is achieved through windows, doors, and ceiling fans. Table 1 provides additional information on the building and the underground water storage tank. The tank is lined with waterproof concrete, has a large capacity, and exchanges heat freely with the ground, making it a reservoir of cold water that is close to the ground temperature. Various water-based hydronic system configurations are available [39], [40]. The simulation for this study utilized a basic radiant floor cooling system that covered half of the entire floor, consisting of PEX pipes embedded in concrete with a marble top cover and insulation on the bottom (Figure 1). The design specifications for the system, which were derived from previous studies, are listed in Table 1

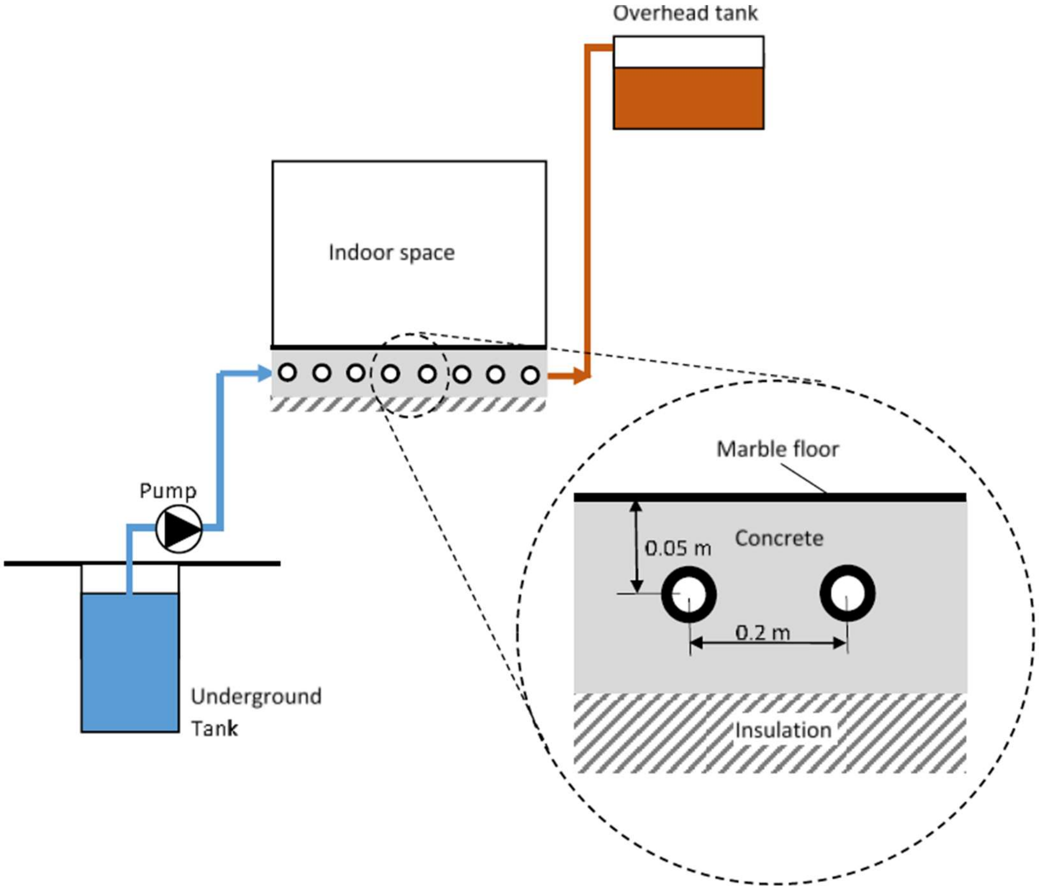


Figure 1 Schematic of the ground-source direct cooling radiant floor system. The composition of the hydronic floor is also shown.

Table 1. Design parameters

Parameter	**Value**
Radiant floor cooling system design parameters	
Pipe material	PEX
Thermal conductivity of pipe material (k_t) [41]	0.38 W m^{-1} K^{-1} (0.22 Btu/h. ft °F)
Pipe nominal diameter (PEX Universe 2020)	1 in.
Pipe outer diameter (D_o) (PEX Universe 2020)	0.0286 m (1.124 in.)

Pipe inner diameter (D_i) (PEX Universe 2020)	0.0222 m (0.875 in.)
Thermal conductivity of concrete (kp) [33]	1.9 W m^{-1} K^{-1} (1.1 Btu ft^{-1} h^{-1} $°F^{-1}$)
Embedded depth (xp) [39]	0.05 m (0.164 ft)
Pipe spacing (M) [44]	0.2 m (0.656 ft)
Floor cover material	Marble
Floor cover specific resistance, r_c [41]	0.0317 m^2 K W^{-1} (0.18 ft^2 h °F Btu^{-1})
Pipe configuration	Series, 45 sections of 9.1 m (30 ft)
Pipe length	420 m (1379 ft)
Flow rate of water [45]	9.39×10^{-5} m^3s^{-1} (89.2 gpm)

Building Parameters

Total number of floors	Three floors plus ground floor
Building size	18.2 m by 18.2 m (60 ft by 60 ft)
Radiant floor dimension (3rd floor)	9.1 m by 9.1 m (30 ft by 30 ft)
Underground tank dimensions (length by width by depth)	12.2 m by 9.1 m by 2.4 m (40 ft by 30 ft by 8 ft)
Underground tank capacity	272 m^3 (9600 ft^3 or 71,876 gallons)

HVAC system

Type	Single air-to-air split air-conditioner
Rated capacity	3.52 kW (1 ton or 12000 Btu/h)
Seasonal cooling COP (SEER)	3.2 (10.9 Btu/kWh)

2.1.2 Heat Transfer Mathematical Model

The heat transfer calculation from the radiant cooling panel can be divided into two steps as shown in Figure 1. The first part is the heat travelling from the surface of the panel to the air inside the room air through convection and radiation (Equation 1). Various correlations suggested by different standards and researchers to calculate the convection heat transfer has been provided by Feng et. al (Feng et al., 2016). For the present study, we used the algorithm developed by Walton [46] (Equation 2). This algorithm with the "TARP" option has been integrated in Energy Plus and has been used by previous researchers (Feng et al., 2016). Finally, the heat that is transferred at the surface cooling systems via radiation can be approximately using Equation 3 provided in the ASHRAE Handbook, HVAC Systems and Equipment [41].

$$q''_{surf} = q''_{conv} + q''_{rad} \quad (1)$$

$$q''_{conv} = 0.7589\,(T_a - T_s)^{1/3} \quad (2)$$

$$q''_{rad} = 5 \times 10^{-8} \cdot [(AUST + 273.15)^4 - (T_s + 273.15)^4] \quad (3)$$

Where, q''_{surf}, q''_{conv} and q''_{rad}, are the heat fluxes from the panel surface (total), from the panel surface via convection and from the panel surface via radiation respectively. T_s and T_a are panel surface and air temperature, respectively. AUST is the area-weighted temperature of all indoor surfaces of walls, ceiling, floor, window, doors, etc. (excluding active cooling surfaces) (AUST was assumed to be equal to T_a which is consistent with section 6.4 of ASHRAE Handbook [41]).

After being absorbed by the radiant surfaces, the heat is transferred between radiant surfaces and the hydronic loop by conduction. This heat is equal to the heat gained by the water in the hydronic loop (Equation 4). The surface temperature is approximately constant; however, the temperature of the water rises as it flows through the hydronic loop. This necessitates the use of NTU and effectiveness (ε) relations for a single-stream heat exchanger (Equation 5 to 6) which have also been used by other researchers for hydronic cooling applications [10].

$$q = q"_s\, A_s = \dot{m}_w\, c_w(T_{out} - T_{in})q = q"_{rad}\, A_s = \dot{m}_w\, c_w(T_{out} - T_{in}) \tag{4}$$

$$\varepsilon = \frac{q}{q_{max}} = \frac{q}{\dot{m}_w\, c_w(T_s - T_{in})} \tag{5}$$

$$\mathrm{NTU} = \frac{U_{sw}A_{sw}}{\dot{m}_w\, c_w} \tag{6}$$

$$\varepsilon = 1 - e^{-\mathrm{NTU}} \tag{7}$$

Where, $\dot{m}_w$ and c_w is the mass flowrate and specific heat capacity of water. T_{in} and T_{out} is the temperature of the water entering and leaving the hydronic loop. U_s and as is the overall coefficient of heat transfer and the area for heat transfer from the surface to the water. During the transfer of from the panel surface to the water, the mass of the panel/slab does not produce any delay (i.e., heat transfer takes place under steady state) except for in the case of TABS with night-time precooling. Various methods to characterize the steady- state resistances have been summarized by Feng et al. (Feng et al., 2016). For the present study, equations provided in the ASHRAE Handbook [41] (Equation were used to calculate the characteristic (combined) panel resistance, r_u (resistance per unit area or specific resistance in m^2KW^{-1} or $ft^2h°F.Btu^{-1}$) which is used to find U_s (Equation 8).

$$\text{Total resistance} = \frac{1}{U_s\, A_s} = \frac{r_u}{A_s} \tag{8}$$

$$r_u = r_t M + r_s M + r_p + r_c \tag{9}$$

$$r_p = \frac{x_p - D_o/2}{k_p} \tag{10}$$

$$r_t = \frac{1}{2\pi\ _t} \ln\left(\frac{D_o}{D_i}\right) \tag{11}$$

Where r_t is the thermal resistance of the wall of the tube per unit pipe spacing in a hydronic system ($m^2KW^{-1}ft^{-1}$ or $ft^2h°F.Btu^{-1}ft^{-1}$), r_s is the thermal resistance between the pipes and panel body per unit spacing between neighboring pipes ($m^2KW^{-1}ft^{-1}$ or $ft^2h°F.Btu^{-1}ft^{-1}$) (r_s = 0 for embedded pipes), r_p is thermal resistance of panel body (m^2KW^{-1} or $ft^2h°F.Btu^{-1}$), r_c is the active panel surface covers thermal resistance (m^2KW^{-1} or $ft^2h°F.Btu^{-1}$) (For marble floor, r_c = 0.0317 m^2KW^{-1} (0.18 $ft^2h°F.Btu^{-1}$) [41].

Equations 1 to 11 were used to develop the mathematical model in Engineering Equation Solver (EES). EES pipe flow function was used to calculate the additional pumping power due to the pressure loss in the radiant pipes. The pump efficiency was assumed to be 70% [47]. The underground tank water temperature and the air temperature in the top floor were measured using an Berrcom JXB-178 infrared thermometer (Accuracy ±0.3°C or ±0.6°F). Multiple readings between 1 PM to 5 PM (building was found to be hottest during this period) were taken for 10 days from March 5th to March 20th. No data was recorded on six days (6th, 9th, 13th, 14th, 16th, and 19th March) due to lack of access to the site. The daily average temperatures were used to estimate the cooling capacity and energy savings under the scenario under which the floor is maintained at 25°C by the Air-conditioners. The measured temperatures and modeling results are presented in the subsequent section.

2.2 Evaporative Cooling System:

2.2.1 Experimental Setup:

For the study, the top roof of a three-story residential building (ground plus two floors) was chosen whose schematic diagram is shown in Figure 2.

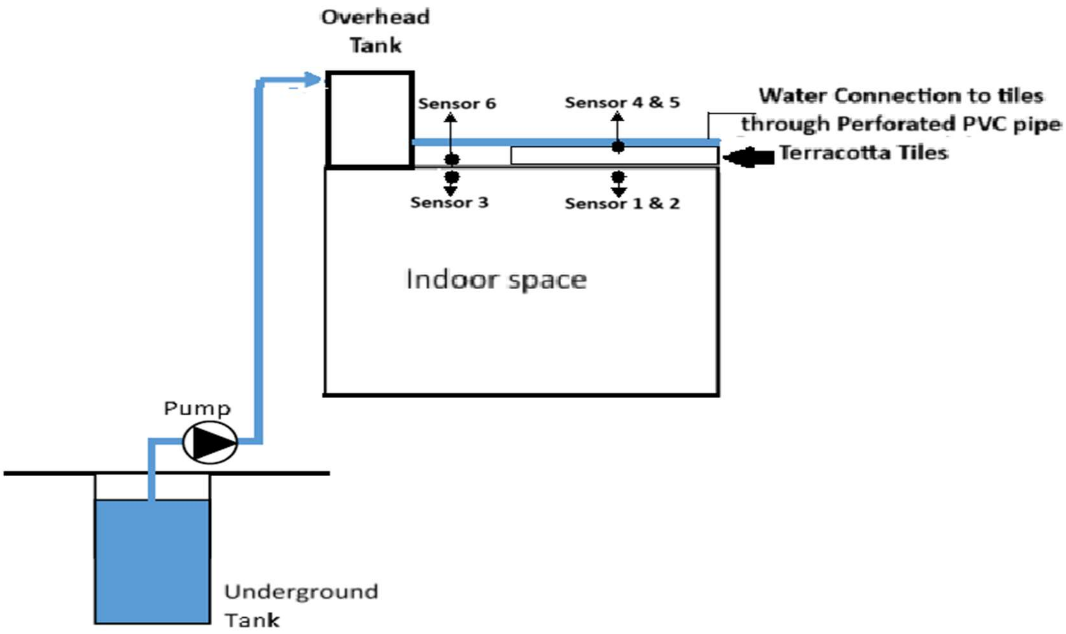


Figure 2 (Schematic diagram of the evaporative cooling system)

The specific floor being studied has no fans or air conditioners because we wanted to assess the impact of evaporative cooling only. Ventilation is done through doors and windows. However, it can have an air conditioning system and ceiling fans. Figure 3 shows the dimensions of the roof, and the total area of the roof was found to be 27.3 m^2. The area covered by terracotta tiles was found to be 15.4 m^2, which is also shown in figure 3 by blue lines. which is approximately 56.4% of the total area.

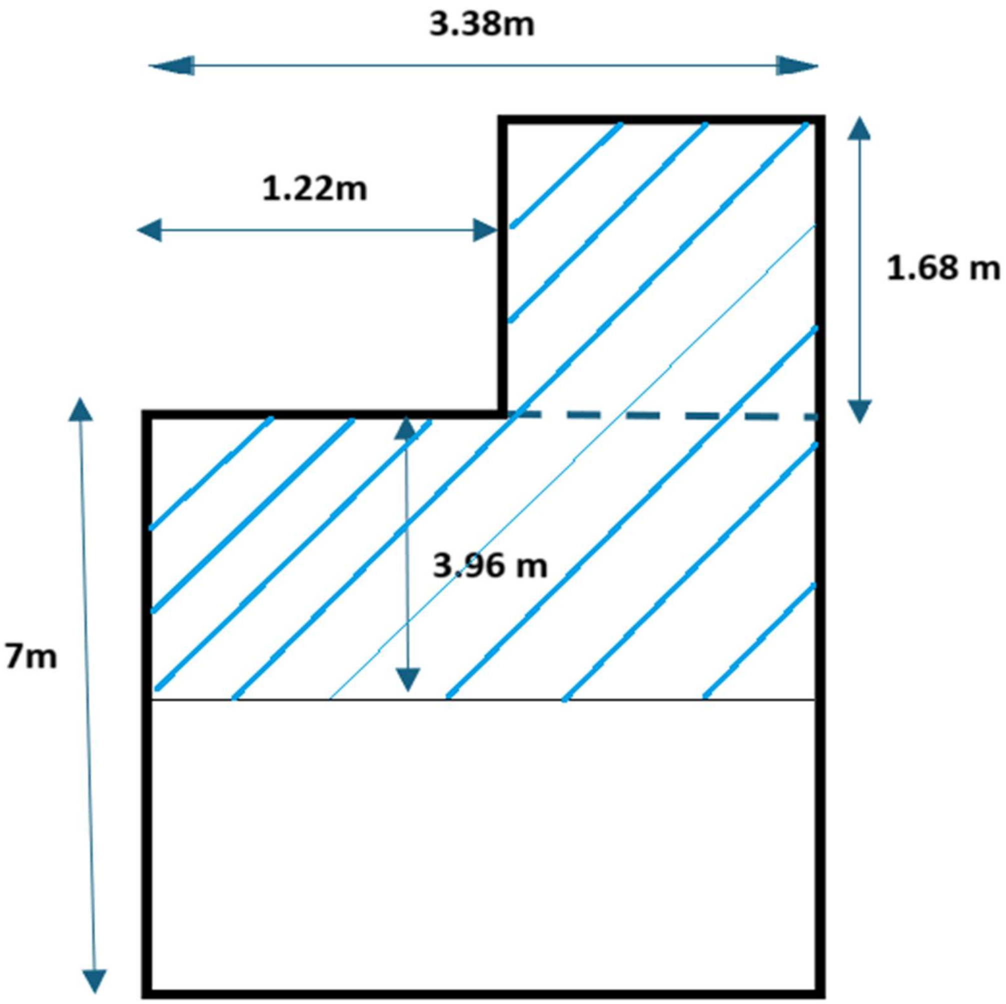


Figure 3 Dimensions of Roof and area covered by terracotta tiles

A water connection was taken from the overhead tank and PVC pipe of diameter 1.9 cm (¾”) was connected from it till the end of the tiles. From this PVC pipe various branches of diameter 1.27 cm (½”) perforated PVC pipes were laid down to supply the water to all the terracotta tiles as shown in figure 5.

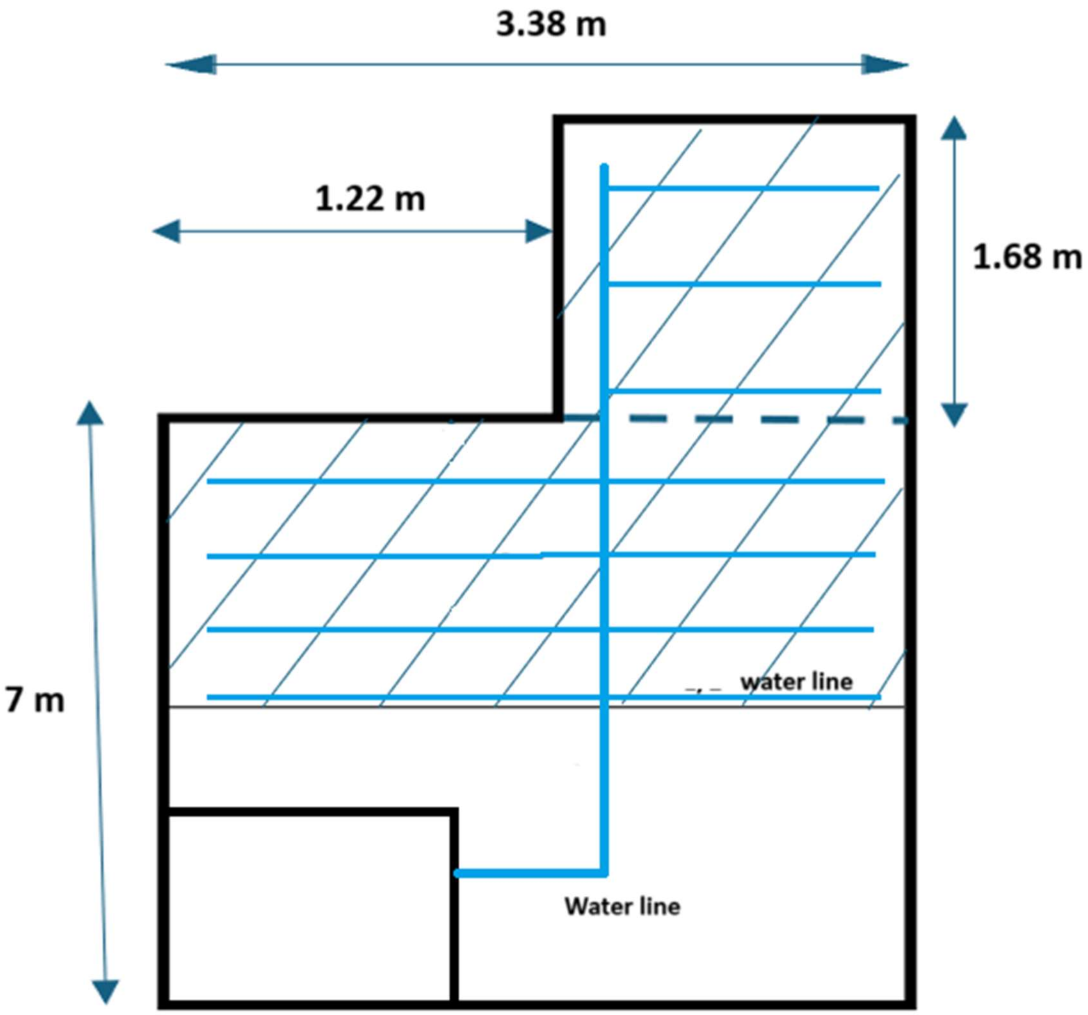


Figure 4 Perforated PVC Pipe layout

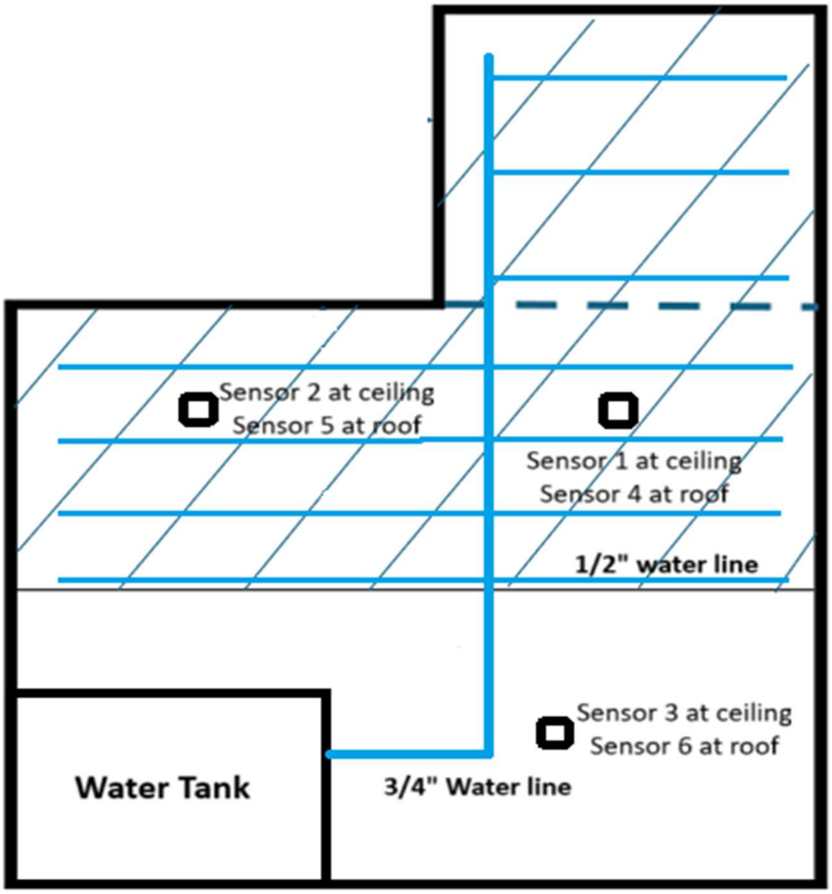


Figure 5 Thermocouples positions

There was a total of six K type thermocouples which were first calibrated and numbered. Then three K type thermocouples were installed on roof in such a way that two of them were on the terracotta tiles and one of them was on the part of roof without terracotta tiles. Just beneath these three sensors, three more sensors were installed on the ceiling in the same manner as shown in figure 6. Temperatures were recorded from these sensors using a digital thermometer and heat images were taken with a thermal imaging gun after every twenty minutes for the peak hour period of 11:30 am till 03:30 pm according to www.timeanddate.com. Additional data such as wind speed, humidity and ambient temperature was also taken from this website. Specifications of these instruments is shown in table 2 below:

Table 2: Specifications of Instruments used.

S.No.	Name of Instrument	Brand & Model Number	Specifications
1	Thermal Imaging Camera	Smart Sensor ST8550	120x90 resolution, 2.8-inch display, 8-14um Infrared response and central spot heating and cooling tracking capabilities, Measuring range: -25°C to 550°C (-13°F to 1022°F), Emissivity: 0.01 to 1.0
2	Digital Thermometer	Mastech MS6514	For K type Sensor's measurement range is -200°C to 1372°C, Precision: ±0.5%

Figure 7,8,9 and 10 shows the experimental setup.

Figure 6 Roof

Figure 7

Figure 8 Roof

Figure 9 Ceiling

Upon starting the experiment, the valve for the water line was opened once every two hours for five minutes because after two hours almost all the water evaporated. It made all the tiles wet and then measurement of temperatures was started. Two types of scatter plots of each day with the first one showing ambient temperature, temperature of ceiling whose roof is terracotta tiles covered and temperature of ceiling whose roof is uncovered and the second one showing the ambient temperature, temperature of roof covered with terracotta tiles and temperature of roof uncovered with terracotta tiles are shown below in which the blue arrow shows the point at which water was turned on.

2.2.2 Data Collection through Digital Thermometer

Figure 10. Scatter Plot for Temperature monitoring: Day 01

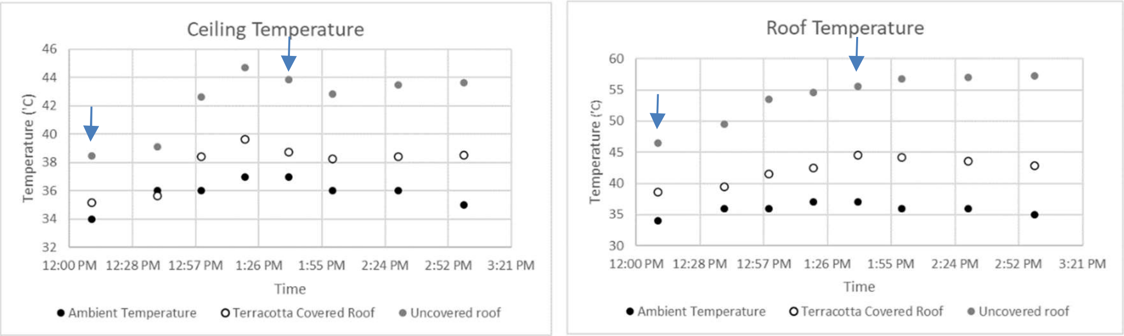


Figure 11. Scatter Plot for Temperature monitoring: Day 02

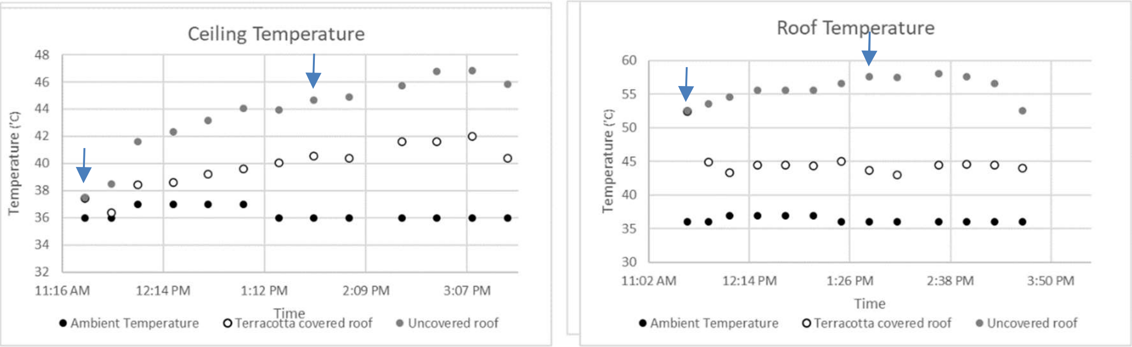


Figure 12. Scatter Plot for Temperature monitoring: Day 03

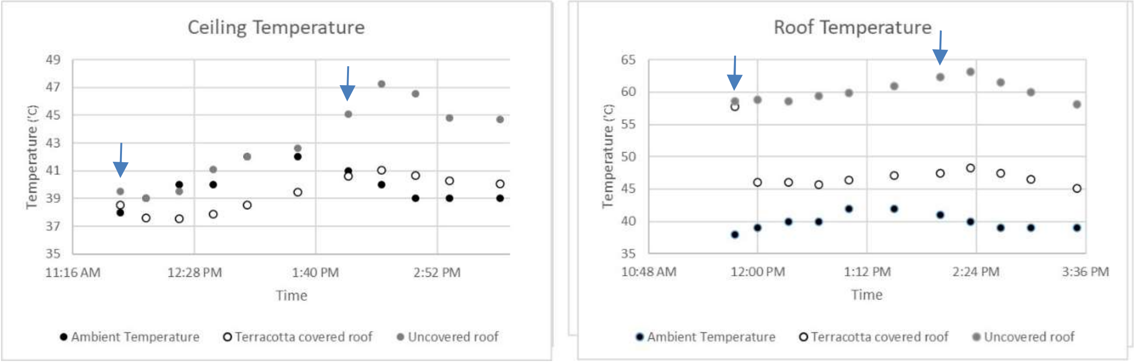


Figure 13. Scatter Plot for Temperature monitoring: Day 04

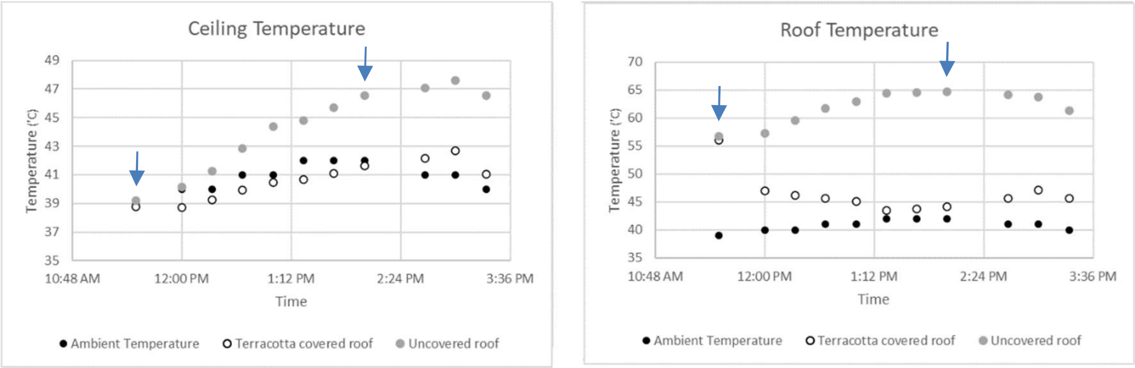


Figure 14. Scatter Plot for Temperature monitoring: Day 05

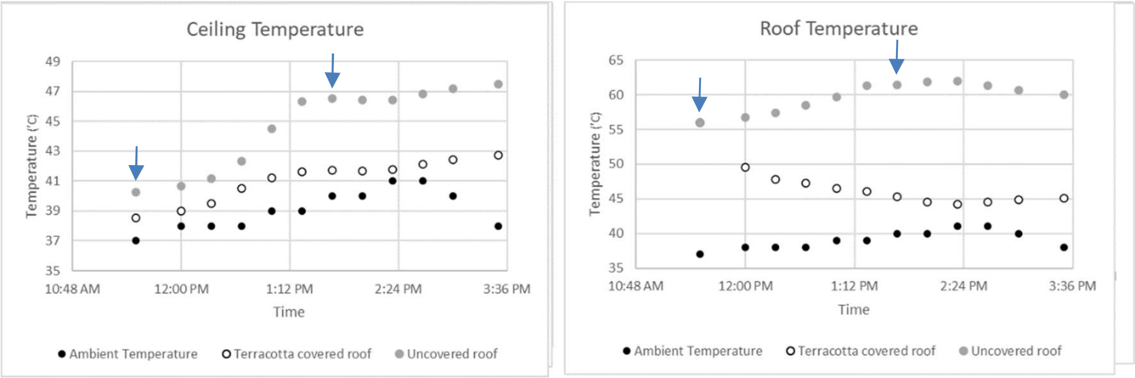


Figure 15. Scatter Plot for Temperature monitoring: Day 06

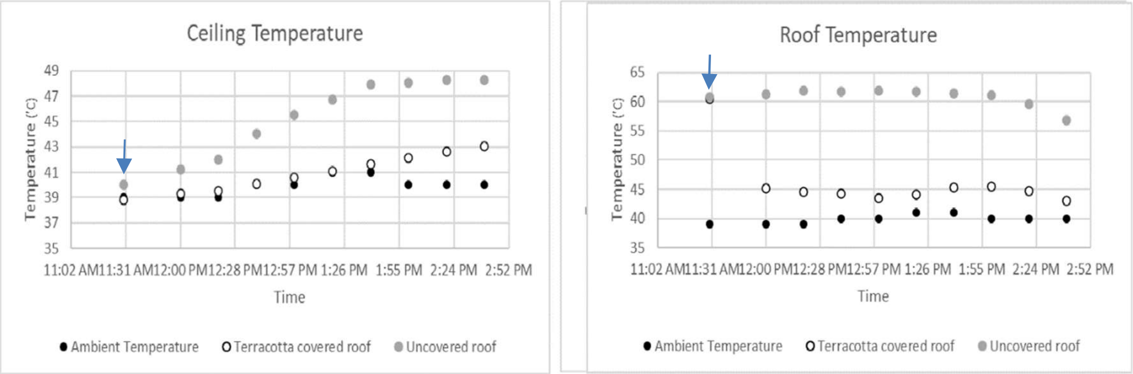
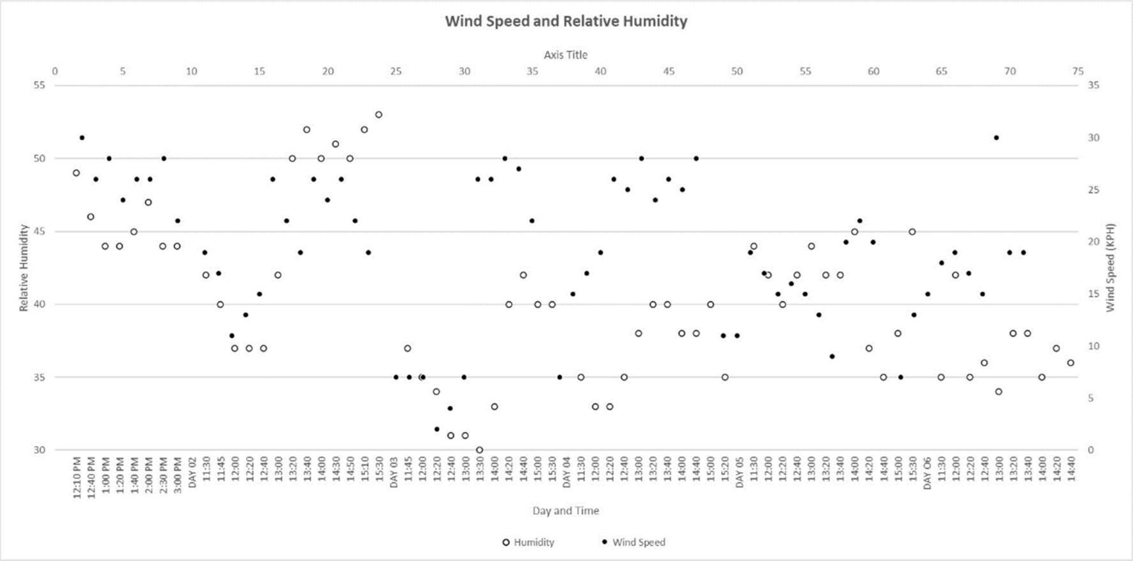


Figure 16. A detailed scatter plot of Relative Humidity and Wind Speed for all the days:



By closely observing the data gathered it can be seen clearly that initially the ceiling whose roof is covered with terracotta tiles and the ceiling whose roof is not covered with terracotta tiles is almost at the same temperature. But just after the first temperature reading water is opened for five minutes, then within the first fifteen minutes the terracotta covered ceiling becomes approximately 2‘C cooler than the ceiling not covered with terracotta tiles at all the days observed. Then within the first hour this temperature difference rises to 4‘C making the ceiling whose roof is covered with terracotta tiles cooler. After the second hour almost all the water has evaporated, now the valve is opened again for wetting the tiles. This practice is continued every day for six days, and almost the same result is achieved which can be seen in above scatter plots. The maximum temperature difference is almost 6’C which is observed at the highest ambient temperature every day.

Also, the roof covered with terracotta tiles and the roof not covered with terracotta tiles is almost at the same temperature at the start of the experiment every day. But just after the first temperature reading water is opened for five minutes, then within the first fifteen minutes the terracotta covered roof becomes approximately 8‘C cooler than the roof not covered with terracotta tiles at all the days observed. Then within the first hour this temperature difference rises to 12‘C making the roof covered with terracotta tiles cooler. After the second hour almost all the water has evaporated, now the valve is opened again for wetting the tiles. Almost the same result is achieved every day for six days. The maximum temperature difference is almost 20’C which is observed at the highest ambient temperature.

2.2.3 Data Collection through Thermal Imaging IR Gun:

Some Infrared sensor images are also attached to further clarification.

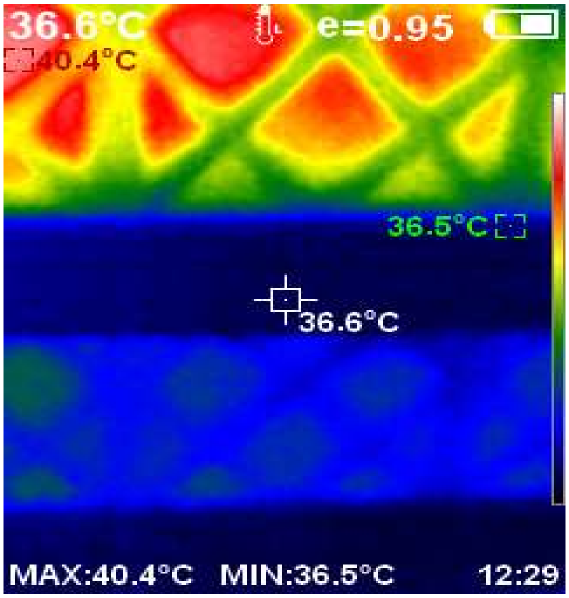


Figure 17. This picture was taken at the ceiling at 12:29 PM on Day 01. It is clearly seen that the temperature of ceiling whose roof is covered with wet terracotta tiles is at 36.6’C and the one without wet terracotta tiles is at 40.4 ‘C

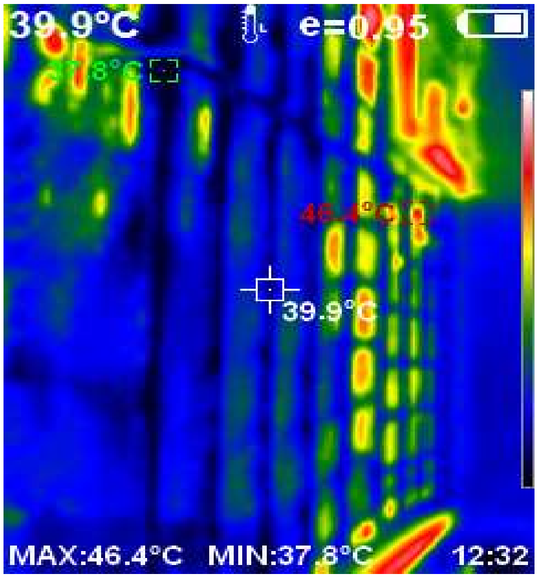


Figure 18. This picture was taken on the roof at 12:32 PM on Day 01. It is clearly seen that the temperature of roof covered with wet terracotta tiles is at 39.9’C and the one without wet terracotta tiles is at 46.4 ‘C.

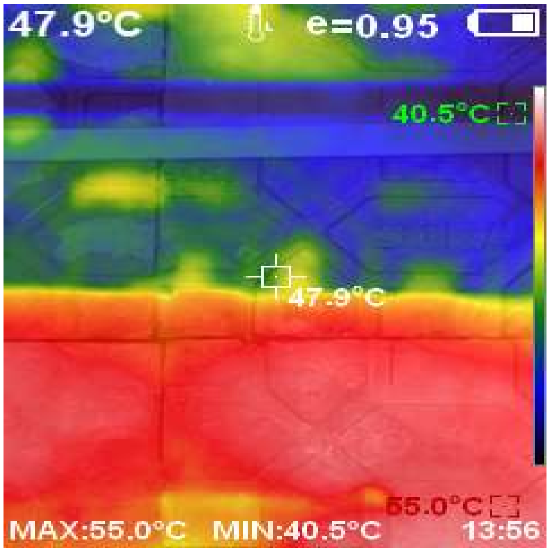


Figure 19. This picture was taken on the roof at 01:56 PM on Day 02. It is clearly seen that the temperature of a roof covered with wet terracotta tiles is 47.9’C and the one without wet terracotta tiles is at 55‘C. It also shows the temperature of the water pipe to be at 40.5’C.

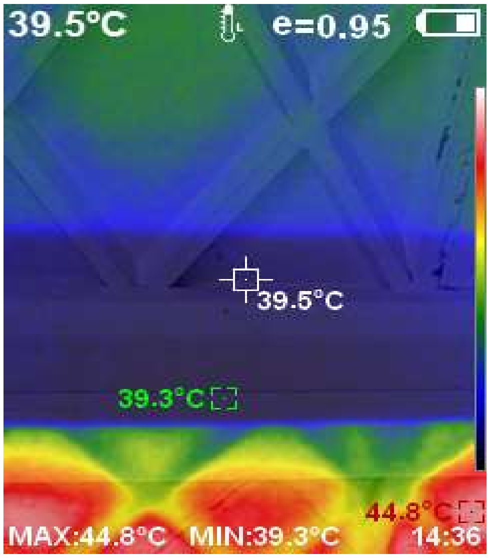


Figure 20. This picture was taken at the ceiling at 02:36 PM on Day 02. It is clearly seen that the temperature of ceiling whose roof is not covered with wet terracotta tiles is at 44.8’C and the ceiling covered with wet terracotta tiles is at 39.5’C

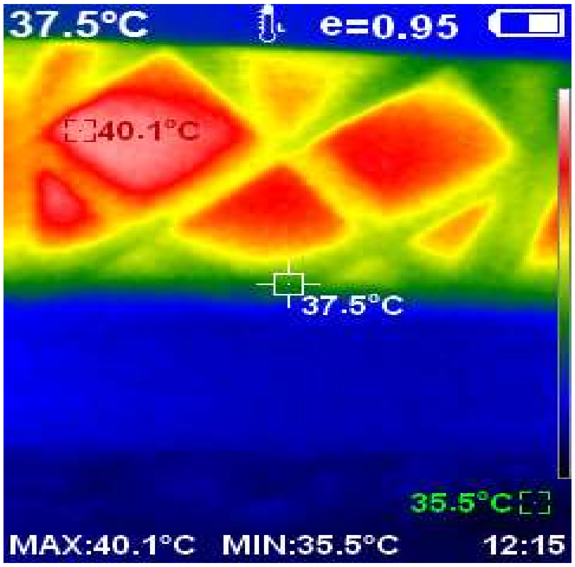


Figure 21. This picture was taken at the ceiling at 12:15 PM on Day 03. It is clearly seen that the temperature of ceiling whose roof is covered with wet terracotta tiles is at 35.5’C and the one without wet terracotta tiles is at 40.1‘C.

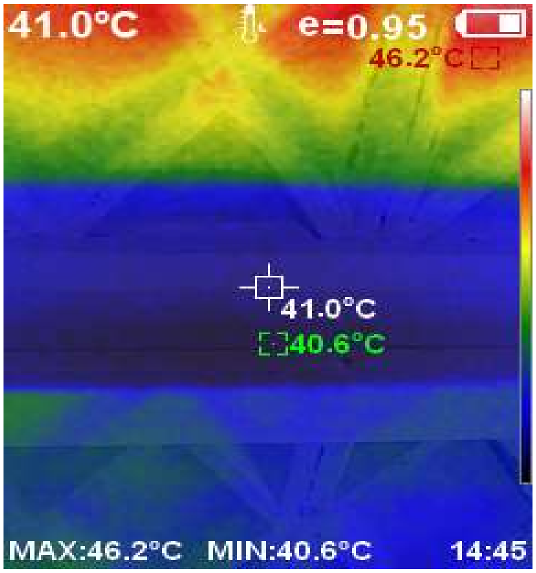


Figure 22. This picture was taken at the ceiling at 02:45 PM on Day 03. It is clearly seen that the temperature of ceiling whose roof is not covered with wet terracotta tiles is at 46.2’C and the ceiling covered with wet terracotta tiles is at 40.6’C

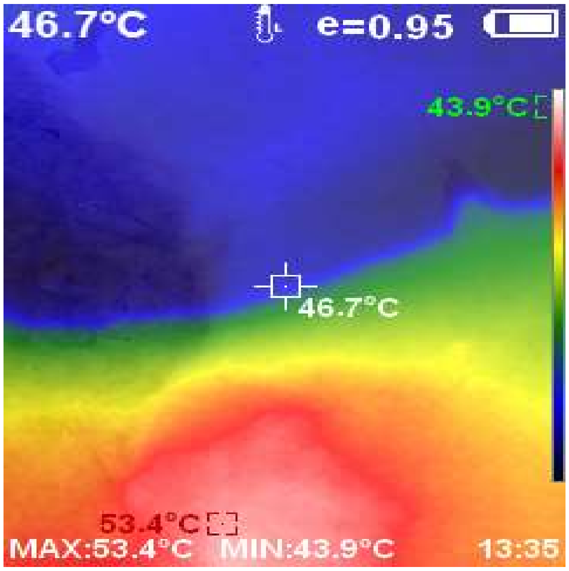


Figure 23. This picture was taken on the roof at 01:35 PM on day 04. It is clearly seen that the temperature of roof not covered with wet terracotta tiles is at 53.4’C and the roof covered with wet terracotta tiles is at 43.9’C

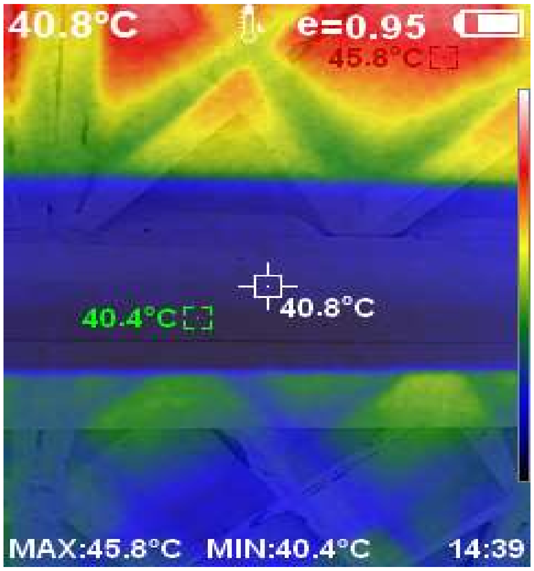


Figure 24. This picture was taken at the ceiling at 02:39 PM on day 04. It is clearly seen that the temperature of ceiling whose roof is not covered with wet terracotta tiles is at 45.8’C and the ceiling whose roof is covered with wet terracotta tiles is at 40.4’C.

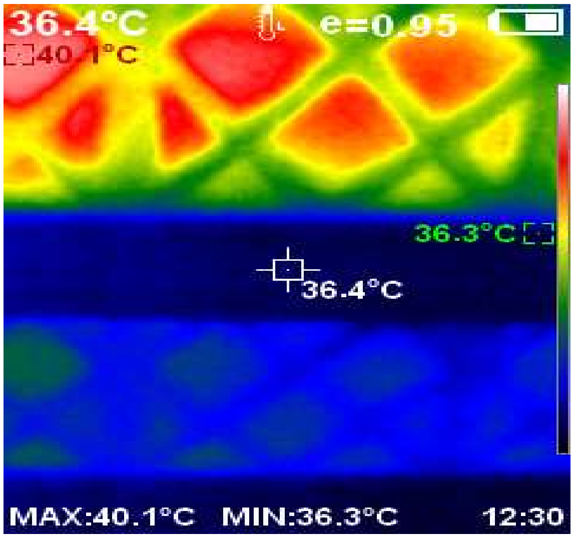


Figure 25. This picture was taken at the ceiling at 12:30 PM on Day 05. It is clearly seen that the temperature of ceiling whose roof is not covered with wet terracotta tiles is at 40.1’C and the temperature of ceiling whose roof is covered with terracotta tiles is at 36.4’C.

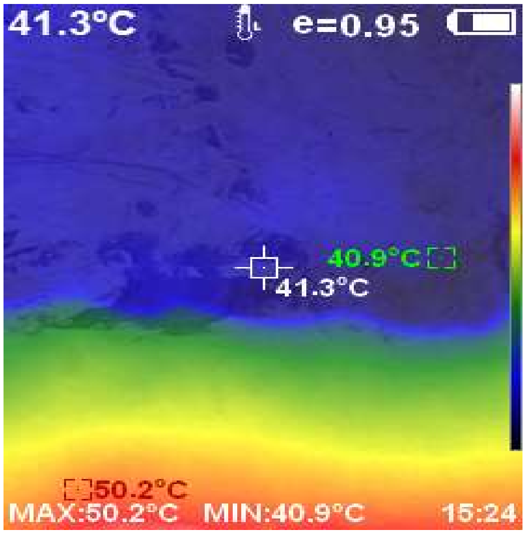


Figure 26. This picture was taken on the roof at 03:24 PM on Day 05. It is clearly seen that the temperature of roof not covered with wet terracotta tiles is at 50.2’C and the roof covered with wet terracotta tiles is at 40.9’C is at 46.3’C

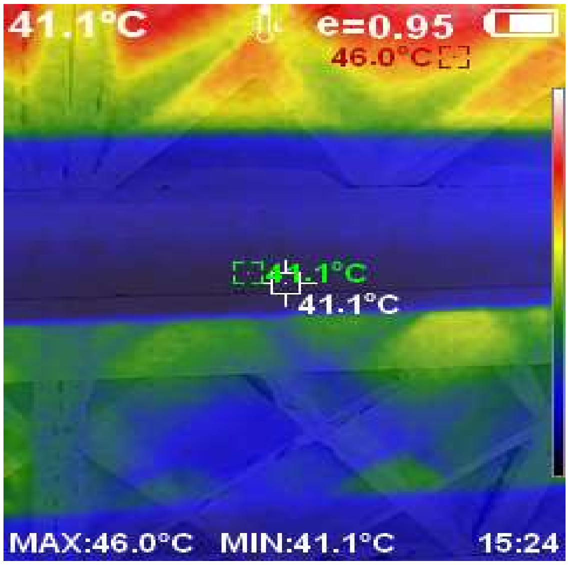


Figure 27. This picture was taken on the ceiling at 03:24 PM on Day 05. It is clearly seen that the temperature of ceiling whose roof is not covered with wet terracotta tiles is at 46’C and the ceiling whose roof is covered with wet terracotta tiles is at 41.1’C

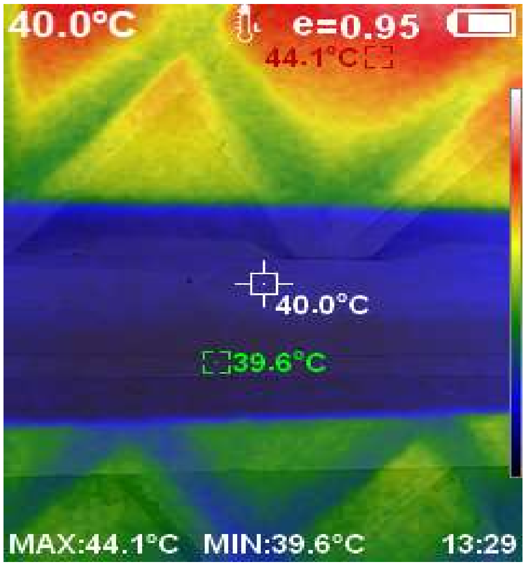


Figure 28. This picture was taken at the ceiling at 01:29 PM on Day 06. It is clearly seen that the temperature of ceiling whose roof is not covered with wet terracotta tiles is at 44.1’C and the temperature of ceiling whose roof is covered with terracotta tiles is at 39.6’C.

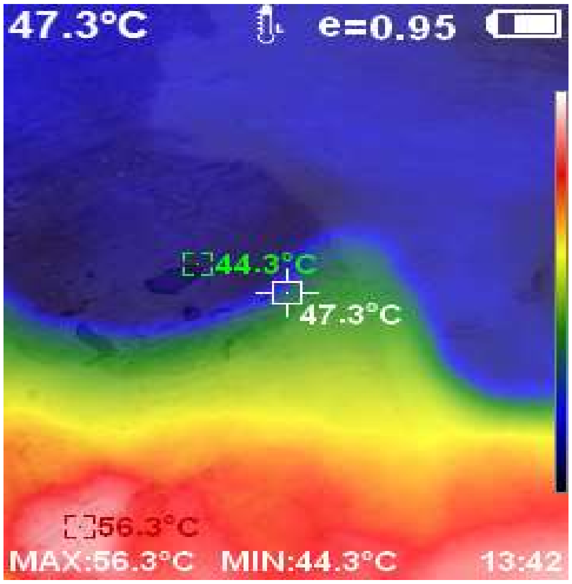


Figure 29. This picture was taken on the roof at 01:42 PM. It is clearly seen that the temperature of roof not covered with wet terracotta tiles is at 56.3'C and the roof covered with wet terracotta tiles is at 44.3'C

2.2.4 COST OF EXPERIMENTAL SETUP (ONE TIME):

No. of tiles=380; Price per tile=25rs

Total tiles price= 9500 Rs

Transportation=2500 Rs

Shifting of tiles from ground floor to roof= 6000rs

Pipes and other accessories= 12000 Rs

Installation= 2500 Rs

Total Cost= 32500 Rs

2.2.5 COST ANALYSIS OF ELECTRICITY CONSUMPTION:

At least 1.5 Ton AC required for 166sqft which consumes 1.5 units per hour.

For 4 hours of peak time 6 units can be consumed

In 30 days, 180 units might be consumed whose price depends upon the overall consumption of electricity as KE tariff rates are different for different numbers of units. On average, one-unit costs around 60 to 70 rupees after including all taxes. Then 60x180=10800 per month. The cost of the setup can be recovered within four months.

2.3 PROPOSED SYSTEM:

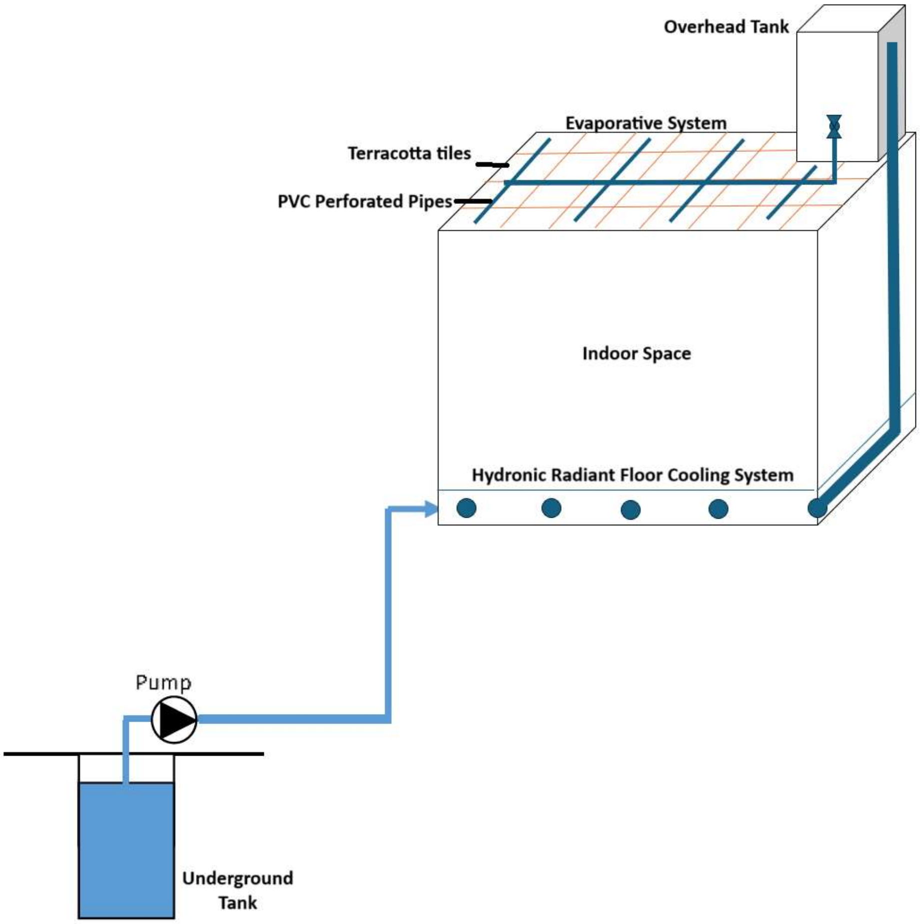


Figure 30. Proposed System

The proposed hybrid cooling system ingeniously integrates the strengths of ground-source hydronic radiant floor cooling and evaporative roof cooling using terracotta tiles to enhance energy efficiency and thermal comfort in residential buildings, especially in hot climates like Karachi. The system operates by circulating cold water from an underground storage tank through a network of pipes embedded in the floors, which absorbs heat from the indoor environment and cools the living spaces effectively. This water is then directed to an overhead storage tank, ensuring that the cooling process does not interfere with the household's water supply. Concurrently, water from the overhead tank is allowed to flow over terracotta tiles installed on the roof. The porous nature of terracotta enables it to retain water, which then evaporates, significantly cooling the roof surface and reducing the heat load entering the building. This dual-action cooling mechanism not only lowers indoor temperatures but also diminishes the need for air conditioning, thereby cutting down on electricity consumption. The combination of hydronic and evaporative cooling maximizes the use of existing water storage facilities and utilizes natural processes, providing a reliable, cost-effective, and environmentally friendly solution for managing thermal comfort in residential settings. This system exemplifies how integrating traditional and modern cooling methods can lead to innovative and sustainable architectural designs.

CHAPTER 3: RESULTS AND CONCLUSIONS

3.1 Result of Hydronic Radiant Cooling System:

Figure 31 shows the daily average temperature of the top floor indoor air, underground tank and outside air measured from 5th March to 20th March. The temperature of 25°C is also shown (dashed line) in the figure. The top floor indoor air temperature is remarkably close to the outdoor air temperature. This is to be expected since the floor under consideration currently has air-to-air split air-conditioners which are only used under extreme heat. The units were not in operation and ventilation from windows and doors along with ceiling fans were being used. Overall, the average top floor indoor air temperature and outdoor air temperature is 32.6°C and 31.7°C. In contrast, the underground tank is consistently colder than the outdoor air (average $\Delta T = 10.2°C$, minimum $\Delta T = 9°C$). Furthermore, except for one day (10 March), the underground tank is always colder than 25°C.

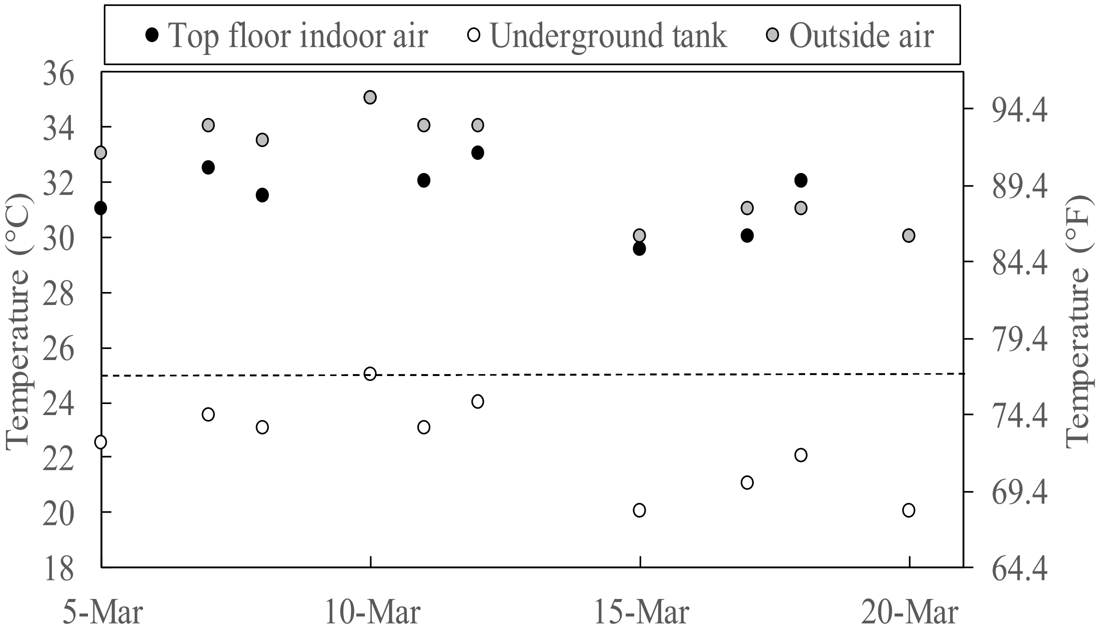


Figure 31. The daily average temperature of the top floor indoor air, underground tank and outside air measured from 5th March to 20th March. The temperature of 25°C is also shown (dashed line).

Figure 32 shows the heat transfer rate (W) and the heat transfer per unit floor area (Wm^{-2}) from 5th March to 20th March. It can be seen that that aside from 10th March, the radiant system contributes to the cooling capacity. On average, the radiant cooling system provides 1020 W cooling to the conditioned space while the maximum cooling rate is 1962W. The average cooling provided per unit radiant floor area is 12.2 Wm^{-2} while the maximum flux is 23.5 Wm^{-2}.

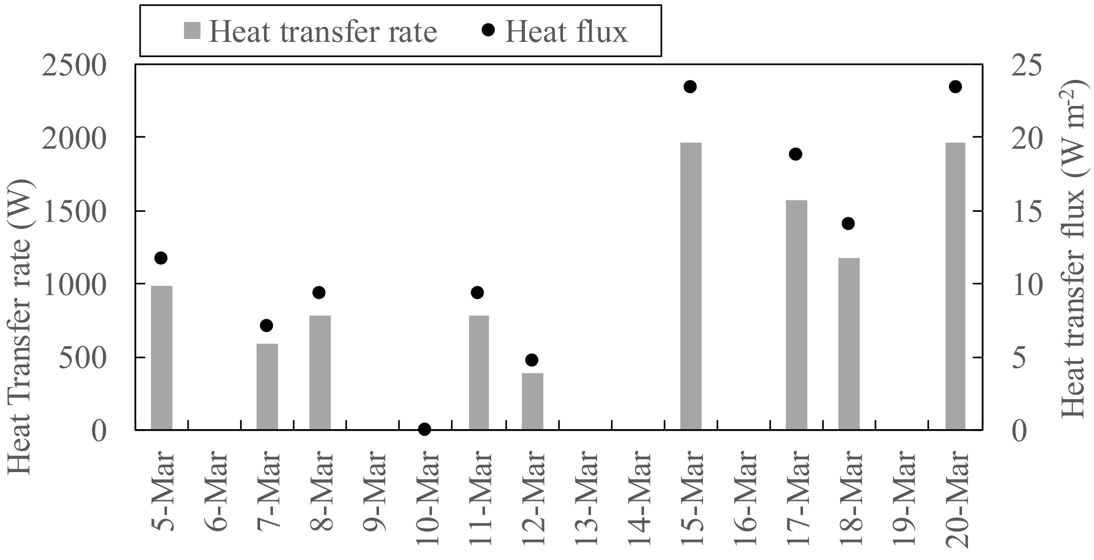


Figure 32 The heat transfer rate (W) and the heat transfer flux (Wm^{-2}) from 5th March to 20th March.

Figure 33 shows the electric power that could be saved if the cooling is provided from a radiant cooling system instead of the current air conditioning system (with a COP of 3.2). It can be seen that on average 319 W of electricity, with the maximum saving of 613 W. The additional pumping power due to the pressure loss in the radiant pipes was also calculated to be 2.79 W which is negligible compared to the electricity saved.

It is crucial to comprehend the assumptions and circumstances that were considered while calculating the savings. It is essential to note that the savings are based on the maximum heat removal from the conditioned space when it is maintained at 25°C using the radiant cooling system. If the conditioned space is hotter than 25°C (as is the case in March), the heat removed by the radiant system will increase which would increase the electricity saved. Conversely, if the building envelope is improved and sources of heat gains are minimized, less heat will need to be removed from the system, decreasing the potential energy savings. Additionally, during periods when the underground tank is hotter than 25°C or the indoor air is colder than 25°C, there will be zero savings.

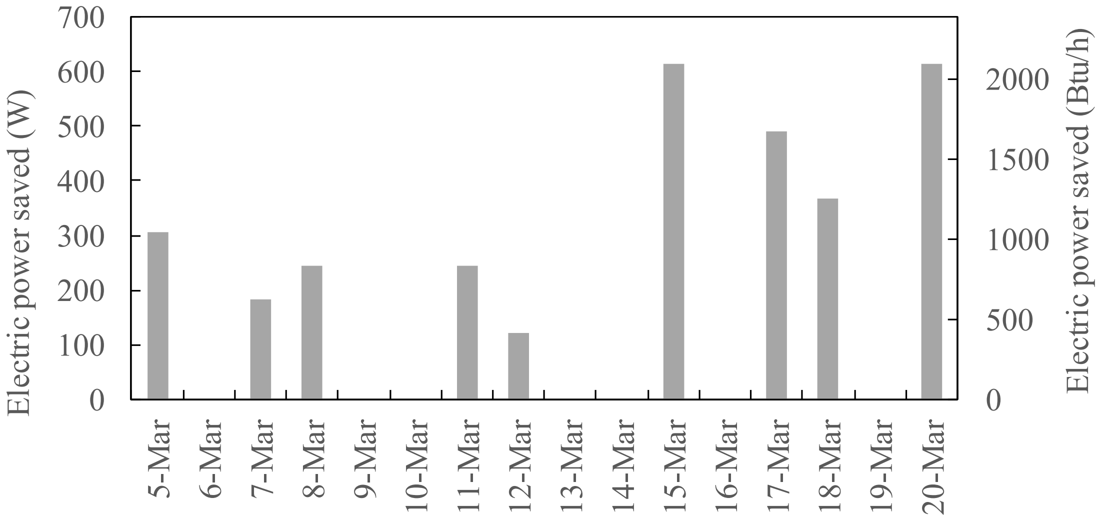


Figure 33 The electric power saved (W) from 5th March to 20th March.

3.2 Result of Evaporative Cooling System:

A low-cost evaporative cooling system was proposed which utilizes water already present in the overhead tank of typical houses in Karachi, Pakistan. This system was installed on a three-storey residential building in Karachi, Pakistan. The cold water from the overhead water tank is flown by gravity through the perforated pipes which are laid on terracotta tiles. The tiles with their excellent absorbent capabilities withhold the water and let it evaporate producing a cooling effect which was measured using 6 K type sensors. 3 of them were installed in ceiling and 3 of them were installed on roof. Also, a thermal imaging gun was used to get a clear picture of the temperature data. A website www.timeanddate.com was used to monitor the humidity, ambient temperature and wind speed. From the above observations it can be concluded that this system does not use any electricity and can provide free cooling of up to 6’C on ceiling of room and up to 20’C on roof of room during peak hours when there is most usage of air conditioners. With a one-time installation cost, this system is totally reliable and durable. As we have covered half of the roof of the lounge to make a comparative analysis of the covered and uncovered roof, it gives us a clear picture of the performance of the evaporative cooling system.

3.3 CONCLUSION:

Two research studies in Karachi, Pakistan, explored innovative, low-cost cooling systems for residential buildings. The first study proposed a ground-source direct radiant floor cooling system for a four-story home. This system pumps cold water from an existing underground concrete storage tank to the radiant floor system, and then the water flows up to an overhead storage tank for building water needs. Temperature measurements taken between 1 PM to 5 PM over several days using an infrared thermometer showed that the system can maintain an indoor air temperature of 25°C, providing an average cooling capacity of 12 Wm-2 and saving approximately 319 W of electricity. The savings are contingent upon the underground tank temperature being lower than 25°C. The study also plans to develop mathematical models to evaluate the building's load and heat transfer in the underground tank, with future validation through experimental setups. Additionally, the system aims to utilize hot water from the overhead tank for heating in areas with substantial heating and cooling requirements.

The second study introduced a low-cost evaporative cooling system for a three-story residential building. This system utilizes water from the overhead tank, which flows by gravity through perforated pipes laid on terracotta tiles. The tiles absorb the water and facilitate evaporation, producing a cooling effect measured using six K-type sensors (three on the ceiling and three on the roof) and a thermal imaging gun. Observations, supported by data from www.timeanddate.com, indicated that the system can reduce ceiling temperatures by up to 6°C and roof temperatures by up to 20°C during peak hours, without consuming electricity. The one-time installation cost makes this system reliable and durable. A comparative analysis of covered and uncovered sections of the roof demonstrated the system's effectiveness.

Both studies highlight sustainable, energy-efficient cooling solutions leveraging existing water storage infrastructure. These systems provide significant cooling benefits and energy savings, with plans for further research and experimental validation to optimize performance and expand their applications.

SUMMARY OF RESEARCH WORK

Two studies in Karachi, Pakistan, explored low-cost residential cooling systems. The first study proposed a ground-source radiant floor cooling system using cold water from an underground storage tank, achieving a cooling capacity of 12 Wm-2 and saving 319 W of electricity when maintaining an indoor temperature of 25°C. Future work includes developing mathematical models for building load and heat transfer, with plans to use hot water for heating. The second study introduced an evaporative cooling system using water from overhead tanks flowing through perforated pipes on terracotta tiles. This system reduced ceiling temperatures by up to 6°C and roof temperatures by up to 20°C during peak hours without electricity. Both systems utilize existing water infrastructure to provide energy-efficient cooling, with further research planned for optimization.

CHAPTER 4: CONCLUSION AND FUTURE RECOMMENDATION

4.1 CONCLUSION:

In conclusion, two innovative, low-cost residential cooling systems were explored for homes in Karachi, Pakistan. The first system, a ground-source radiant floor cooling setup, utilized cold water from an underground storage tank to achieve a cooling capacity of 12 Wm-2, saving 319 W of electricity when maintaining an indoor temperature of 25°C. This approach highlights the potential for significant energy savings through efficient use of existing water storage infrastructure. The key findings underscore the importance of maintaining optimal indoor and tank temperatures, and future work will focus on refining mathematical models for building load and heat transfer, along with implementing a complementary heating system. The second system, an evaporative cooling method, employed water from overhead tanks flowing through perforated pipes on terracotta tiles, successfully reducing ceiling temperatures by up to 6°C and roof temperatures by up to 20°C during peak hours without any electricity usage. The strength of this system lies in its simplicity, reliability, and cost-effectiveness, using the natural cooling properties of evaporation. Both studies demonstrate the feasibility and efficiency of leveraging existing water infrastructure for sustainable residential cooling, paving the way for further optimization and broader application.

4.2 Future Recommendations:

To further enhance the performance of the proposed hybrid cooling system without relying on electricity, several recommendations can be considered:

Advanced Insulation Materials: Incorporating advanced insulation materials in walls, roofs, and floors can significantly reduce heat transfer, thereby enhancing the efficiency of both hydronic and evaporative cooling systems.

Water Quality Management: Regular monitoring and maintenance of water quality in the storage tanks can prevent scaling and clogging, ensuring optimal performance and longevity of the system.

Thermal Energy Storage: Implementing passive thermal energy storage systems can store excess cooling energy during off-peak hours and release it during peak demand, improving the system's efficiency and reliability.

Green Roofing: Combining the terracotta tiles with green roofing elements can provide additional cooling through plant transpiration and shade, further reducing the heat load on the building.

Building Orientation and Design: Optimizing the building's orientation and architectural design to maximize natural ventilation and shading can complement the cooling system and enhance overall thermal comfort.

By implementing these strategies, the performance and efficiency of the cooling system can be significantly enhanced without the need for additional electricity.

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LIST OF PUBLICATIONS

1. A conference Paper on Hydronic System whose title is “Ground-source direct radiant cooling system using existing overhead and underground water storage tanks for South Asian weather." Was presented in 10th International Conference on Advances in Environment Research (ICAER 2024), Tokyo, Japan. The Paper is published in the International Journal of Engineering and Technology (IJET).