Low-Cost Night Sky, Longwave Radiative Cooling Techniques for Green Building Design

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Abstract—India and Iran traditionally used drop in temperature during nights for the purpose of cooling. Yakhchals of Iran, ice pits and step wells of India provided ice and cool water during harsh summers. There have been recent advances in materials, especially photonic coating material which promises day and night longwave radiative cooling. This has ignited the interest of designers to incorporate longwave radiative cooling concepts in the building design. Climate change and rapid urbanization is causing severe and long summers in India. Non availability of continuous electric power supply and increased energy tariffs is a compelling reason to look at other sustainable alternatives apart from compressor-based air conditioning systems to cool homes. Traditional air conditioning systems in a way use the night drop in temperature for optimization and saving through Thermal Energy Storage (TES) systems. Day time solar shortwave UV radiation is extensively used by solar radiative heaters. Silicon solar cells covert the day time solar radiation into electric energy. Night sky, longwave radiation-based systems are not common and extensive. This paper reviews successful designs which are using longwave radiation for cooling. Current successful radiative cooling designs are expensive and require huge capital investment. Furthermore, designs assume availability of large quantities of water. In India, shortage of water and availability of uninterrupted electricity are two important parameters while designing any system. This paper proposes a novel design based on longwave radiator producing ample quantity of cool water in the night. This cool water is stored in an evaporative cooling chamber during the day time and used as cooling medium for evaporative coolers, there by conserving water and electricity. Prototypes of longwave radiator is built and experimental results are reported. This paper focuses on low-cost design using locally available material in India and techniques that can be adopted for small homes.

Keywords—Radiative cooling, Longwave radiation, Infrared radiation, Passive Cooling, Sky radiant cooling, green building, Photonic coating

1.0 INTRODUCTION

Hot days and cool nights are common phenomenon during summer in India due to tropical climate conditions. Traditionally Indians have made cultural and social adjustments to deal with climate. Organizing marriages and social gatherings in the late evenings, sleeping on the open-air terraces are just few examples. From the times of Emperor Ashoka construction of step wells is institutionalized for the comfort of travellers (“Stepwell”, n.d.). Stepwells of India are still operational and functional. They not only conserve and store water they also act as cool resting place for travellers (Ghai 2018). Fascination and craving for desserts of Moghul rulers has led to construction of ice pits on the banks of Ganges River (Hayden 2013).

Yakhchals of Iran effectively use the cold night desert temperature to make ice and store throughout the year

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("Yakhchāl" 2022). These traditional structures are architectural marvels and there is compelling reason to draw inspiration from them and design sustainable green buildings which are not dependent on fossil fuel-based energy for giving comfort to occupants. Modern building cooling based on compressor and refrigerant consumes tremendous amount of energy. According to IEA International Agency report, 10% of global electricity is consumed for air conditioning ("The Future of Cooling – Analysis" 2018). Such large consumption of energy contributes to climate change and global warming. It is very important to explore alternate and sustainable mechanisms and techniques to cool buildings.

2.0 LONGWAVE RADIATION COOLING BASICS

Earth and atmosphere emit infrared longwave radiation of electromagnetic waves with the wavelengths of 3-100µm into outer space in the form of thermal radiation. It is called Outgoing Longwave radiation ("Outgoing longwave radiation" 2022). Any surface that is warm radiates energy. Sun at 5,500 °C emits in the visible spectrum of light and at near infrared light wave lengths. Earth with average temperature of 15 °C emits longer wavelength infrared radiation. Earth's atmosphere allows all the incoming solar radiation. Most of the atmosphere is transparent to infrared radiation and allow the infrared radiation emitted by the earth to pass into outer space. A small portion of atmosphere made up of greenhouse gases, are opaque to infrared radiation and reflect back to earth. This phenomenon is responsible for radiation balance and maintaining the earth's temperature. Without this process, earth would have become a very cold planet. Increase in the greenhouse gases due to industrialization and human activity last two centuries has disturbed the radiation balance and causing global warming and climate change and this phenomenon is termed as 'Greenhouse' effect ("Greenhouse effect" 2022) (Iowa State University, n.d.).

Radiative cooling process effectively uses night surface cooling phenomenon to cool water as a medium and use the cool water during the day time for cooling the buildings ("Radiative cooling" 2022).

The following figure gives the details of frequency and wavelength of electromagnetic spectrum ("Electromagnetic spectrum" 2022).

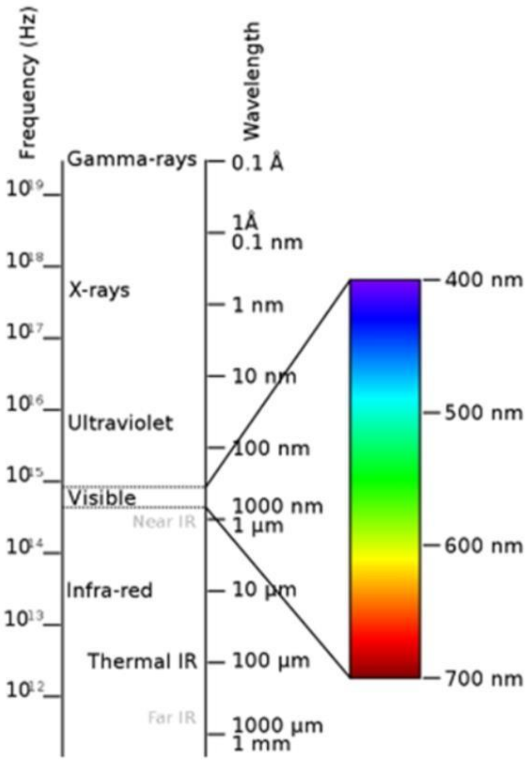

Figure 1 Electromagnetic Spectrum (Electromagnetic spectrum 2022)

3.0 REVIEW OF EXISTING BUILDINGS THAT HAVE IMPLEMENTED RADIATIVE COOLING SYSTEMS

Night sky radiant cooling is not rocket science. However, it requires resourcefulness, eye for detail for local conditions and clever design and implementation. Over the years, many building are designed using the concept and achieved uninterrupted energy savings for several years (McKay 2013).

In 1967, Harold Hay and John Yellott built a building and on its roof was a series of ponds with a total area

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of 170 square feet and covered by movable insulating panels.

During the summer season, during day time panels were closed to insulate water from gaining temperature. In the night, panels were retracted to expose to night sky. Due to longwave radiation, water lost the temperature. During winter season, the process was reversed. During day time water was exposed to Sun to gain temperature and night panels were closed to retain the heat and achieved uniform temperature of 21 Degrees Celsius inside the building.

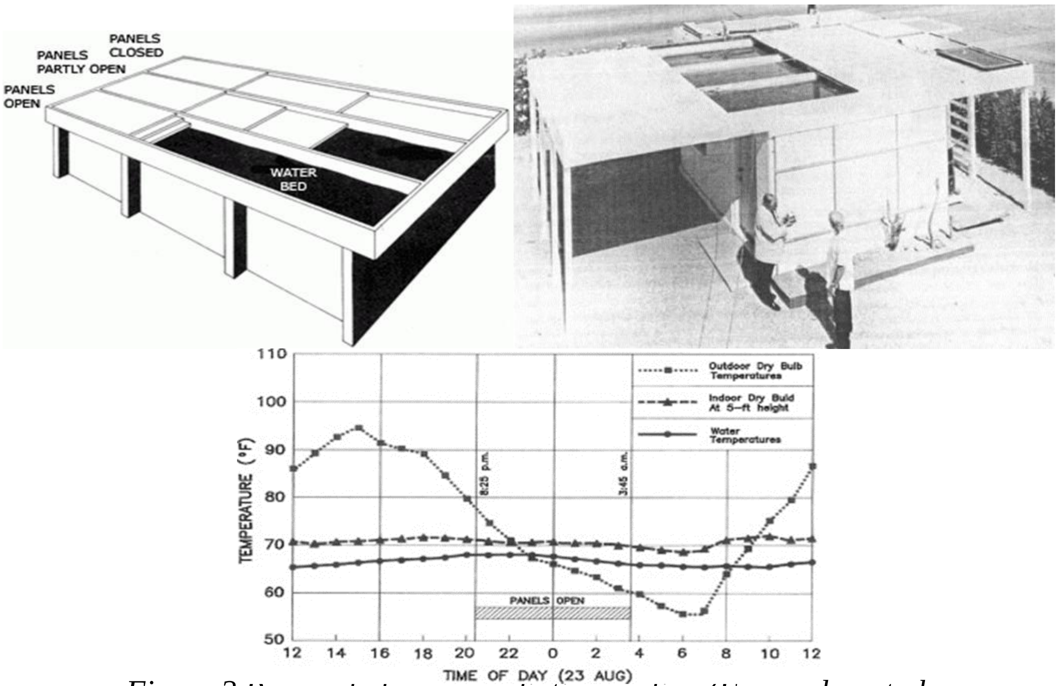

Figure 2 Research done on radiative cooling (Fernandez, et al. 2015)

The US Department of Energy in its research article published in 2015 highlights the potential of radiative cooling (Fernandez et al. 2015). Research paper reviews WhiteCapR, WhiteCapF and WhiteCapT systems manufactured by RoofScience Corporation. Design involves maintaining 76 mm layer of water on the roof at all times. On the water layer, interlocking polystyrene panels float. Panels are sprayed with water which is evaporatively and radiatively cooled and circulated to radiant panels within the building. The schematic diagrams are shown below (Fernandez et al. 2015, 5,6).

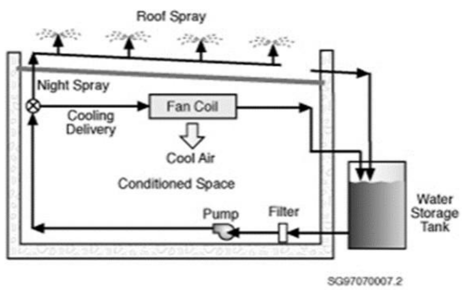

Figure 2: WhiteCapT schematic from Collins and Parker (1998).

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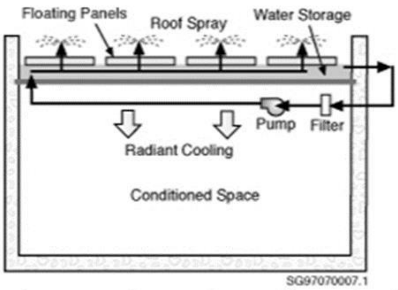


Figure 1: WhiteCapR schematic from Collins and Parker (1998).

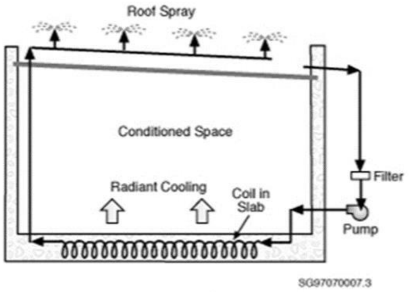


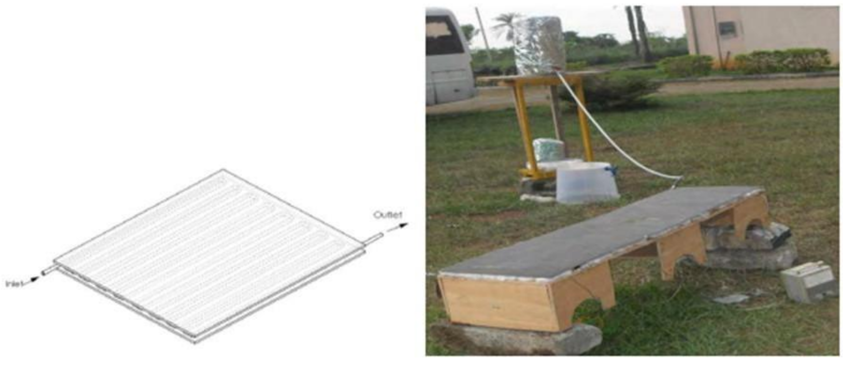
Figure 3: WhiteCapF schematic from Collins and Parker (1998).

All the configurations have successful installation and resulted in substantial energy savings.

4.0 LONGWAVE RADIATORS

Solar heaters based on Flat-plate collectors - Evacuated-tube collectors capturing day time solar radiation are very common in India. They are extensively used on roof tops across India providing hot water for bathing purpose and saving electricity. In Indian cities like Bangalore, government has made it mandatory to install solar heaters on roof tops (BESCOM, 2007) (De Rooij 2019). Longwave radiators for cooling purpose are not available in the market. This paper reviews few low cost longwave radiators and proposes a novel longwave radiator based on material available in the local market.

N. V. Ogueke et al. in their research paper submitted to World Renewable Energy Congress- 2011-Sweden has presented an experimental longwave radiator using half an inch copper tubing (Ogueke, Onwuachu, and Anyanwu 2011, 2112).



(a) (b)

Fig 1 (a): Schematic diagram of the thermal radiator and (b): the pictorial diagram of the experimental rig.

Figure 3 Scematic and Experiment on Thermal radiator (Etzion and Erell 1999)

Yair Etzion et al. in their research publication discuss the design of a low cost longwave radiator based on polycarbonate (Etzion and Erell 1999).

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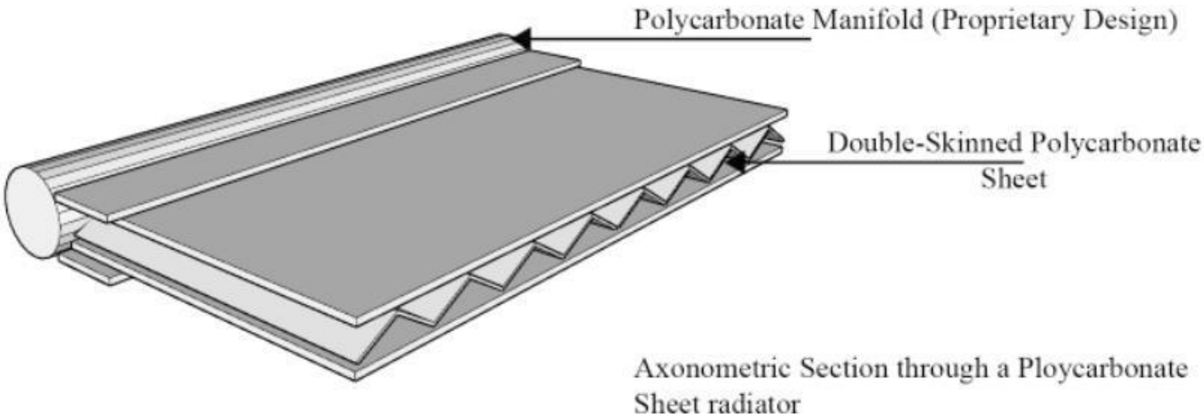

Figure 4 Axonometric section (Etzion and Erell 1999)

The above papers present deep mathematical analysis of IR radiators which can be used by designers. Deriving inspiration from the above work, a prototype longwave radiator is built using LDPE based drip irrigation hose.

Figure 5 Based on research done, prototype of Longwave radiator made using drip irrigation hose

It is built on 3 feet by 3 feet wooden plywood frame and 72 feet of 16 mm diameter drip irrigation pipe. Wooden frame is painted black to increase the radiation. This paper reports the experimental results using this prototype radiator.

IR emissivity table of different material is given in the following reference (Thermoworks, n.d.).

All substances emit radiation at temperatures above absolute temperature. Coating with black paint enhances the emissivity. Emissivity of materials is defined as the ratio of the energy radiated from a substance's surface to the energy radiated from an ideal emitter (black body emission/black body radiation) under the same conditions. It is a value between 0 for an ideal reflector and 100% for an ideal emitter (Acktar, n.d.). Rapid advances are being made in photonic devices. Amit Kumar Goyal et al. in their research paper review photonic devices (Goyal and Kumar 2020). New radiators can be built in future based on the availability of photonic material at affordable prices.

4.1 IR Radiator based radiant cooling system

This paper proposes a low-cost radiant cooling system suitable for small buildings in India. Scarcity of water and non-availability off electric power are the major parameters while designing. System is based on IR Radiator prototype. System consists of tank with water with a submersible pump. Water is filled late in the evening through overhead tank. Through the night, submersible pump, circulates water through IR radiator which is directly exposed to sky. Next day morning, cool water is transferred to a tank placed in evaporative cooling chamber. During the day time, the cool water from this storage tank is used through drip irrigation pipes to wet evaporative mats located in evaporative cooler fans (desert/swamp coolers) or they can be used to wet Khus Mats (Chrysopogon zizanioides, commonly known as vetiver and khus) which are popular in India as alternate to air coolers and air conditioners (Parikh 2019) ("Chrysopogon zizanioides" 2022) ("Evaporative cooler" 2022).

Schematic diagram of the system is given below.

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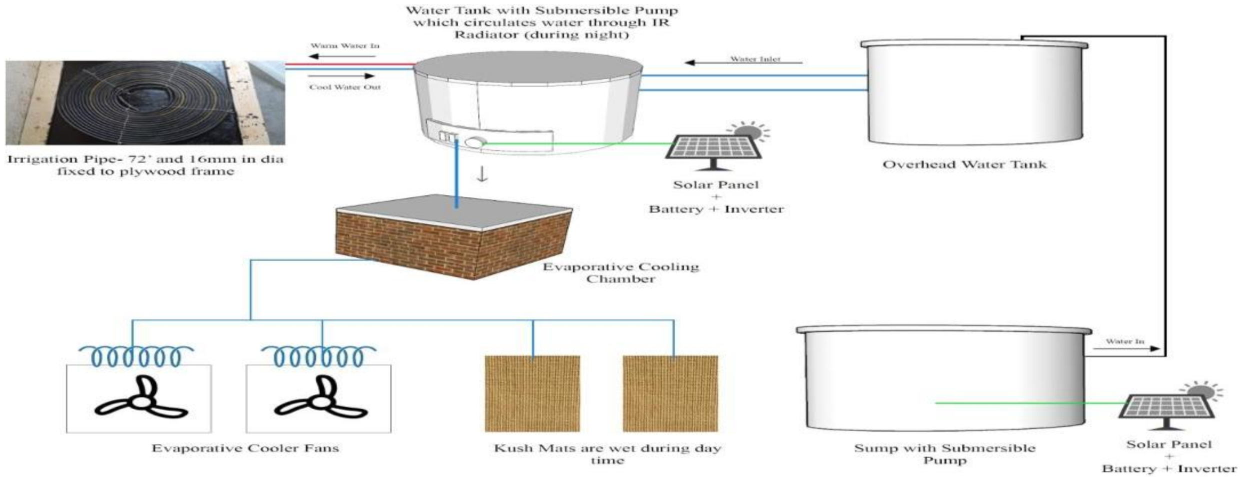
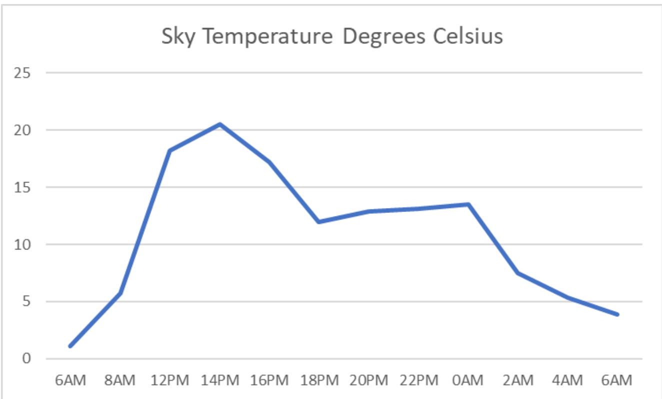


EXPERIMENTAL RESULTS

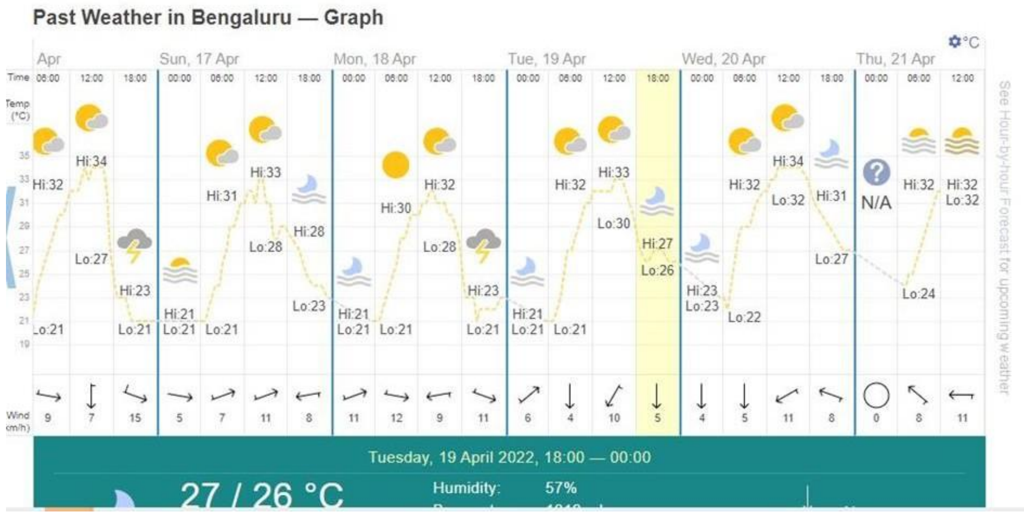
Radiant cooling systems us Sky as a heatsink to achieve cooling. Measuring sky temperature accurately is important for designing radiant cooling system and also for proper placement of the radiator. Very limited research is done on this subject(Karn, Chintala, and Kumar 2019).

NASA research publication gives an easy method to measure Sky Temperature using Infrared Thermometer. This technique is used to measure the sky temperature and results are documented (Mims 2018).

Results of Sky Temperature Measured at Bangalore 17/April/22 to 18/April/22 is tabulated below:



Ambient temperature during that period is documented below (timeanddate, n.d.):



As indicated by the data, there is ample temperature difference to achieve radiative cooling.

5.0Preliminary Experiments with Longwave radiator

Experiments were performed on water stored using small plastic trays with black coated surface, small area roof top with black coating, concrete shallow pot and a small water pond exposed to night sky. Initial

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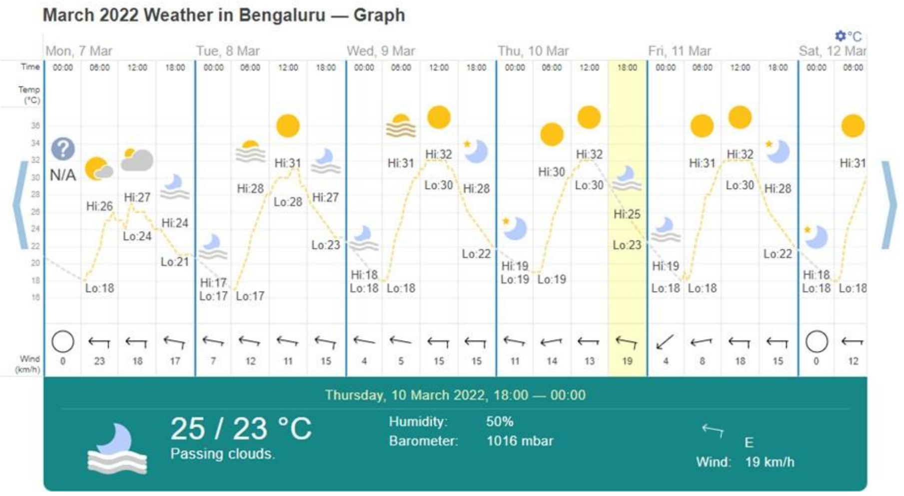
temperature was around 27 Degrees Celsius. During this period of experimentation after full night exposure temperatures were recorded and compared with temperature of water in an underground sump and overhead tank.

Description	Temperature Degrees Celsius at 5.30AM on 8 March 22
Overhead Tank	28.2
Underground Sump	27.7
Plastic Tray	22.2
Cement pot	23.2
Pond	25.2
Layer of water on roof top	22.8

Weather during that period is given in the image below (timeanddate, n.d.). It can be concluded that shallow layers of water exposed to night sky 5 to 6 Degrees Celsius drop while overhead plastic tank , concrete sump and concrete pond temperature dropped by 1-2 Degrees Celsius.



Experimental results of Longwave radiator with water storage drum and submersible pump

An experimental set-up was made with radiator prototype, drum filled with water and a submersible pump. Set-up of the prototypeis shown below:

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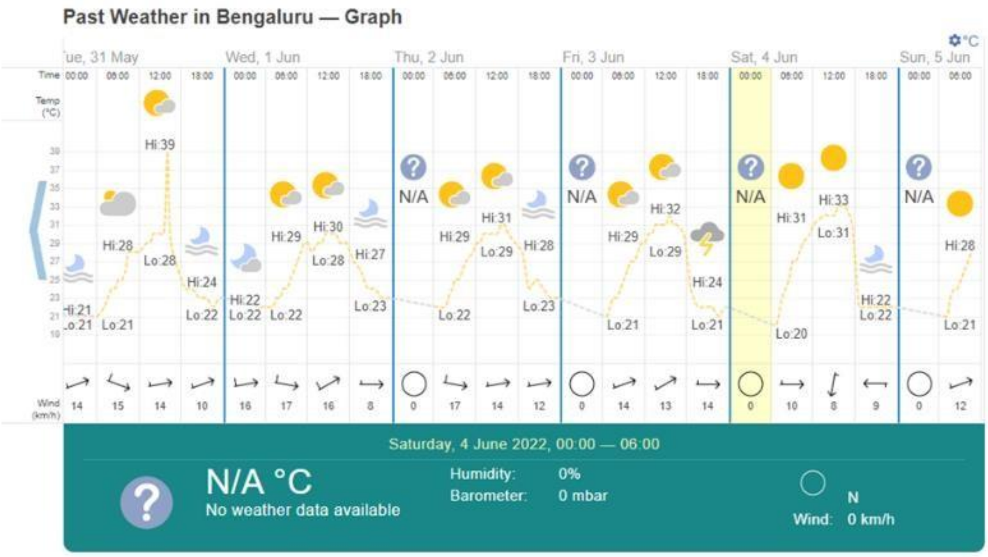
On 31/May/2022 at 6 PM water temperature inside the drum measured 27.4 Degrees Celsius. Throughout the night, the submersible pump circulated the water in the radiator and looped it back into the drum. Next day morning at 6 AM temperature measurements were taken and tabulated below.

Description	Temperature Degrees Celsius
Drum attached to radiator	23.8
Shallow tub	21.8
Shallow cement pot	22.1
Pond	24.9
Sump	26.9
Overhead Tank	25.8

Weather conditions are captured in the image (timeanddate, n.d.) below:



Water in the radiator drum temperature reduced by 4 Degrees Celsius and around 200 litres of water at 23.8 Degrees Celsius wasmade available.

CONCLUSION

Longwave radiative cooling is a viable option. The system proposed in this paper is based on resource constraints in India and suitable for small buildings. Experimental results of prototype radiator are encouraging and validate the proof of concept. Current research and breakthroughs in materials are likely to produce selective and high infrared emissive material. New material, especially photonic material is likely to produce cooling even in the day time. Improved longwave radiators can produce air conditioning without

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fans and refrigerant compressors and can lead to huge savings in terms of energy consumption. Longwave radiative cooling systems are still in infancy and more research is needed to commercially produce viable cooling systems.

REFERENCES

[1] Acktar. n.d. "High Emissivity Materials." Acktar ltd. Accessed July 7, 2022. https://www.acktar.com/products-services/high-emissivity-materials.

[2] BESCOM. 2007. *Conservation of Energy*. Bangalore, Karnataka: BESCOM, Karnataka. https://bescom.karnataka.gov.in/storage/pdf-files/DSM/2- Circular-by-BESCOM-on-mandatory-use-of-Solar-Water-Heater.pdf.

[3] "Chrysopogon zizanioides." 2022. Wikipedia. https://en.wikipedia.org/wiki/Chrysopogon_zizanioides.

[4] De Rooij, Dricus. 2019. "Solar Water Heating." Sinovoltaics. https://sinovoltaics.com/learning-center/technologies/solar-water-heating/.

[5] "Electromagnetic spectrum." 2022. Wikipedia. https://en.wikipedia.org/wiki/Electromagnetic_spectrum.

[6] Etzion, Yair, and Evyatar Erell. 1999. "Low-Cost Long-Wave Radiators for Passive Cooling of Buildings." *Architectual Science Review* 42 (June): 79-85. 10.1080/00038628.1999.9696856.

[7] "Evaporative cooler." 2022. Wikipedia. https://en.wikipedia.org/wiki/Evaporative_cooler.

[8] Fernandez, N., W. Wang, K. Alvine, S. Katipamula, and Pacific Northeast National Laboratory. 2015. "Energy Savings Potential of Radiative Cooling Technologies." *U.S. Department of Energy under Contract DE-AC05-76RL01830*, (November). https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-24904.pdf.

[9] "The Future of Cooling – Analysis." 2018. IEA. https://www.iea.org/reports/the-future-of-cooling.

[10] Ghai, Rajat. 2018. "Stepwells in Gujarat are a lesson on community-based water harvesting." Down To Earth. https://www.downtoearth.org.in/news/water/pride-in-ruins-60781.

[11] Goyal, Amit K., and Ajay Kumar. 2020. "Recent advances and progresses in photonic devices for passive radiative cooling application: a review." SPIE Digital Library. https://www.spiedigitallibrary.org/journals/journal-of-nanophotonics/volume-14/issue-03/030901/Recent-advances-and- progresses-in-photonic-devices-for-passive-radiative/10.1117/1.JNP.14.030901.full?SSO=1.

[12] "Greenhouse effect." 2022. Wikipedia. https://en.wikipedia.org/wiki/Greenhouse_effect.

[13] Hayden, Bruce. 2013. "MAKING ICE FROM EARTHEN PITS IN ANCIENT INDIA." THEN AND NOW. https://pazhayathu.blogspot.com/2012/02/water-cooler-air-conditioning-before.html.

[14] Iowa State University. n.d. "Part 1: The Greenhouse Effect | Imaging the Universe." Imaging the Universe. Accessed July 7, 2022. https://itu.physics.uiowa.edu/labs/foundational/earths-changing-climate/part-1-greenhouse-effect.

[15] Karn, Ashish, Venkateshwarlu Chintala, and Suresh Kumar. 2019. "An investigation into sky temperature estimation, its variation, and significance in heat transfer calculations of solar cookers." (April). https://onlinelibrary.wiley.com/doi/10.1002/htj.21459.

[16] McKay, Graham. 2013. "It's Not Rocket Science #5: Night Sky Radiant Cooling." misfits' architecture. https://misfitsarchitecture.com/2013/03/01/its-not-rocket-science-5-night-sky-radiant-cooling/.

[17] Mims, Forrest M. 2018. "Measuring the Temperature of the Sky and Clouds." My NASA Data. https://mynasadata.larc.nasa.gov/sites/default/files/2018-12/Measuring%20the%20Temperature%20of%20the%20Sky%20and%20Clouds.pdf.

[18] Ogueke, Nnamdi, C.C Onwuachu, and Emmanuel Anyanwu. 2011. "Experimental Study of Long-Wave Night Sky Radiation in Owerri, Nigeria for Passive Cooling Application." (November). 10.3384/ecp110572110.

Copyright @ 2019 Authors

[19] "Outgoing longwave radiation." 2022. Wikipedia. https://en.wikipedia.org/wiki/Outgoing_longwave_radiation.
[20] "Outgoing longwave radiation." 2022. Wikipedia. https://en.wikipedia.org/wiki/Outgoing_longwave_radiation.
[21] Parikh, Kush. 2019. "Khus Curtains: An Alternative of AC or Coolers for Home." Gharpedia. https://gharpedia.com/blog/khus-curtains-an- alternative-of-a-c-or-coolers/.
[22] "Radiative cooling." 2022. Wikipedia. https://en.wikipedia.org/wiki/Radiative_cooling.
[23] "Stepwell." 2022. Wikipedia. https://en.wikipedia.org/wiki/Stepwell.
[24] Thermoworks. n.d. "Infrared Emissivity Table." ThermoWorks. Accessed July 8, 2022. https://www.thermoworks.com/emissivity-table/.
[25] timeanddate. n.d. "Past Weather in Bengaluru, Karnataka, India — Yesterday or Further Back." Time and Date. Accessed may, 2022. https://www.timeanddate.com/weather/india/bengaluru/historic.
[26] "Yakhchāl." 2022. Wikipedia. https://en.wikipedia.org/wiki/Yakhch%C4%81l.

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