Development of nocturnal radiative cooling system

Group Name: Shreetama Sahu (S22102769)

Pritam Choudhary (S22102754)

Karan Kumar Padhan (S22102750)

Project Supervisor: Dr. Kishore Singh Patel

Department of Mechanical Engineering

National Institute of Technology Rourkela

ABSTRACT

Radiative cooling (RC) is a passive cooling strategy that emits longwave radiation in the atmospheric window(8-13µm). RC can send waste heat generated to outer space without being trapped in the atmosphere. Earlier night-time radiative cooling has been achieved but significant day-time radiative cooling has not achieved yet. Since the naturally available RC materials have very low spectral emissive property and low solar reflectivity as compared to the recently developed nanomaterials, metamaterials, and photonic radiators. In this study we demonstrated a radiator consists of a top layer coating of TiO_2 nanoparticles and a bottom layer of SiO_2 nanoparticles over an aluminum substrate. The top TiO_2 nanoparticles layer has excellent solar reflective properties which reflects the radiation coming from the sun and atmosphere, and the bottom SiO_2 nanoparticles layer have excellent emission property which emits heat to outer space in the atmospheric window. It can achieve a few degrees Celsius below ambient during its day-time operation but during night-time under favorable condition of dry air, high humidity, and clear sky significant temperature reduction nearly 4-5 °C below ambient has been achieved with a radiative cooling potential of 88 W/m^2, conducted on a rooftop of a building. The performance of these radiators highly depends on their design features and the weather condition. Since nanoparticles are widely available so this set up can be applied to a larger area based on economy and convenient.

Keywords: Radiative cooling, longwave radiation, atmospheric window, day-time operation, night-time operation

NOMENCLATURE

SYMBOLS	NAME OF VARIABLES	UNIT
L_{in}	Atmospheric radiation	W/m^2
σ	Stefan-Boltzmann constant	Wm^2/K^4
e_s	Saturated vapor pressure	hPa
KT_d	Clearness index	-
T_a	Ambient temperature	ºC
T_r	Surface temperature of radiator	ºC
q_c	Radiative cooling potential	W/ m^2
ε	Emittance	-
λ	Wavelength	µm
θ	zenith angle	rad
τ	transmittance	-
φ	inclination angle	rad
ρ	density	Kg/m^3
α	absorptivity	-
I	Spectral radiation intensity	W/m^2. sr.µm
A	Surface area of the radiator	m^2

CHAPTER-1
INTRODUCTION

As the population density in metropolitan areas rapidly rises, so does the demand for energy for space cooling. 15% or more of a building's total energy consumption is used for space cooling. Compared to the widely used vapor compression refrigeration systems, passive cooling is a great deal simpler, more reliable, and environmentally friendly. Furthermore, a radiative cooler that is built into a photovoltaic/thermal collector might have two uses. It can supply thermal and electrical during the day and cooling energy at night. Reducing energy use, lowering carbon dioxide emissions, and supplying clean energy are the major goals. Considering that the temperature of space is 3K while the earth's surface is roughly 300K. When a body's temperature rises above 0K, radiation is released. A surface can lower its temperature by emitting long-wave infrared radiation in the atmospheric window (8–13 µm) using the passive cooling technique known as radiative cooling. It has received a lot of attention from researchers since it is a successful and sustainable method of reducing energy consumption using radiators based on widely available synthetic material such as polymers, pigmented paints, organic and inorganic films. The potential for daytime radiative cooling has been demonstrated through the creation of nanomaterials, metamaterials, and photonic radiators. In this study, we were going to demonstrate plot on yearly average state-wise variation of radiative cooling potential and investigate the experiment for the radiative cooling potential of a TiO_2 and SiO_2 nanoparticles-based radiator. Both the results from the theoretical and experiment have been compared and the effect of geographical and climate conditions on its cooling potential has been demonstrated.

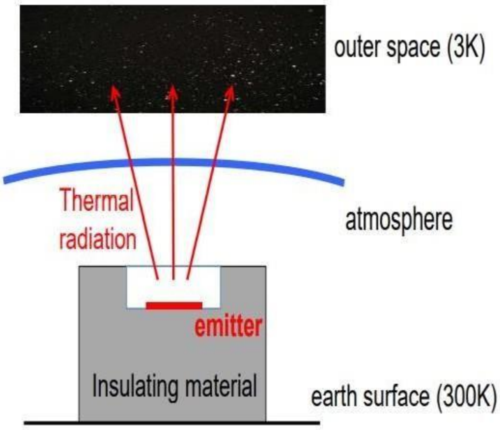

Figure1: Schematic of a simple radiative cooling device.

CHAPTER-2

LITERATURE REVIEW

Before starting the study, the following papers have been studied to understand the type of work in the field of jet flows such as-

Raman AP et al. [1] have experimentally demonstrated a sub-ambient cooling of 5 ^{o}C in presence of solar radiation on the rooftop of Stanford, California. The hafnium dioxide (HfO2) and silicon dioxide (SiO2) alternative films that make up the photonic radiator can have their thicknesses established using a complex numerical optimization approach on a silicon wafer with a silicon layer that is 750 mm thick and a silver layer that is 250 mm thick.

Chowdhary AK et al. [2] have created a radiative cooler with a cooling potential of 115 W/m^2 that can run both during the day and at night. The silver layer serving as the ground metal on an aluminum substrate is covered by a thin film of cascaded silicon dioxide and aluminum nitrate for the radiative cooler. The radiative cooler's ineffective performance during the day is its main flaw.

Nwaji GN et al. [3] have determined the radiative cooling potential at a particular location using meteorological data such as ambient temperature, saturated vapor pressure, and clearness index to determine the atmospheric radiation using some mathematical relation and a map to show the variation of radiative cooling potential for the case of Spain, Switzerland, Germany, and Sweden. The cooling potential of such a device not only depend on its design features but also on the weather condition.

Hua Bao et al. [4] have demonstrated a double-layer coating of solar reflective nanoparticles of titanium dioxide (TiO_2) and a solar selective emission layer of silicon dioxide (SiO_2) or silicon carbide (SiC) over an aluminum substrate which can achieve 17 ^{o}C and 5 ^{o}C below ambient during the night-time and daytime respectively under favorable condition of dry air, high humidity, and clear sky.

Hu M et al. [5] have purposed a concept of integration of radiative cooling technologies with existing photovoltaic/thermal (PV/T) collector to have dual functionality since both have flat plate structure. Solar PV/T collector with a simple glass cover or LDPE film can achieve nearly 9.5 ^{o}C below the ambient temperature during a clear sky nighttime operation.

Catalanotti S et al. [6] have demonstrated a PVF film coated over an evaporated aluminum has high emissivity in the atmospheric window and high reflectivity beyond that region. The polymer materials such as polyvinyl fluoride (PVF or Tedlar), polyvinyl chloride (PVC), poly methyl pentene (TPX), polydimethylsiloxane (PDMS), and polyethylene terephthalate (PET) are used for nocturnal radiative cooling. Since the polymers lose their mechanical strength the durability of these radiators is the main concern and cannot be neglected in real applications.

Michell and Biggs [7] have demonstrated an experiment by applying pigmented paint containing titanium dioxide (TiO_2) over galvanized steel to achieve radiative cooling. The estimated cooling potential was found to be 22 W/m^2 with a sub-ambient temperature of 5 ^oC below ambient temperature. Many researchers have been working on the improvement of pigmented paint film-based radiators to achieve daytime radiative cooling because it is flexible with regular paint making it more applicable for real-life applications.

Granqvist CS et al. [8] has demonstrated that silicon dioxide (SiO) coating of 1µm thickness over a highly reflecting surface like polished aluminum or silver substrate has the best cooling performance among the other inorganic coating film. Since silicon compounds are transparent to solar radiation so the solar radiation is reflected by the bottom substrate.

Zhu L et al. [9] experimentally show a thermal blackbody that is clearly transparent, based on a silica photonic crystal. Such a blackbody preserves or even significantly increases the sunlight absorption when placed on a silicon absorber exposed to sunlight, but radiative cooling lowers the temperature of the silicon absorber beneath it by up to 13 °C. By combining the idea of radiative cooling with the usage of sunlight, demonstrates how new technological possibilities can be created.

Zou C et al. [10] demonstrated dielectric resonator meta surface are hypothesized and experimentally proven improved by metal loading to obtain significant broadband thermal emission over a large angle at mid-infrared frequencies. This idea leads to passive cooling systems that can reduce temperature by 10 °C below ambient.

CHAPTER- 3

OBJECTIVES, THEORATICAL MODEL, RADIATIVE COOLING POTENTIAL MAP AND METHODOLOGY

3.1. OBJECTIVES

- To perform a theoretical radiative cooling potential map for the case of India.
- Experimental values of radiative cooling potential at a location.
- Experimental values of the temperature difference between radiator temperature and ambient temperature.
- Experimental values of the temperature difference between inlet water temperature and outlet water temperature supplied to the device.
- Comparison of experimental values and numerical values for the Rourkela climate conditions.

3.2. THEORATICAL MODEL

Radiative cooling is a passive cooling strategy that utilizes atmospheric window transmission to send waste heat into space. Consider a radiative cooler having an emissivity ε (λ, θ) at a temperature T is subjected to a clear sky during daytime its net radiative cooling potential can be determined as followed:

$$q_{net} = q_{rad}(T) - q_{sky} - q_{sun} - q_{loss} \quad (1)$$

Where $q_{net\text{-}cooling}$ is the net radiative cooling potential, W, q_{rad} is the thermal radiation potential emitted by the radiator at temperature T(K), W, q_{sky} is the absorbed infrared radiation from the sky by the radiators, W, q_{sun} is the absorbed infrared radiation from the sun by the radiator ,W, q_{loss} is the convection and conduction loss by the radiators.

$$q_{rad}(T_r) = A\,\pi \int_0^{+\infty} \int_0^{\frac{\pi}{2}} \varepsilon\,(\lambda, \theta)\ I\,(\lambda, Tr)\ \sin\,(2\theta)\ d\theta\ d\lambda \quad (2)$$

$$q_{sky} = A\,\pi \int_0^{+\infty} \int_0^{\frac{\pi}{2}} \alpha\,(\lambda, \theta)\ I\,(\lambda, T)\ \sin\,(2\theta)\ d\theta\ d\lambda \quad (3)$$

$$q_{sun} = A\,G \frac{\int_0^{+\infty} \alpha\,(\lambda,\theta)\, I\,(\lambda)\, d\lambda}{\int_0^{+\infty} I\,(\lambda)\, d\lambda} \quad (4)$$

$$q_{loss} = h\,A\,(T_a - T_r) \quad (5)$$

Where A surface area of radiator at surface temperature T_r, ε (λ, θ) denotes the spectral directional emissivity of the radiator at surface temperature T_r, I (λ, Tr) denote the spectral radiation intensity of a blackbody at temperature T_r and T_a denotes the ambient temperature.

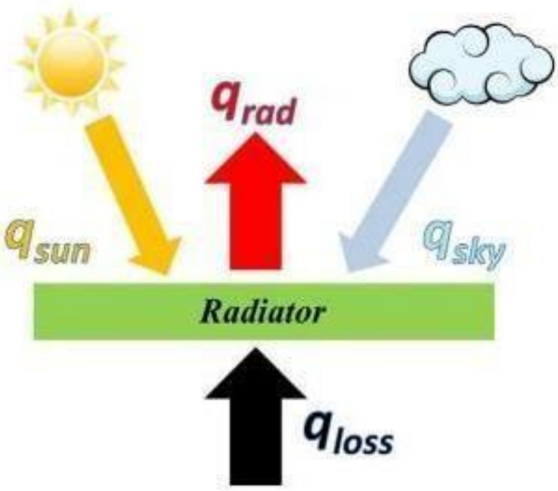

Figure 2: Energy flows of radiator. q_{sun} is the absorbed solar radiation, q_{sky} is the absorbed atmospheric radiation, q_{rad} is the thermal radiation, and q_{loss} is the intrinsic cooling loss.

3.3. RADIATIVE COOLING POTENTIAL MAP

There are certain assumptions that we consider while calculating the radiative cooling performance at a particular location for simplification that are:

- The radiating surface's spectral emissivity is not affected by temperature or angle.
- The surface temperature of the radiator is equal to the ambient temperature.
- In the temperature field, the radiating surface is homogeneous.
- The losses due to conduction and convection from the side frame of the radiating surface have been neglected.

We can use the climate data available for analysis from the Meteorological database. Where weget the data of ambient temperature, saturated vapor pressure, and clearness index for 365 days. Then we can calculate the atmospheric radiation at that location using formula 6.

$$L_{in} = \sigma \cdot [94 + 12.6 \log(100 \cdot e_s) - 13 \cdot KT_d + 0.341 \cdot (T_a + 273.15)]^4 \qquad (6)$$

Then we can calculate the ideal radiative cooling potential at that location using formula 7.

$$q_{c,ideal}(T_a) = \sigma T_a^4 - L_{in} \qquad [W/m^2] \qquad (7)$$

We use the radiative cooling potential of the different states of India to show the variation in the potential map by using QGIS software.

3.4. METHODOLOGY

To conduct the experiment, we will need a backside thermal insulator, a copper tube, a double layer nanoparticle coated radiator, and a glass cover. Insulation is provided by 25 mm thick plywood covered with 20 mm thick polystyrene on the backside. Water is circulated inside the backside thermal insulator using zig-zag copper tubes with internal diameters of 6mm. One end of the copper tube is connected to the tank from which water is drawn and the other end is connected to another tank from which water is collected. A 2 mm thick aluminum sheet coated with bottom layer of silicon dioxide (SiO_2) having a thickness of 1µm and a top layer of titanium dioxide (TiO_2) having a thickness of 1µm is placed over the copper tube. The glass cover is placed at the top of back side thermal insulator having an airgap of thickness 50 mm. The coating of the nanoparticles over the aluminum sheet is done by using plasma-spray coating where the power of coating material is melted by using a plasma jet having a temperature around 10000K and sprayed uniformly over the aluminum sheet to make the radiator.

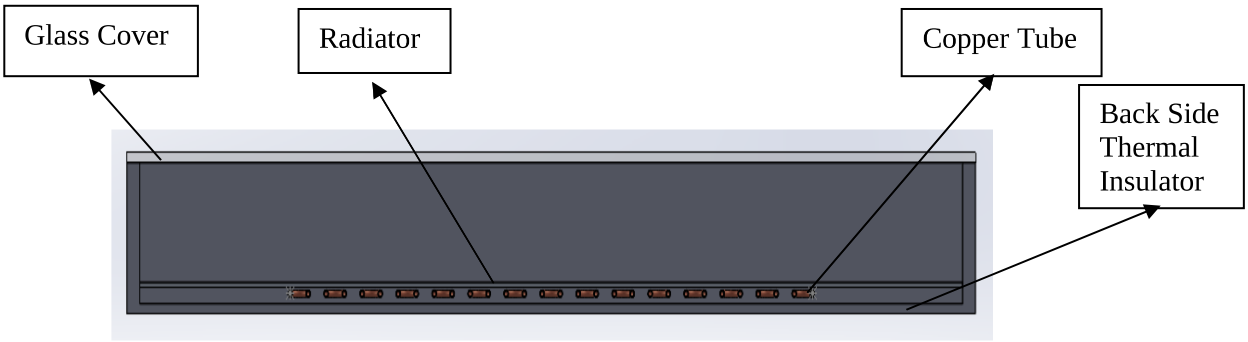

Figure 3: Schematic diagram of a nocturnal radiative cooling device.

Figure 4: Experimental setup of radiative cooling potential device.

During working condition, we supply water from a tank to one end of the copper tube, the heat transfer takes place from water to the copper tube due to heat conduction and convection. Since the radiator is connected to the copper tube heat is further transfer to the radiator. Finally, the radiator dumps the heat in space at the outlet of copper tube we get water having a lower temperature as compared to the inlet. The function of glass cover and airgap is to reduce the effect of surrounding convective heat transfer to the system and the function of copper tube is circulated the water. The back side thermal insulator is used to reduce the heat conduction from the roof to the system and the radiator is used to radiate heat in the form of infrared radiation into the space.

To calculate the experimental value of radiative cooling potential at Rourkela climatical condition we measure the inlet water temperature (T_i), outlet water temperature (T_o), ambient temperature (T_a) and radiator temperature (T_r) with the help of a K type thermocouple with four probes.

$$Quseful = \dot{m}S\ (T_i - T_o) \tag{8}$$

Where, ṁ is the mass flow rate of water in Kg/s.

S is the specific heat capacity of water in J/Kg K

We can get the maximum useful radiative cooling potential when the outlet water temperature is equal to the radiator temperature.

$$Qmax = \dot{m}S\ (T_i - T_r) \tag{9}$$

To get the effectiveness (ε) of the radiative cooling device we divide $Quseful$ by $Qmax$.

$$\varepsilon = \frac{Quseful}{Qmax} \tag{10}$$

CHAPTER-4

RESULTS AND DISCUSSION

4.1. RADIATIVE COOLING POTENTIAL MAP

The state-wise variation of average yearly radiative cooling potential has been calculated using ambient temperature, saturated vapor pressure, clearness index and atmospheric radiation data for 365 days. This map also demonstrates the dependence of radiative cooling potential based on geographical and climatical condition. States having lower values of clearness index or higher value of cloudiness have lower radiative cooling potential as we can see in Jammu and Kashmir, Sikkim, and Meghalaya. States having higher values of clearness index or lower value of cloudiness have higher radiative cooling potential as we can see in Tamil Nādu, Gujarat, and Kerala.

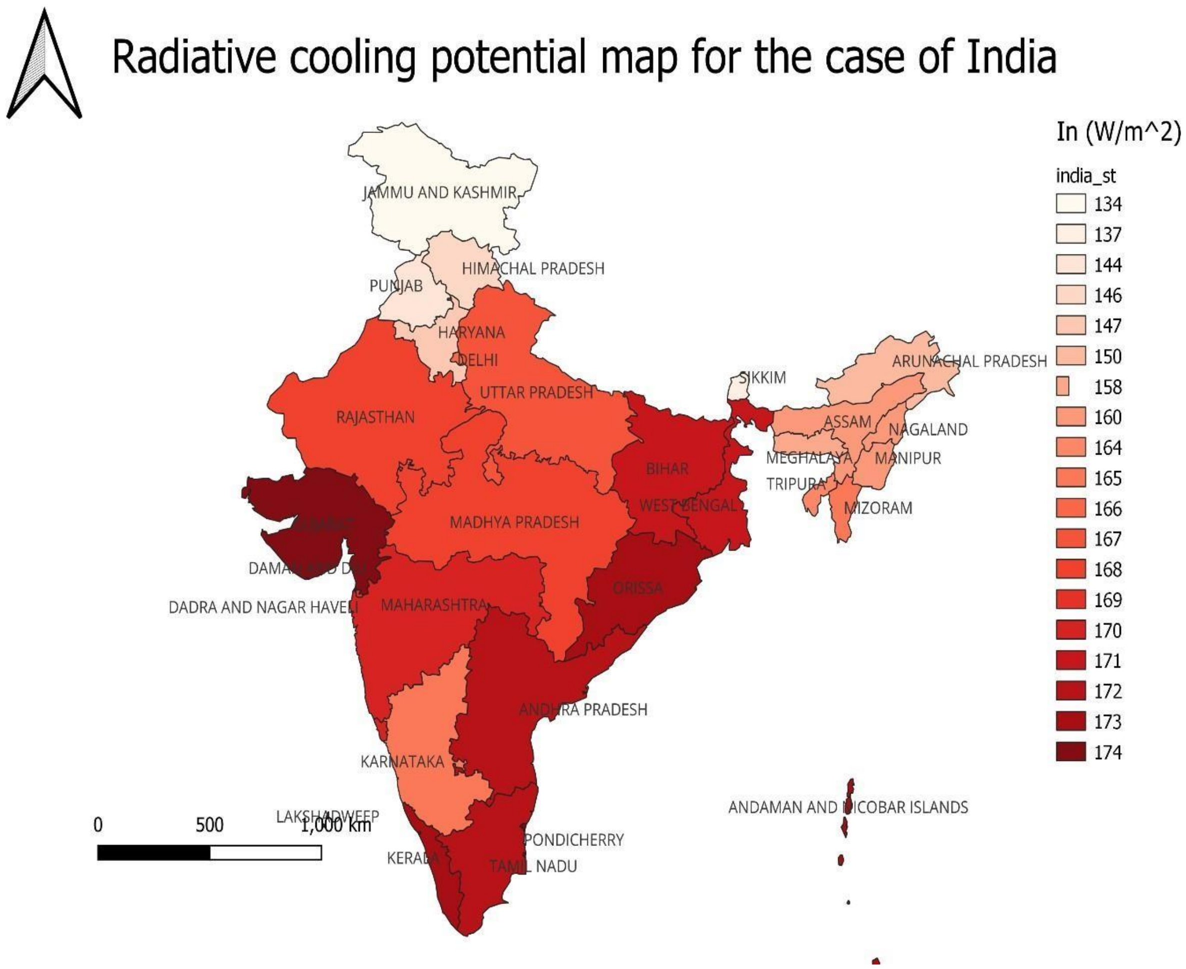

Figure 5: State-wise variation of average yearly radiative cooling potential for the case of India.

4.2. TEMPERATURE DIFFERANCE

From the experimental setup a shown in Figure 3, we can get the ambient temperature, inlet water temperature, outlet water temperature and radiator surface temperature. The double layer nanoparticles coated radiator can reached 4-5 ^{o}C below the ambient temperature on a clear sky night under some favorable climate condition and it can cool the water 2-3 ^{o}C lower than the inlet water temperature. All these temperatures are measured using a K type thermocouple with a limit of ±1.10 ^{o}C or ±0.4%. It can be noted that as the sunset the water and ambient temperature decreases similarly the radiator temperature also decreases making it more efficient. These graphs show the variation of temperatures from 8 PM to 4 AM in an interval of one hour.

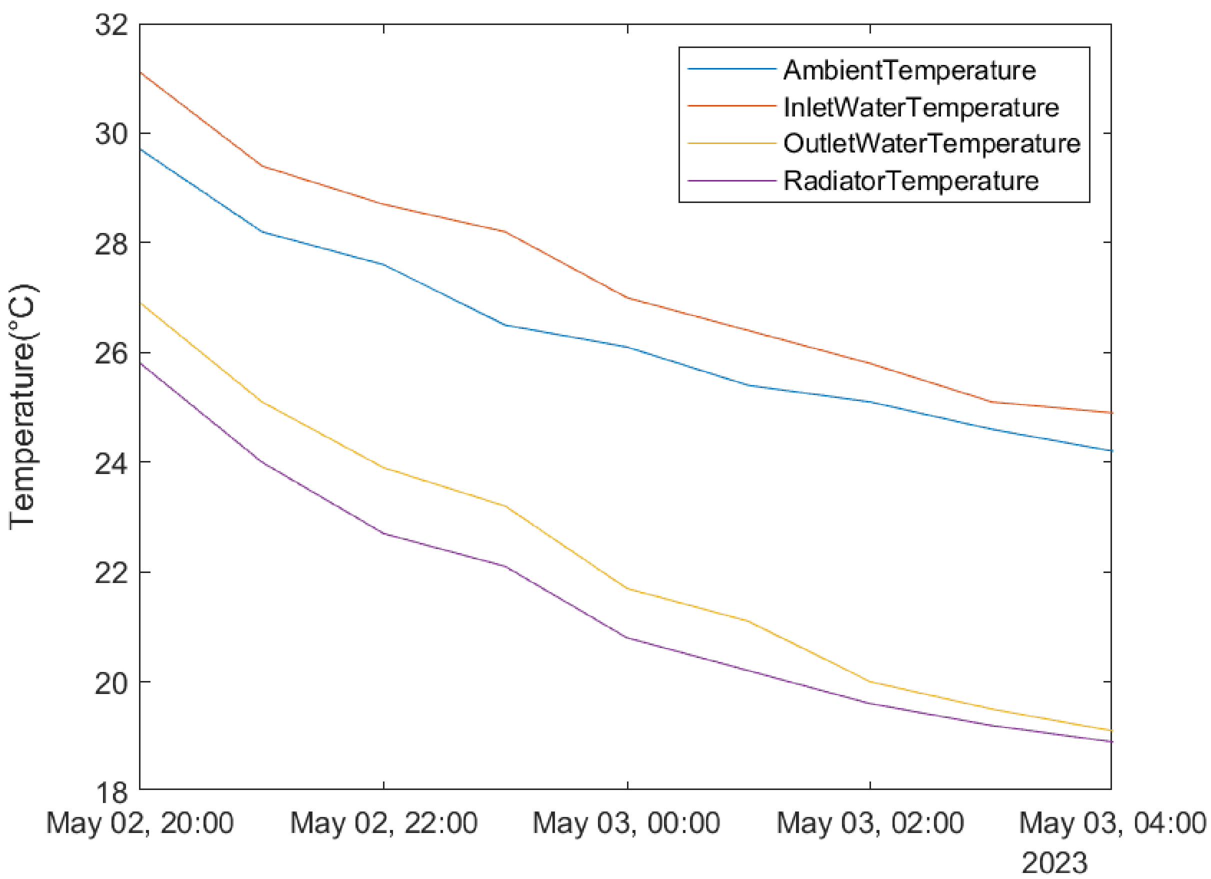

Figure 6: Temperature difference on date 02.05.2023.

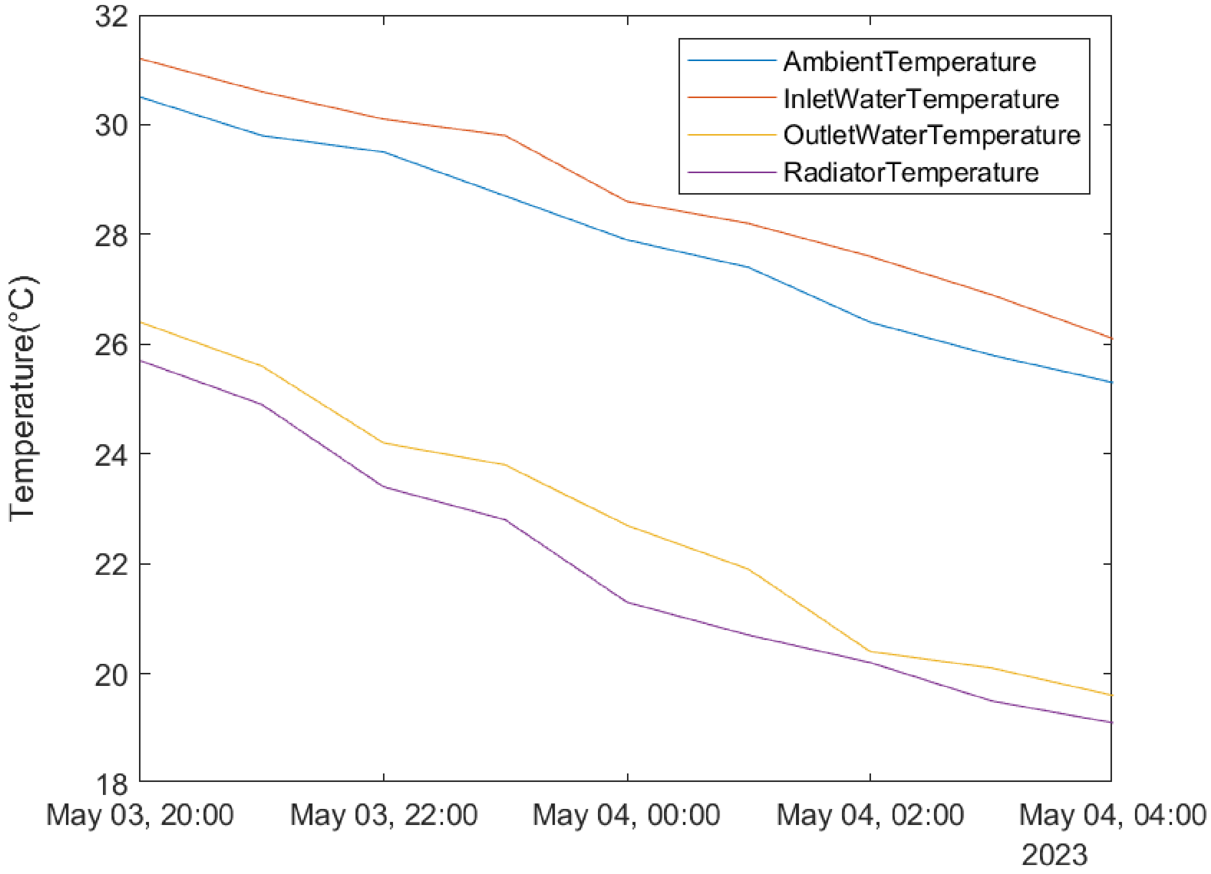

Figure 7: Temperature difference on date 03.05.2023.

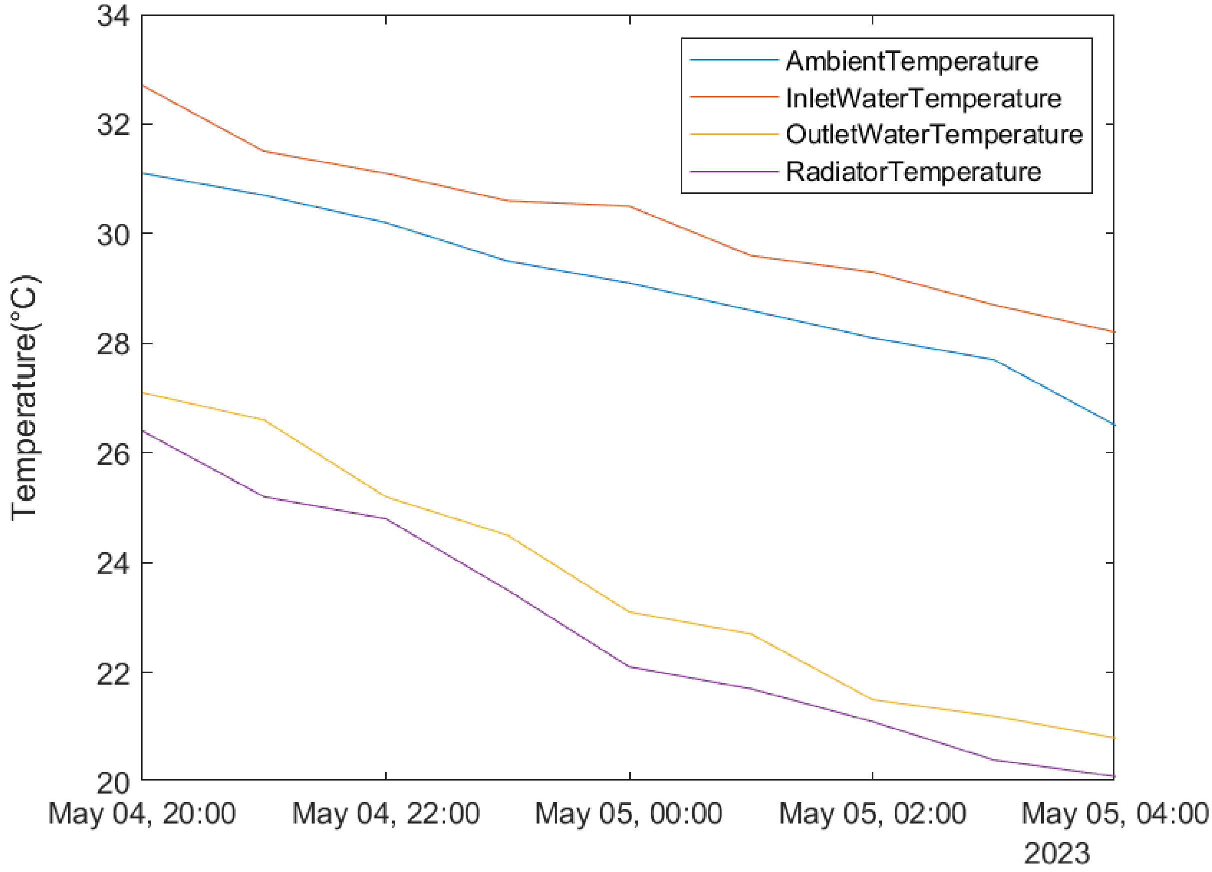

Figure 8: Temperature difference on date 04.05.2023.

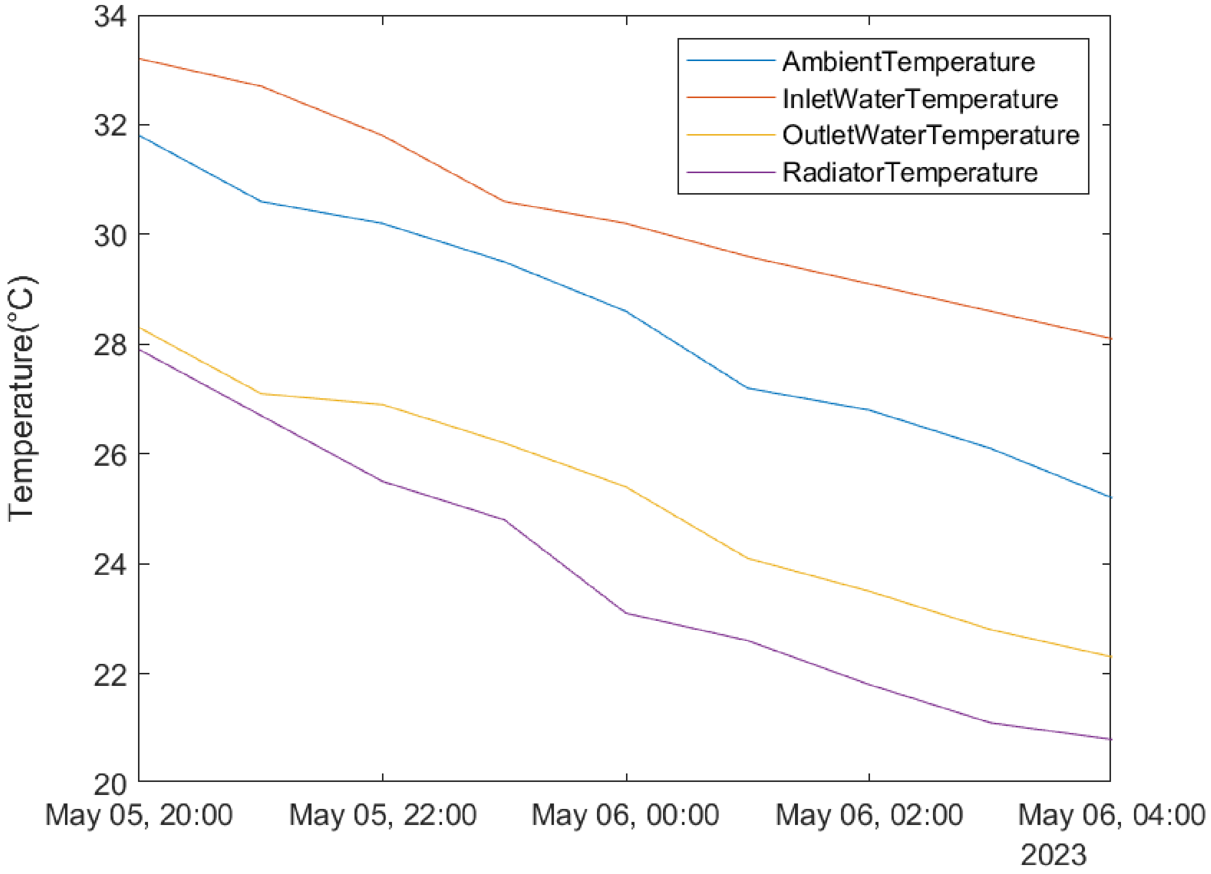

Figure 9: Temperature difference on date 05.05.2023.

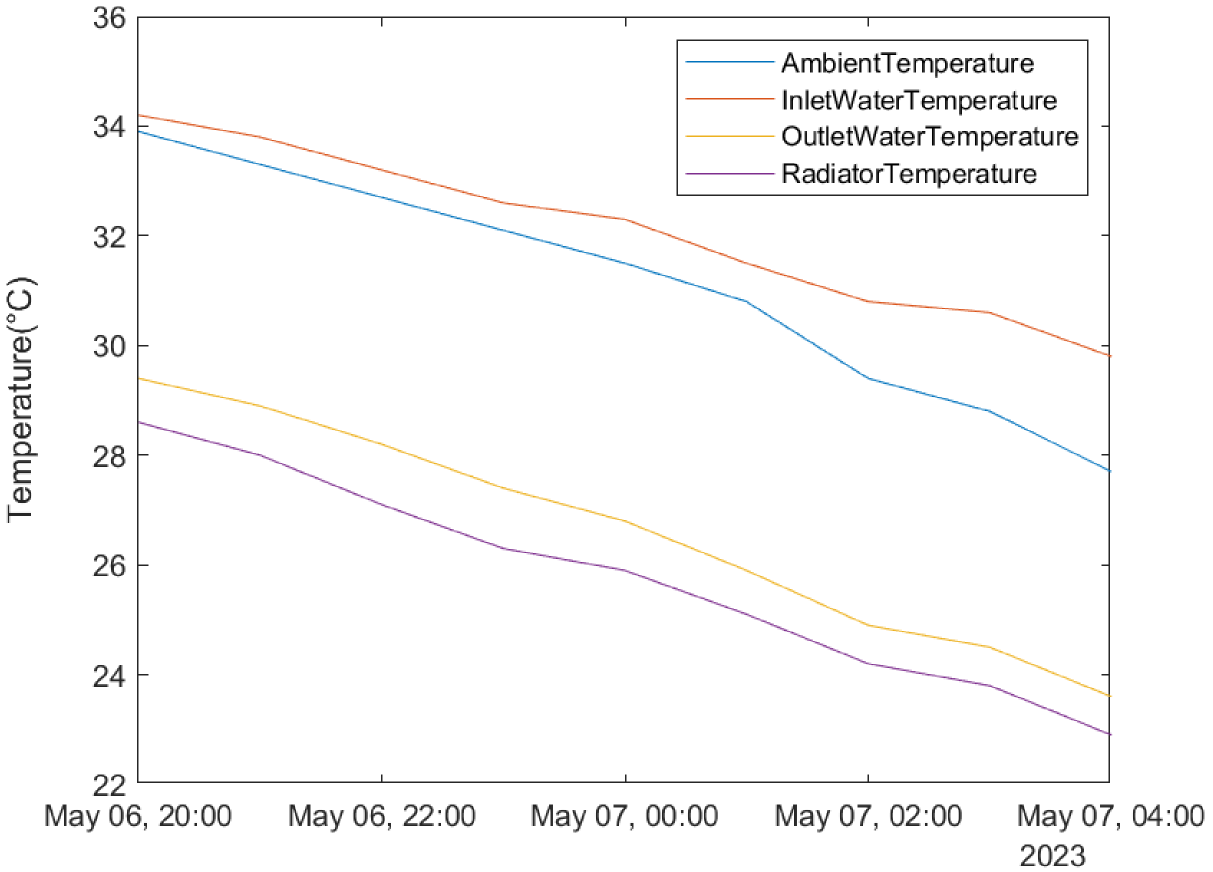

Figure 10: Temperature difference on date 06.05.2023.

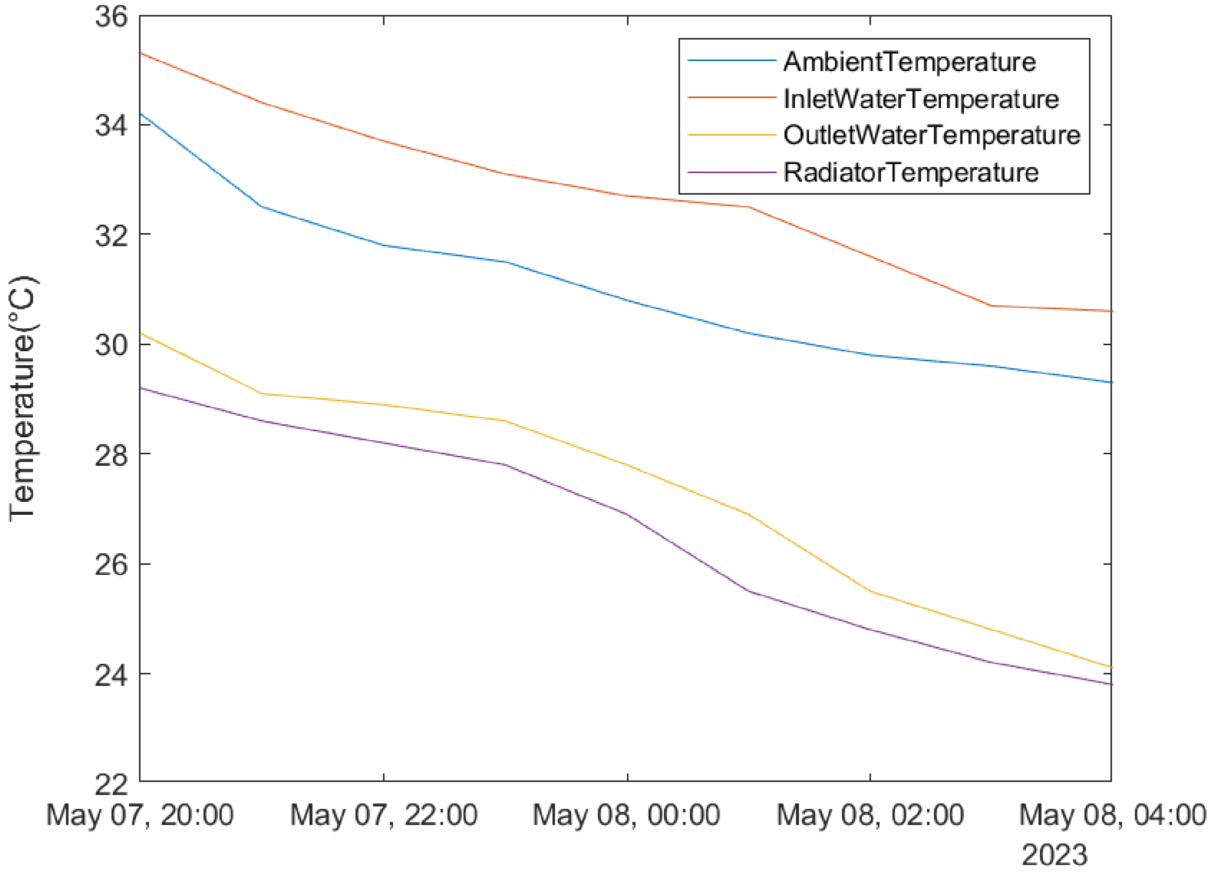

Figure 11: Temperature difference on date 07.05.2023.

4.3. RADIATIVE COOLING POTENTIAL

The experimental value of radiative cooling potential was obtained by using equation 8. Under some favorable climate condition and clear night sky the double layer nanoparticles coated radiator can reached a radiative cooling potential up to 88 W/m^2 during its nighttime operation in the absence of solar radiation. The effective of the double layer nanoparticle coated radiator was obtained to be 77.67% using equation 10. From the graphs we can conclude that the radiative cooling potential generally increases as the earth temperature reduces due to the absence of solar radiation. During daytime the radiator temperature would become higher than the ambient temperature as the radiation coming from the sun is higher order as compared to the radiation emitted by the radiator. It can be also noted that when the temperature is high, and sky is clear its radiative cooling potential increases.

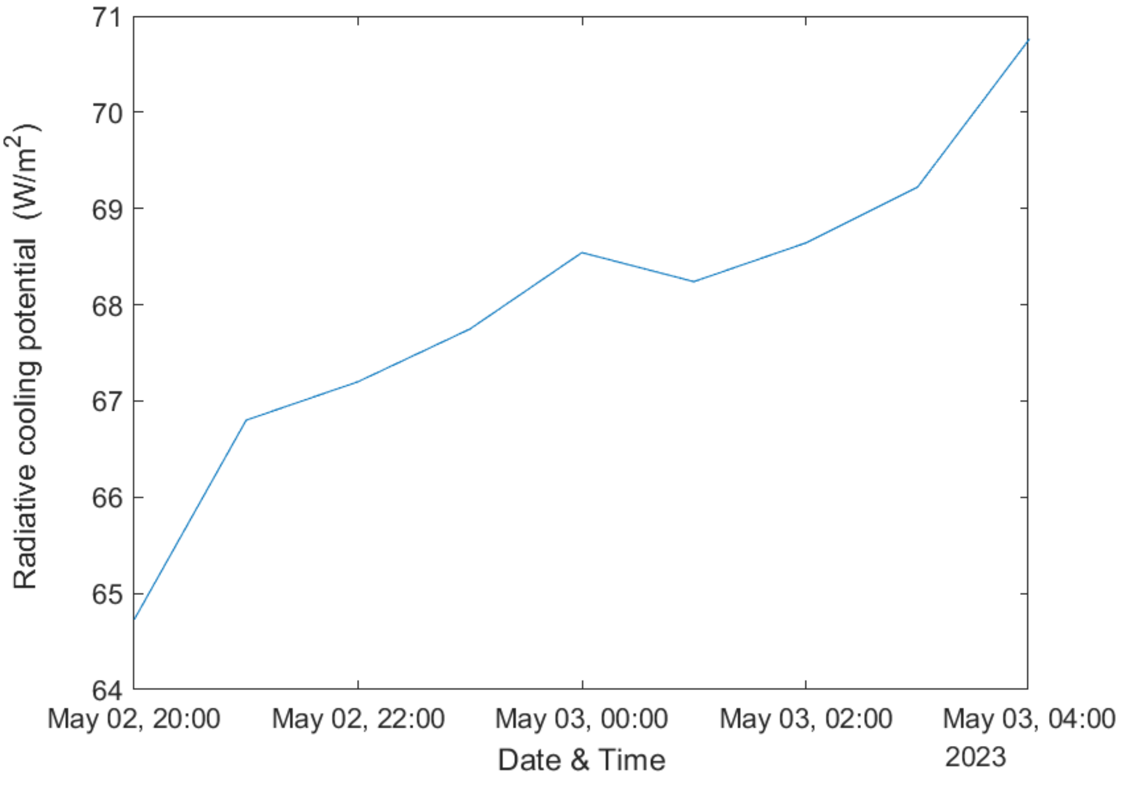

Figure 12: Experimental value of radiative cooling potential in Rourkela climate condition.

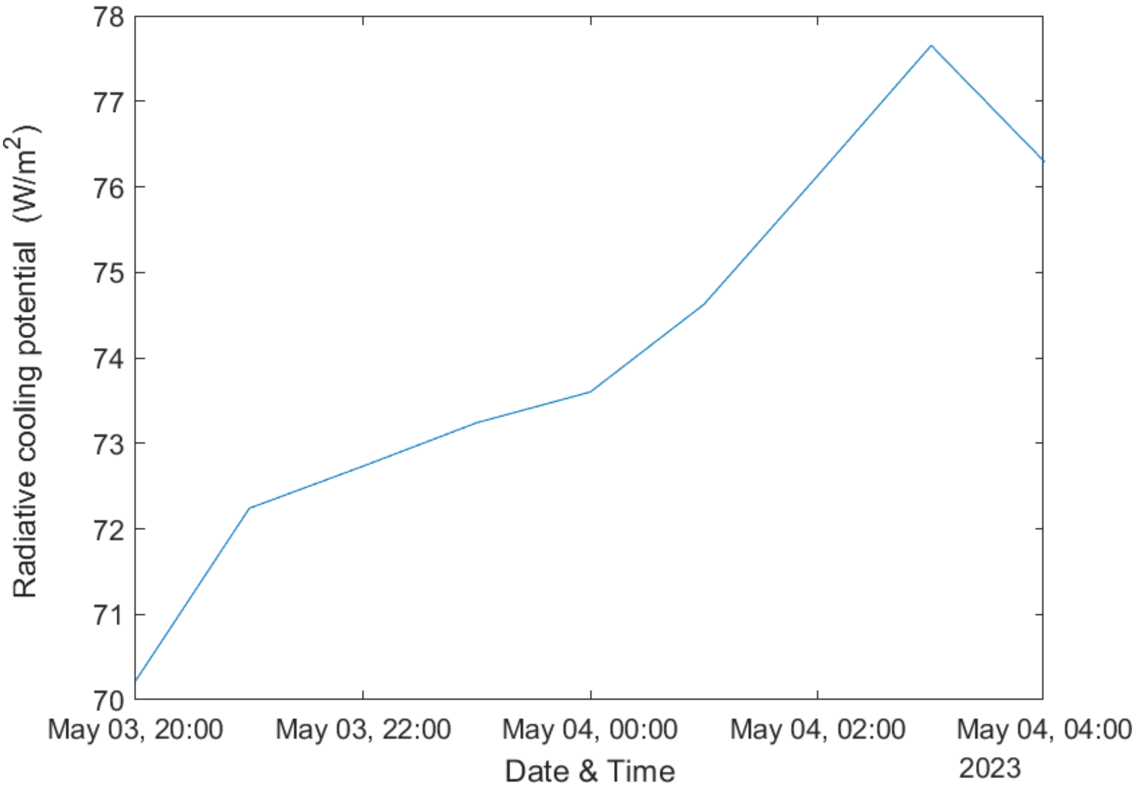

Figure 13: Experimental value of radiative cooling potential in Rourkela climate condition.

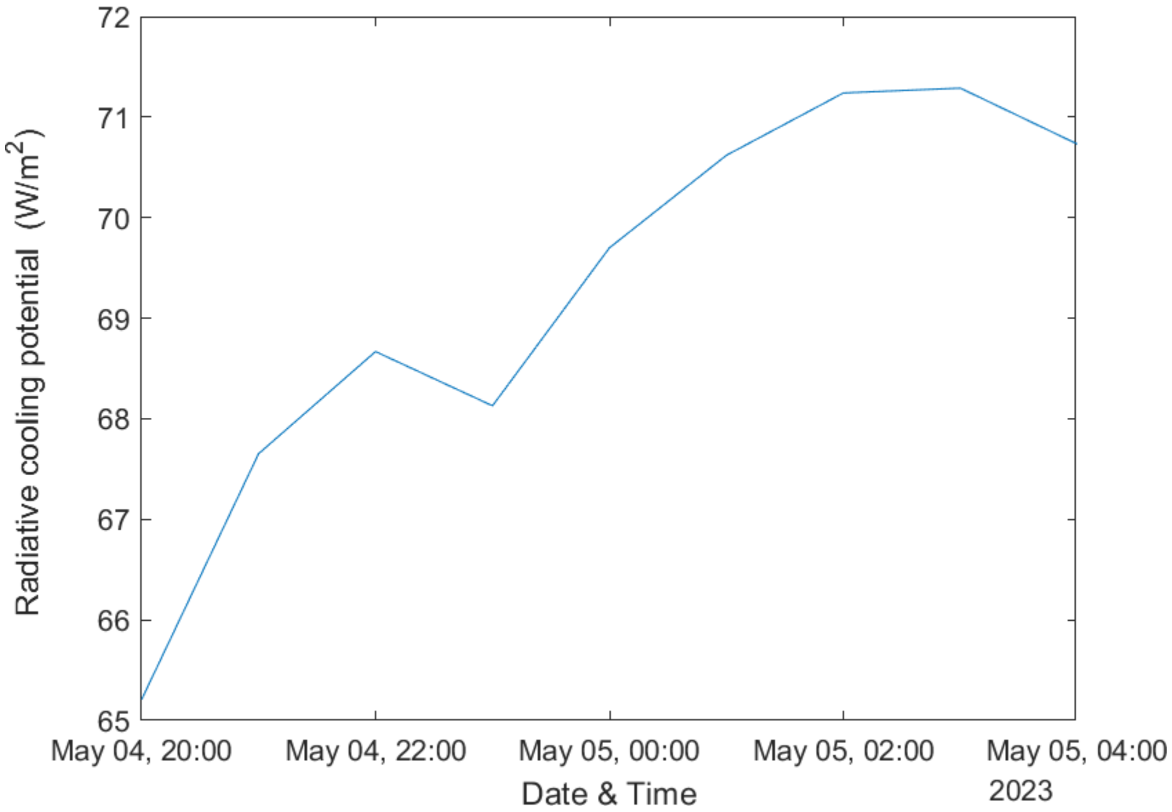

Figure 14: Experimental value of radiative cooling potential in Rourkela climate condition.

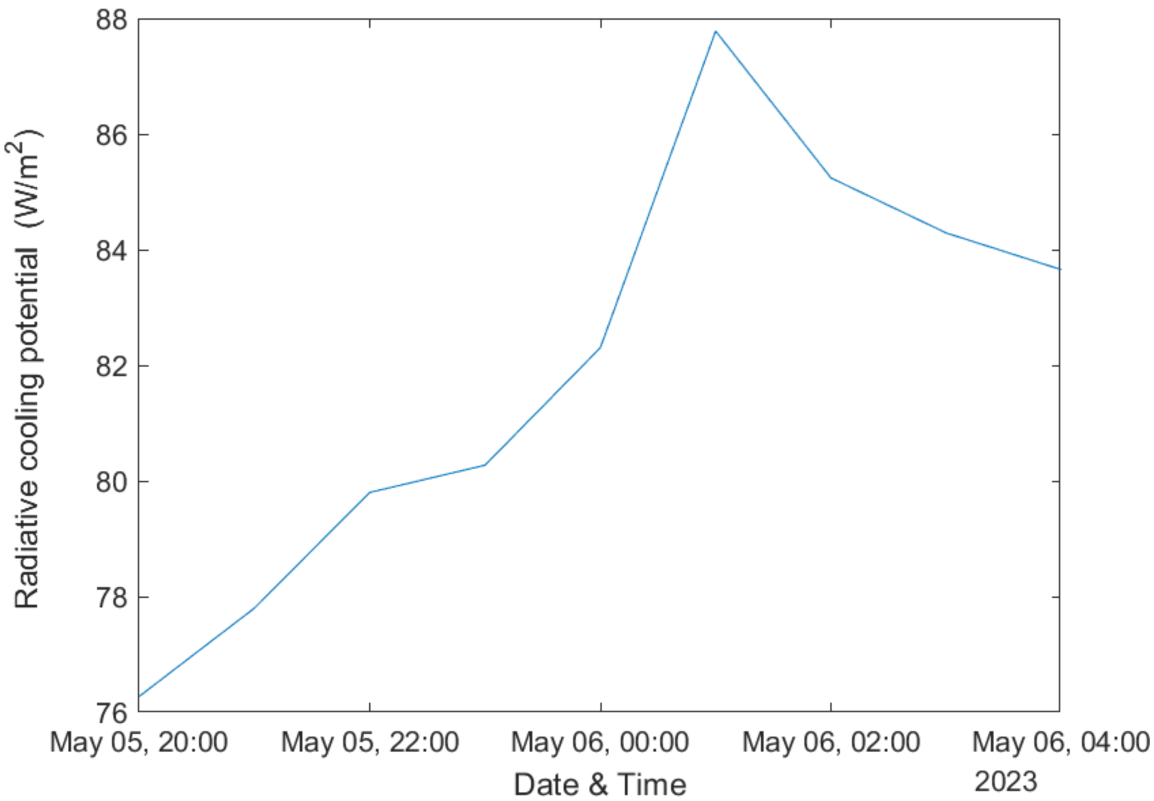

Figure 15: Experimental value of radiative cooling potential in Rourkela climate condition.

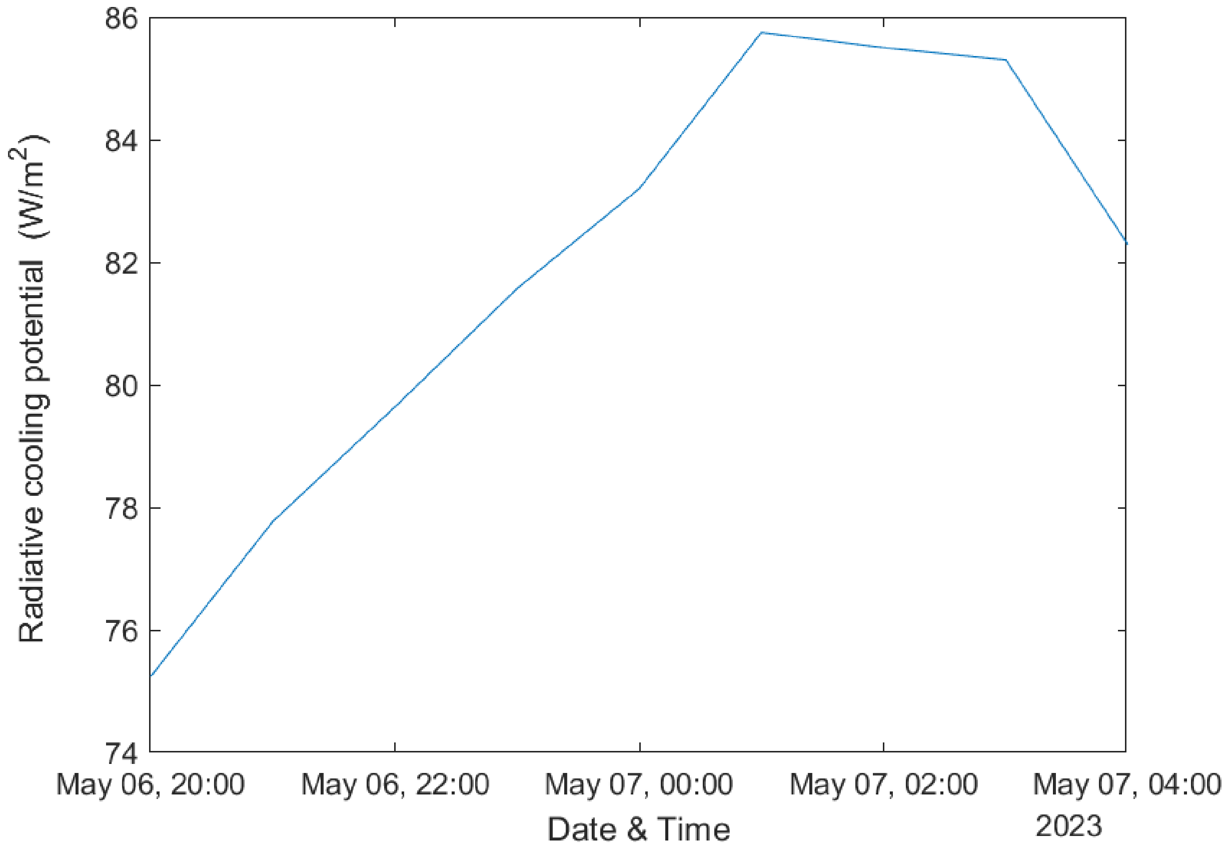

Figure 16: Experimental value of radiative cooling potential in Rourkela climate condition.

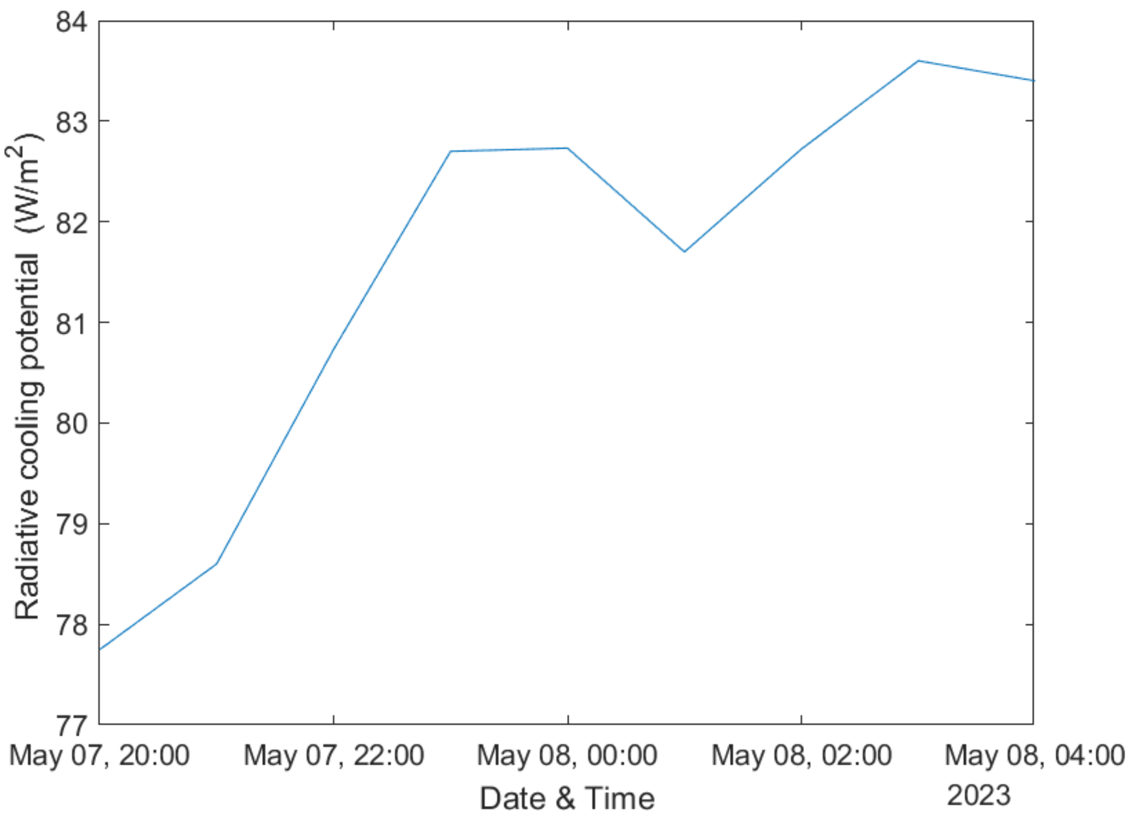

Figure 17: Experimental value of radiative cooling potential in Rourkela climate condition.

CHAPTER-5

CONCLUSIONS AND FUTURE SCOPE

CONCLUSION:

In the present study, we demonstrated a theoretical approach to determine state-wise variation of the radiative cooling potential using meteorological data such as ambient temperature, saturated vapor pressure, clearness index and atmospheric radiation. Then we demonstrated an experimental analysis on double layer of TiO_2 and SiO_2 nanoparticles coated radiator in Rourkela climate condition. The radiator can reach 4-5 ^oC below the ambient temperature and can reached a radiative cooling potential of 88 W/m^2 during its overall nighttime operation in the absence of solar radiation. The effectiveness of the radiator was found to be 77.67%. The variation in the radiative cooling potential map shows the dependency of radiative cooling potential on geographical and climate condition.

FUTURE SCOPE:

A few modifications in the given experiment will allow to have experimental investigations such as:

- Radiative cooling device is used as a cooling tower in vapor compression refrigeration systemto improve overall efficiency.
- Integration of radiative cooling device into the existing photovoltaic/thermal collector to have dual functionality.

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