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# Investigation of Temperature Reducing Performances of Passive Daytime Cooling Materials under Outdoor Conditions

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## Abstract

Due to the rapid depletion of conventional energy sources and rising fuel and energy costs, efforts to reduce energy consumption have increased rapidly in recent years. Research shows that a significant portion of the total energy used in buildings (20% - 40%) is spent on cooling. The high production and operating costs of existing cooling systems, as well as their long-term harmful effects on the environment and human health, have led to alternative solutions that can reduce their use. One such solution is the development of materials that can reduce the heat generated by solar energy in buildings. These materials are called Passive Daytime Radiative Cooling (PDRC) materials, which, in principle, dissipate heat caused by solar energy into the environment as thermal radiation (specifically through the atmospheric infrared window between 8 μm and 13 μm), and therefore can significantly reduce the use of existing cooling systems. In this work, the cooling performances of three different PDRC materials in the field were investigated. The measurements were carried out in Kocaeli/Türkiye, where it has a Mediterranean and oceanic climate, between June and September under the influence of solar irradiance, ambient temperature, and wind speed. It was observed that PDCR materials reduced temperatures by within 4˚C - 8˚C with an uncertainty of approximately 10%.

## Keywords

PDRC, Cooling, Solar Energy

## 1. Introduction

Research shows that cooling accounts for the largest share of residential energy consumption. Due to the rapidly increasing world population, constantly changing and evolving living conditions, global warming, etc., this energy consumption tends to increase, and this situation results in higher energy demands [1]. In order to meet this ever-increasing energy demand and prevent it from becoming a major problem in the future, in addition to the research on renewable alternative energy sources, the work on solutions that can directly reduce the need for cooling is increasing. Among the solutions developed in this context, the use of Passive Daytime Radiative Cooling (PDRC) materials in residential buildings has become a very popular topic. The PDRC materials provide cooling without electrical energy input and therefore have a significant impact on global energy consumption [2]-[6]. These PDRC materials basically have a high reflectivity in solar region (250 nm - 2500 nm) and they have the ability to radiate the heat, which can be generated in their structures due to the absorbed solar radiation and ambient temperature, into the atmospheric infrared region (8 - 13 mm) [2] [7]. As a result, they can keep the materials relatively cooler by approximately 3% to 8% compared to other coatings.

Due to these properties, studies on the usability of PDRC materials in various sectors in many applications, such as roofs, walls, windows, paints, textiles, etc., are increasing rapidly [8]. In order to use these PDRC materials in the specified applications, their heat reduction performance must be investigated and measurable results must be revealed. In this context, numerous methods have been developed to investigate the thermal and optical properties and cooling performances of these PDRC materials [9]-[15]. However, even though these methods provide important information for the heat-reducing performance parameters of PDRC materials, they are not sufficient for commercialization [16]-[18]. Therefore, a systematic and comprehensive work is required to develop reliable test protocols to determine the performance properties (cooling properties) of PDRC materials.

Because of this vital need, within the “European Partnership on Metrology” programme, a project work whose name is Metrological Framework for Passive Radiative Cooling Technologies (21GRD03 PaRaMetriC) [19], was realized with the involvement of large number of participants from National Metrology Institutes, research and development centers, universities and companies.

The overall goal of the PaRaMetriC project is to establish a metrological framework for the evaluation of passive radiative cooling technologies in order to enable their comparison. This will require the identification of suitable figures of merit as performance indicators, together with the definition of standardized testing conditions and protocols.

In this work, in order to carry out temperature reducing performance measurements of PDRC materials, an outdoor measurement system having a meteorological station consisting of irradiance, ambient temperature, wind speed and direction sensors, a thermally isolated sample test box, and the data acquisition and logging units was established in TUBITAK UME. The tasks handled within the content of this work covers description of measurement system and measurement of temperature reducing ability with metrological parameters.

## 2. Materials and Method

### 2.1. Description of PDRC Materials and Measurement System

Passive daytime radiative cooling (PDRC) is commercially available paints and coating materials having high reflective and thermally-emissive surfaces which lower the temperature of any object where they are coated. In this work, three PDRC materials with thin film coatings manufactured by different companies were investigated.

The setup shown in Figure 1 was established to measure the temperature reducing performance of PDRC materials in outdoor environment. The measurement system, comprise a meteorological station consisting of irradiance, ambient temperature, wind speed and direction sensors, a thermally isolated sample test box, the data acquisition and logging units.

The whole system was installed on the roof of a two-floor building, away from any obstacles that could affect wind speed and irradiance. Locations of the sensors of meteorological station were determined according to standard that have been used for similar application (determining the temperature of photovoltaic modules) [20]. The supporting system as shown in the left side of Figure 1, used to mount the sensors and a thermally isolated sample test box, is designed such a way that (above 0.6 m local horizontal plane or ground level), it minimizes heat conduction and the interference of heat between sensors and the thermally isolated sample test box. The pyranometer was mounted to the supporting system almost within 0.3 m in the plane of the thermally isolated sample test box, the wind speed sensor and ambient temperature sensor were installed approximately 0.7 m above the top of thermally isolated sample test box in a position where it will not shade the PDRC materials.

The thermally isolated sample test box constructed for the temperature reducing performance measurements of PDRC materials is shown in the upper right section of Figure 1, and has two sections, each with 40 cm × 40 cm × 25 cm dimensions. To achieve high insulation, this thermally isolated sample test box was made from foam, covered with glass wool and wood. One of the sections in this thermally isolated sample test box is used for the temperature measurements of substrate, and another one is used for the temperature measurements of substrate + PDRC materials. The substrate used for these tests is an aluminum with a 1 mm thickness. This aluminum has an emissivity range from 0.09 to 0.24 and thermal conductivity of 237 $W \cdot m^{-1} \cdot K^{-1}$.

In each section of the thermally isolated sample test box, two Pt 100 temperature sensors are located. One of these sensors was attached just under the samples, another one was hang inside the empty space as shown on the right lower side of Figure 1.

In this measurement system, two data acquisition and recording units were used. One was used to collect and record data from the irradiance, ambient temperature and wind speed sensors, and the other was used to collect and record data from the temperature sensors inside the thermally isolated sample test box. Before the measurements, the calibrations of all sensors used in this system were carried out at the National Metrology Institute of Türkiye, which is called UME.

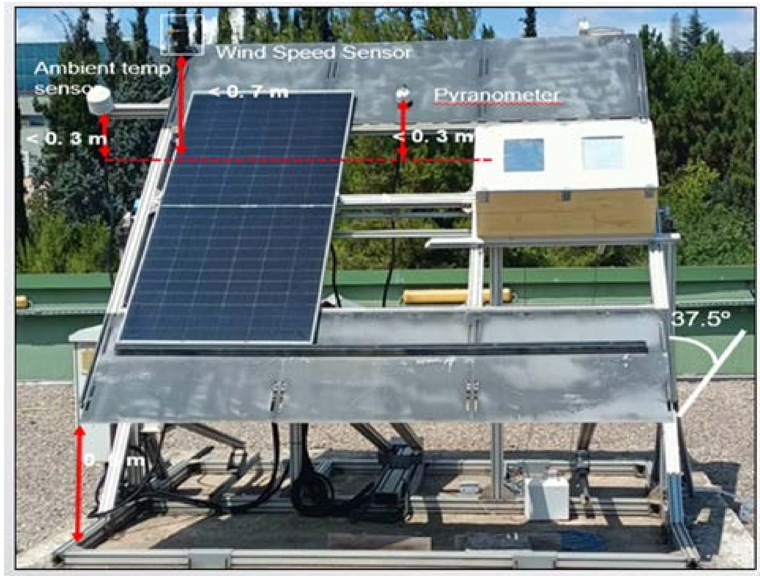



Figure 1. Outdoor temperature reducing measurement facility.

## 2.2. Measurement of Temperature Reducing Ability with Metrological Parameters

In this work, the temperature reducing capacity of three different Passive Daytime Radiative Cooling materials was measured. Before the measurements, the calibrations of all sensors used in this system were carried out at the National Metrology Institute of Türkiye, which is called UME. At the measurement stage, initially insulation capabilities of the sections in the thermally isolated sample test box, and then the offset differences in the sensors used in these measurements were investigated. After that, each time a pair of samples shown in Figure 2 was placed in the sample holders of thermally isolated sample test boxes, and the measurements were performed.

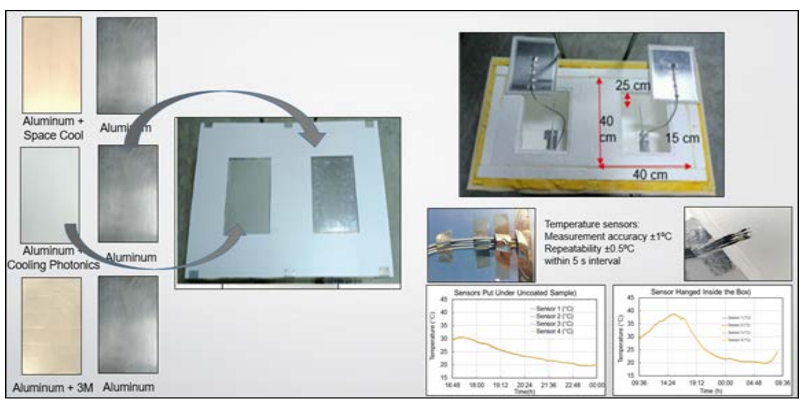



Figure 2. Thermally isolated sample test box, replacement of PDRC materials and characterization of temperature sensors.

The data generated both from the meteorological sensors (irradiance, ambient temperature and wind speed sensors) and the temperature sensors (Pt100) from the thermally isolated sample test box were measured by the related data acquisition and recording units. The measurements with the measurement system set to 0˚ inclination angle were carried out between June and July, and the measurements with the measurement system set to 37.5˚ inclination angle were carried out between August and September. The reason for choosing 0˚ and 37.5˚ inclination angles are; roof of the buildings are either straight (have 0˚ inclination angle) or tilted between 0˚ and 40˚ inclination angles. The 37.5˚ inclination angle is standardized for photovoltaic applications. Therefore, in this work test measurements were performed 0˚ and 37.5˚ inclination angles and the results are compared for the performance evaluation. The measurement results obtained for all PDRC materials are given in Figures 3-5.

## 3. Results and Discussions

The graphs in Figures 3-8 show the measurement results for the temperature reducing performance of PDRC materials. In these measurement results the graphs on the upper left side show the temperature values recorded by the temperature sensors indicated in Figure 2. In these graphs, the data shown in red and red colors represent, respectively, the temperature values obtained with the sensors attached to under the aluminum and hung inside thermally insulated sample test box in aluminum side. On the other hand, the data shown in dark blue and blue colors are the temperature values obtained with the sensor attached to under the aluminum + PDRC material and hung inside thermally insulated sample test box in aluminum + PDRC material side. As can be seen from these graphs, the temperatures in the section where the aluminum is located, that is, the section without PDRC coating, are higher than the temperatures in the section where the aluminum + PDRC is located, that is, the section with PDRC coating. These data demonstrate that PDRC materials exhibit passive cooling, meaning they conduct heat away from the material’s structure, resulting in relatively less heating. Moreover, these data also demonstrate the effects of factors such as irradiance, wind speed, and ambient temperature on PDRC material performance.

In the graphs in Figures 3-8, the graph on the upper right shows the changes in irradiance, the graph on the middle left shows the changes in wind speed, and the graph on the middle right shows the changes in ambient temperature during the measurement period. Comparing the graphs of temperature data with the graphs of ambient conditions, the fluctuations in irradiance cause temperatures to increase, while fluctuations in wind speed cause temperatures to decrease.

In order to investigate the effect of inclination angle on the temperature of PDRC materials, measurements were performed in two different inclination angles (0˚ and 37.5˚). The graphs in Figures 3-8 are the results of measurements taken at two different inclination angles for each PDRC material. Comparing the measurement results carried out for all the PDRC materials it is seen that the temperatures in the measurements conducted at 37.5˚ inclination angle are higher than those in the measurements conducted at the 0˚ inclination angle. This effect may be related to difference of irradiance levels on the earth's surface.

The temperatures measured by sensors are temperatures formed under the influence of various environmental factors. The relation between the measured temperatures of sensors with environmental conditions, can be shown as given in Equation (1) [21].

$$T_m = T_{amb} + G/(u_0 + u_1.v) \quad (1)$$

where, $T_m$ is the temperature of the measured device, $T_{amb}$ is the ambient temperature, $G$ is the total solar irradiance incident on the active surface of the device, $v$ is the wind speed, $u_0$ and $u_1$ are the coefficients, respectively describes the influence of the irradiance and the wind impact on the temperature.

Using Equation (1), the temperatures of PDRC materials at any temperature, irradiance, ambient temperature and wind speed can be estimated, provided that $u_0$ and $u_1$ coefficients are known. These coefficients can be derived from the slope and axis intercept points of $G/(T_m - T_{amb})$ versus wind speed ($v$) graph obtained from the measurement data.

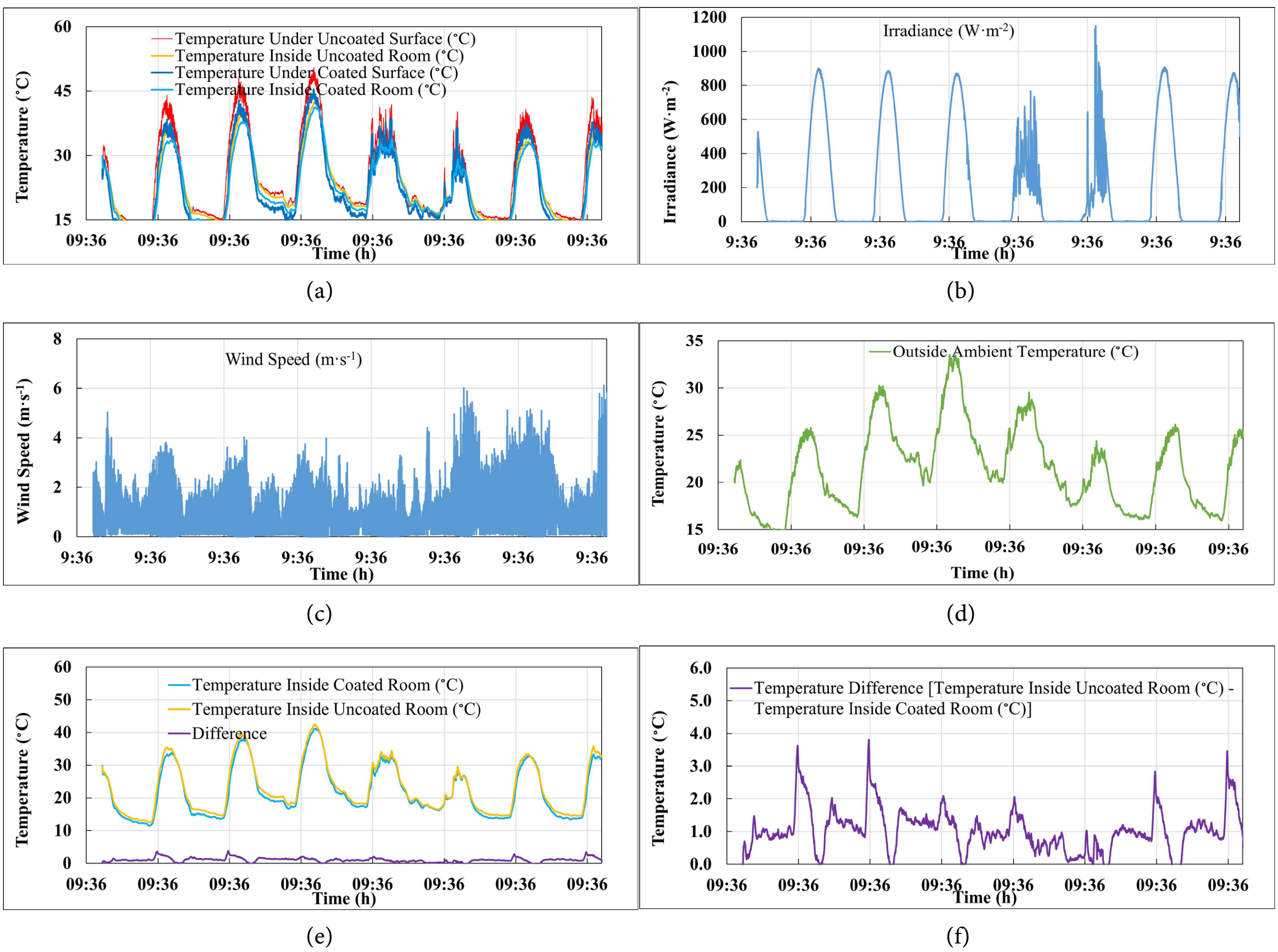



**Figure 3.** Temperature reducing capacity of PDRC material1 at 0˚ inclination angle.

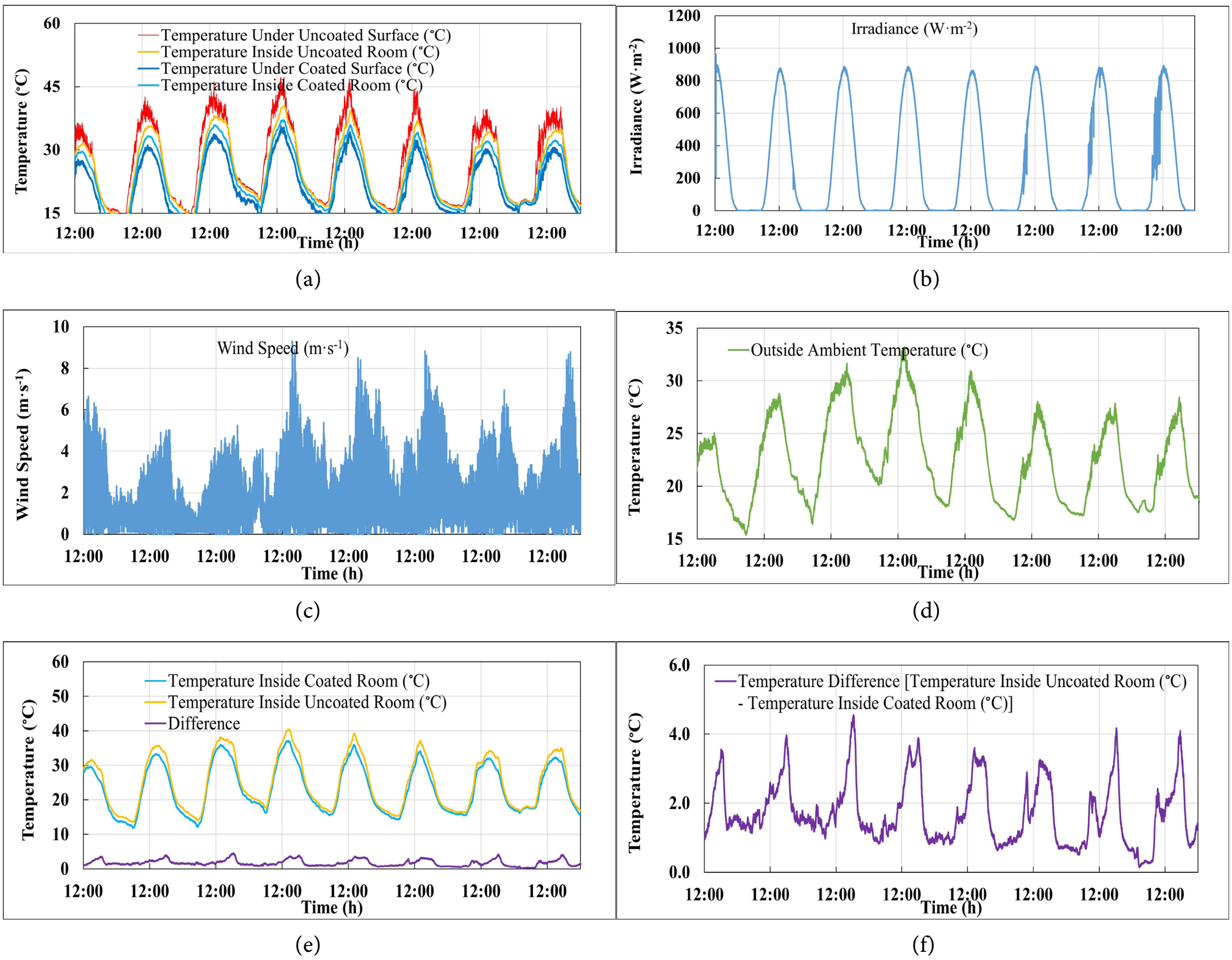
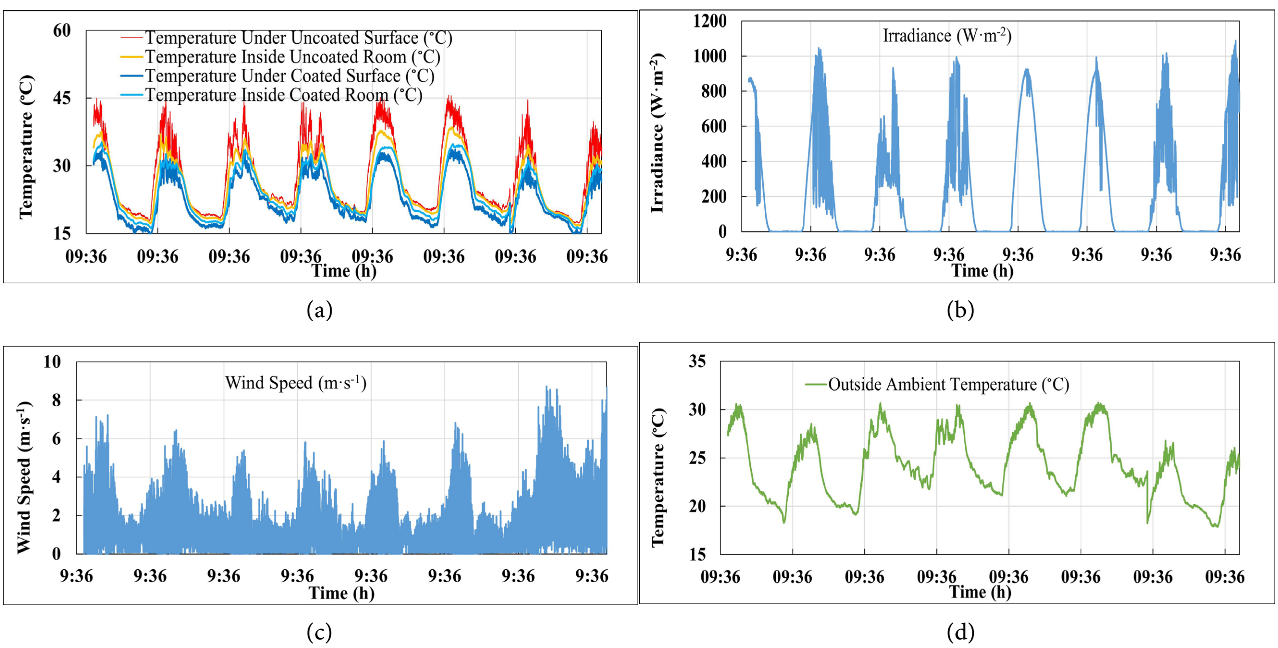



**Figure 4.** Temperature reducing capacity of PDRC material1 at 37.5˚ inclination angle.



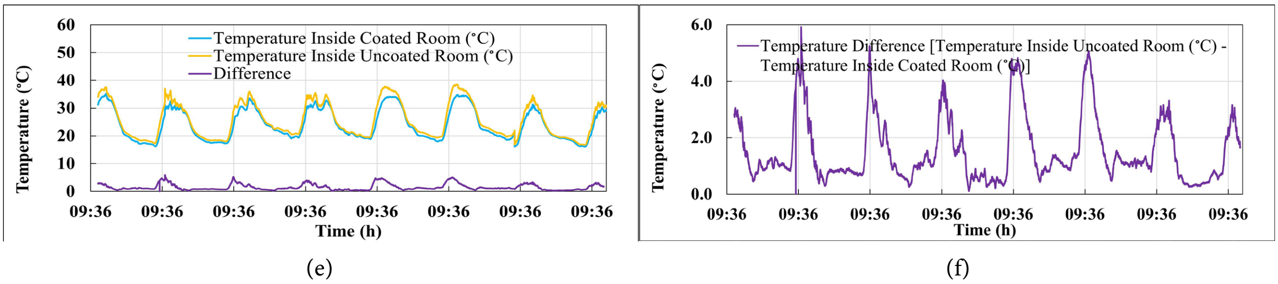



**Figure 5.** Temperature reducing capacity of PDRC material2 at 0˚ inclination angle.

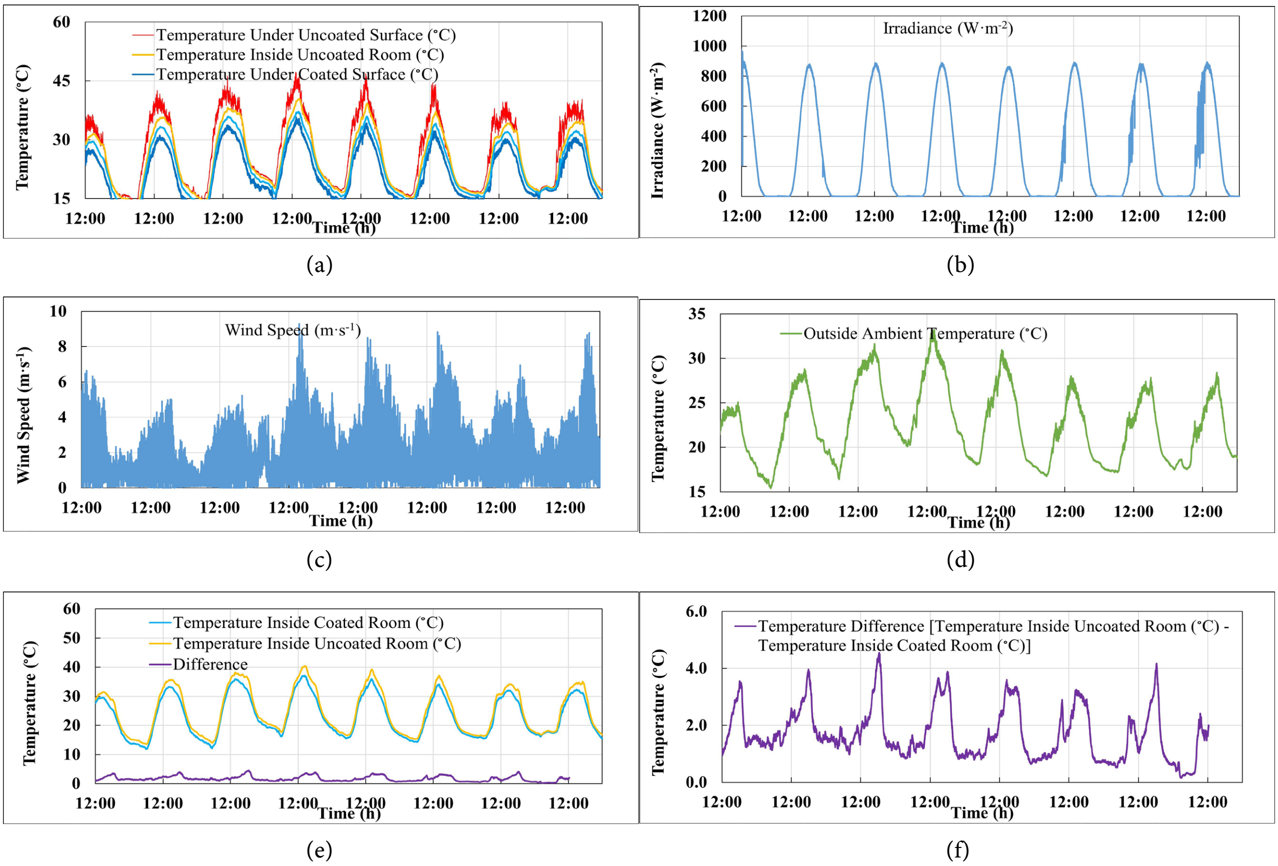



**Figure 6.** Temperature reducing capacity of PDRC material2 at 37.5˚ inclination angle.

In the graphs in **Figures 3-8**, the graphs in the lower right side show the effects of the PDCR materials. In other words, they are the temperature difference between materials coated with PDRC materials and the materials are not coated with PDRC materials. As it can be seen that at 0˚ inclination angle, about 1.5˚, 3.5˚ and 3.6˚ temperature differences were recorded respectively for thee PDRC material1, PDRC material 2 and PDRC material 3. On the other hand, at 37.5˚ inclination angle, about 3.5˚, 4.2˚ and 5˚ temperature differences were recorded respectively for thee PDRC material 1, PDRC material 2 and PDRC material 3. Comparing the temperature reducing abilities at 0˚ and 37.5˚ inclination angles, at 37.5˚ inclination angle, the higher temperature differences were recorded.

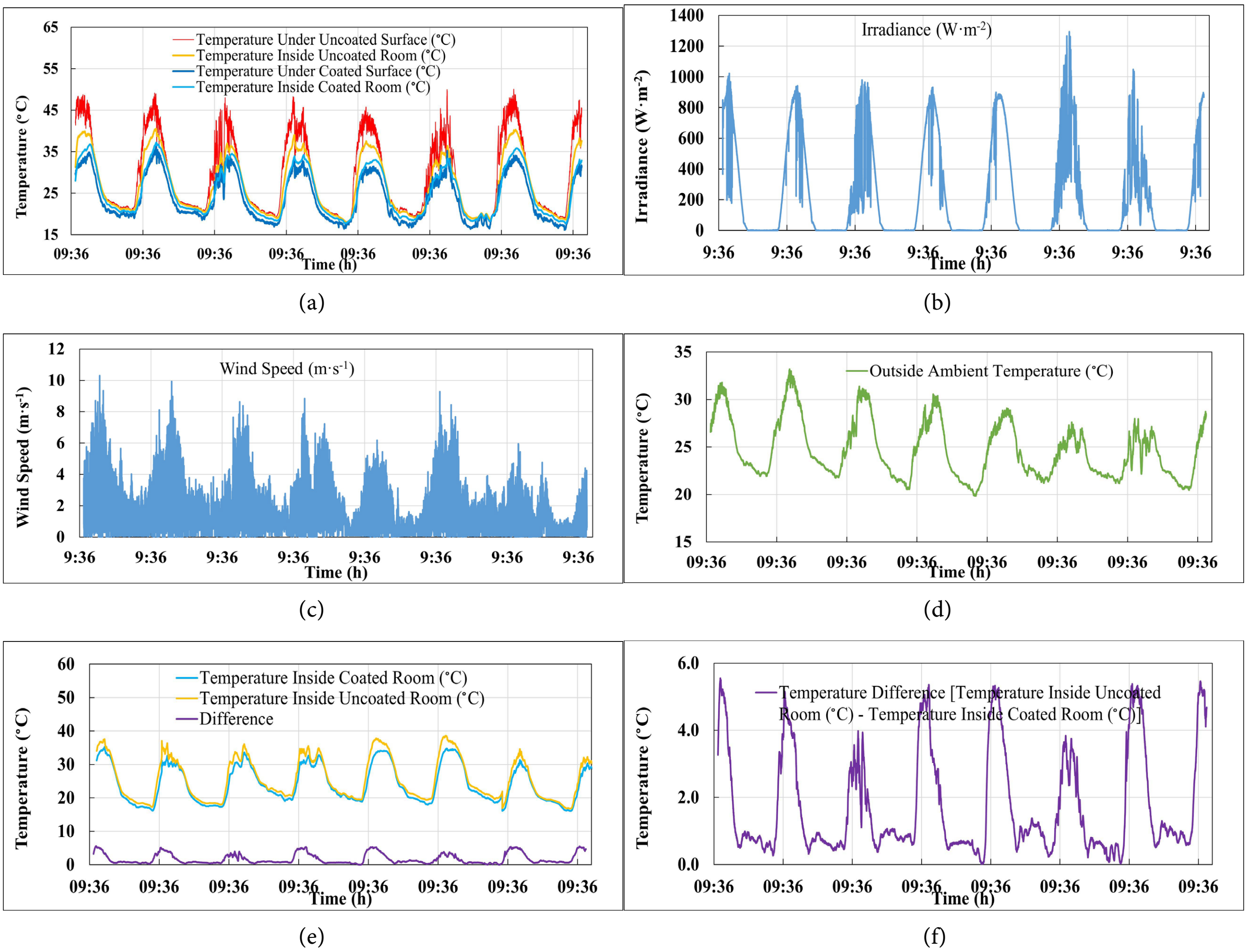
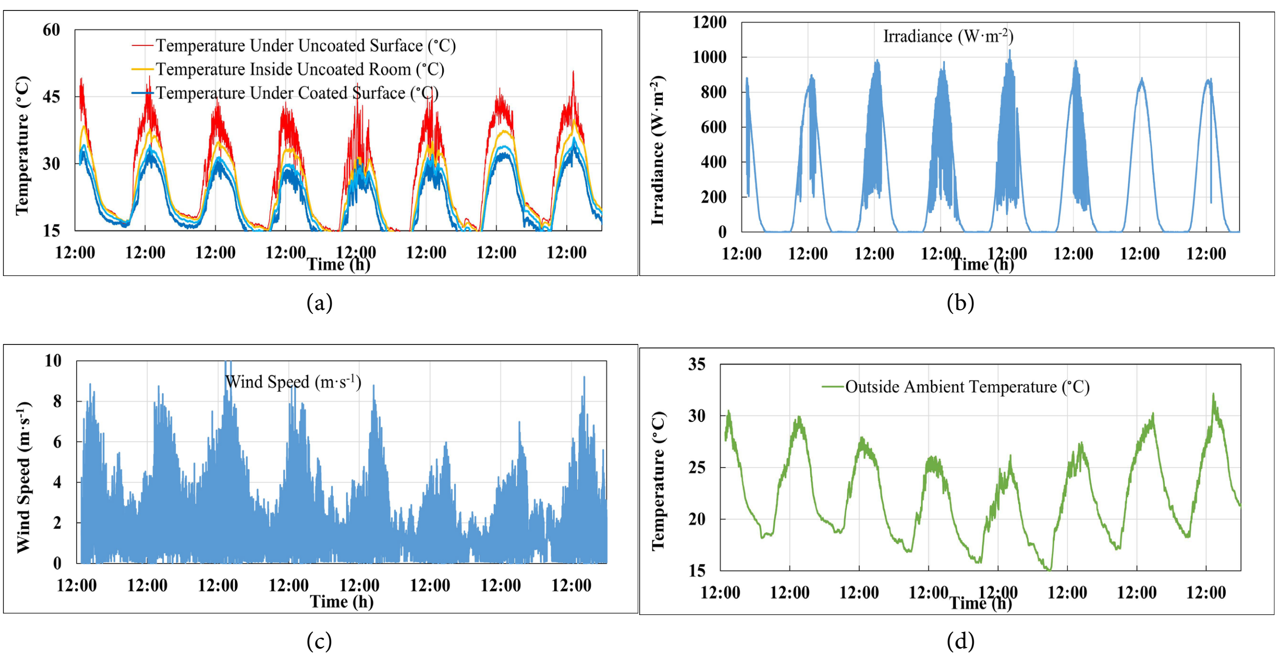
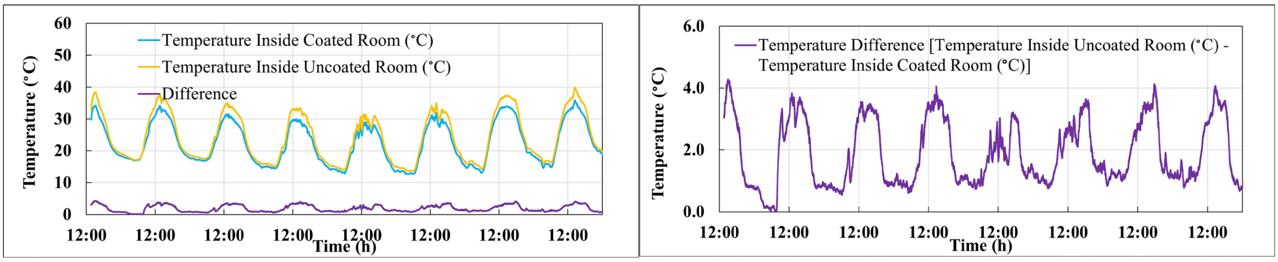



**Figure 7.** Temperature reducing capacity of PDRC material3 at 0˚ inclination angle.






(e) (f)

**Figure 8.** Temperature reducing capacity of PDRC material3 at 37.5˚ inclination angle.

## 4. Uncertainty Budget Estimation

The aim of this study was to establish the temperature-reducing ability of PDRC materials in a metrological traceable manner. Therefore, sensors whose calibrations were traceable to the National Metrology Institute were used in the measurements. To determine the accuracy of the calculated temperature reductions for PDRC materials, factors that could affect the measurements were identified, and their effects on the measurement results were calculated. In order to calculate the uncertainties in the temperatures of PDRC materials the model function derived from Equation (1), as given in Equation (2) was used. The parameters in Equation (2) are given in Table 1, and the uncertainty calculated using these parameters are given in Table 2.

$$T_m\left(\delta_{ac}T_m+\delta_{res}T_m+\delta_{cert}T_m\right)=T_{amb}\left(T_{amb}+\delta_{ac}T_{amb}+\delta_{res}T_{amb}+\delta_{cert}T_{amb}\right)+\frac{G\left(G+\delta_{ac}G+\delta_{res}G+\delta_{cert}G\right)}{\left(u_0+u_1\cdot v\left(\delta_{ac}v+\delta_{res}v+\delta_{cert}v\right)\right)} \quad (2)$$

**Table 1.** Uncertainty parameters of Equation (2).

| $T_m$ | Measured temeperature by Pt100 |
|---|---|
| $\delta_{ac}T_m$ | Pt100 accuracy |
| $\delta_{Res}T_m$ | Pt100 resolution |
| $\delta_{Cert}T_m$ | Pt100 calibration certificate |
| $G$ | Measurements by irradiance sensor |
| $\delta_{ac}G$ | Irradiance sensor accuracy |
| $\delta_{Res}G$ | Irradiance sensor resolution |
| $\delta_{Cert}G$ | Irradiance sensor calibration certificate |
| $T_{amb}$ | Temperature determined by ambient sensor |
| $\delta_{ac}T_{amb}$ | Ambient sensor accuracy |
| $\delta_{Res}T_{amb}$ | Ambient sensor resolution |
| $\delta_{Cert}T_{amb}$ | Ambient sensor calibration certificate |
| $v$ | Measurements wind speed sensor |
| $\delta_{ac}v$ | Wind speed sensor accuracy |

**Continued**

| | |
|---|---|
| $\delta_{Res}V$ | Wind speed sensor resolution |
| $\delta_{Cert}V$ | Wind speed calibration certificate |
| $u_0$ | Intersection point determined from the $G/(T_m - T_{amb})$ |
| $u_1$ | Slop determined from the $G/(T_m - T_{amb})$ |

**Table 2.** Uncertainty parameters of Equation (2).

| Symbol | Source of Uncertainty | Uncertainty Contribution |
|---|---|---|
| $T_m$ | Measured temeperature by Pt100 | 0.27% |
| $\delta_{ac}T_m$ | Pt100 accuracy | 0.06% |
| $\delta_{Res}T_m$ | Pt100 resolution | 0.06% |
| $\delta_{Cert}T_m$ | Pt100 calibration certificate | 0.25% |
| $G$ | Temperature determined by ambient sensor | 0.70% |
| $\delta_{ac}G$ | Ambient sensor accuracy | 0.06% |
| $\delta_{Res}G$ | Ambient sensor resolution | 0.06% |
| $\delta_{Cert}G$ | Ambient sensor calibration certificate | 0.25% |
| $T_{amb}$ | Measurements by irradiance sensor | 4.40% |
| $\delta_{ac}T_{amb}$ | Irradiance sensor accuracy | 0.06% |
| $\delta_{Res}T_{amb}$ | Irradiance sensor resolution | 0.06% |
| $\delta_{Cert}T_{amb}$ | Irradiance sensor calibration | 2.00% |
| $V$ | Measurements wind speed sensor | 0.12% |
| $\delta_{ac}V$ | Wind speed sensor accuracy | 0.05% |
| $\delta_{Res}V$ | Wind speed sensor resolution | 0.01% |
| $\delta_{Cert}V$ | Wind speed calibration certificate | 0.09% |
| $u_0$ | Intersection point determined from the $G/(T_m - T_{amb})$ | 0.63% |
| $u_1$ | Slop determined from the $G/(T_m - T_{amb})$ | 0.86% |

## 5. Conclusion

In this work, the aim was to investigate the temperature-reducing ability of PDRC materials in a metrologically traceable manner. For this, an outdoor measurement system having a meteorological station consisting of irradiance, ambient temperature, wind speed and direction sensors, a thermally isolated sample test box, and the data acquisition and logging units was established in TUBITAK UME. Before the measurements, both characterization and calibration of measurement system and sensors were done. The PDRC materials studied in this work are the materials with thin film coatings manufactured by different companies. The temperature reducing abilities of PDRC materials were studied at two inclination angles (0˚ and 37.5˚). At 0˚ inclination angle, about 1.5˚, 3.5˚ and 3.6˚ temperature differences and at 37.5˚ inclination angle, about 3.5˚, 4.2˚ and 5˚ temperature differences were recorded respectively for the PDRC material 1, PDRC material 2 and PDRC material 3. Comparing the temperature reducing abilities at 0˚ and 37.5˚ inclination angles, at 37.5˚ inclination angle, the higher temperature differences were recorded. To determine the accuracy of these measurements, the factors that could affect the measurements were identified, and their effects on the measurement results were calculated. It was observed that PDCR materials reduced temperatures by within 4˚C - 8˚C with an uncertainty of approximately 10%.

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## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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