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NUMERICAL INVESTIGATION OF A TEST BOX FOR RC MATERIALS

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Abstract: *RC (RC) has emerged as a promising technology for passive cooling applications, offering a sustainable and energy-efficient solution to alleviate the increasing demand for air conditioning. This study focuses on a numerical investigation aimed at understanding and optimizing the test box used to evaluate the thermal performance of samples of RC materials. The numerical simulations employ advanced computational models to analyze key factors influencing the thermal behavior of the test box under varying several boundary conditions. The study also explores the thermal interaction between the test box and its surroundings, considering the effects of ambient temperature and air heat transfer coefficient. The numerical simulations provide valuable insights into the dynamic thermal behavior of the test box, aiding in the development of optimized designs that minimize parasitic heat gains, which may hide the actual cooling performance of the RC sample under real conditions. The outcomes of this numerical investigation contribute to the ongoing efforts in the field of RC, and the development of a test box for RC materials.*

Keywords: RC, numerical simulation, sub ambient temperature, emissivity, test box.

1. INTRODUCTION

RC (RC) is a renewable cooling technology that uses specially designed surfaces and materials to emit infrared radiation (IR), allowing objects to cool by dispersing heat to the cold space. For the fabrication of RC test boxes, selecting appropriate materials is crucial. Thermal insulating foams help to minimize conduction heat transfer and reduce the heat exchange between the sample and the environment; reflective surfaces are usually used for test boxes when testing daytime RC (DRC) to reflect the solar radiation and prevent the test box from overheating; and transparent materials in the infrared region are usually suitable windshield covers to allow the IR to pass through and reduce convective gains. Together, these materials contribute to creating a controlled environment ideal for testing RC materials [1]. To demonstrate the reliability of the RC materials, a number of researchers focus on the creation of a test box for RC that uses various measurement strategies [2]. Di Han et al. [3] reported that for the evaluation of materials for RC, the sample should be supported by a thick polystyrene foam using a test box to decrease heat conduction; they also suggested the use of aluminum foils to reflect the incoming solar radiation in the case of DRC material testing. Junwei Liu et al. [4] conducted experiments to investigate the effectiveness of RC in the presence and absence of a wind cover using a test box covered by a windshield cover made from 12.5 μm of polyethylene (PE). The PE film employed to decrease non-radiative heat exchange between the radiative cooler and its surroundings, while not blocking thermal radiation. Xianze Ao et al. [5] presented an experimental study of the cooling capabilities of DRC surfaces. The apparatus employed in their investigation comprises a test box measuring 40 x 40 x 10 cm. The test box is filled by an insulating layer, 8 cm thick. A sample measuring 15 x 15 cm is placed in the horizontal center of the box to serve as a RC surface. They utilized 20 μm thick low-density PE (LDPE) as windshield to avoid convection because LDPE has strong transmissivity at almost all wavelengths. And to reduce the absorption of solar radiation, aluminum foil is used to cover the rest of the surfaces in the test box. Haddouche et al. [6] presented an experimental study of a test box for RC materials testing. The impact of aluminum foil or white paper as sun reflecting surfaces, and the presence or absence of wind shield was investigated. Due to the lack of numerical modeling of the test box for RC material testing in the literature, this paper presents a numerical model of the test box used for testing nighttime RC materials. The impact of various climatic parameters such as ambient temperature and air heat transfer coefficient are investigated, and also the impact of the substrate material and the thickness of the substrate material.

2. DESCRIPTION OF THE TEST BOX

A parallelepiped hardwood box with external dimensions of 32 x 32 x 16 cm and a wall thickness of 2 cm is used as the test box for RC material testing [6]. The test box is used to test some materials for daytime and nighttime RC and shows which material could be more suitable for RC technology. The test box should be constructed in a manner that minimizes all parasitic heat. For this the wooden box is filled with polystyrene, a low thermal conductive material, and the external lateral walls must be covered by a reflective material to reflect the maximum amount of solar radiation in the case of DRC materials testing. The test box is also covered by a 60 μm low density PE windshield of an infrared transmissivity of 0.83. The PE windshield is used to reduce the convective heat gains from the environment. Figure 1 and figure 2 show a detailed schematic diagram of the described test box.

3. NUMERICAL MODEL

In this study a numerical simulation using a finite element method is applied to model the test box. Figure 2 shows the mesh of the numerical model. In this model, the test box consists of various materials as described in the previous section; the model considers only nighttime RC. The test box is a wooden box used as a structure and also has the role of contributing to the reduction of the conductive heat transfer. The wooden box is filled with polystyrene foam to further increase the thermal insulation of the RC material to be tested. This numerical model considers: the thermal conduction in the external wooden box and also through the polystyrene foam and between the polystyrene foam and the sample, natural convection between the enclosed air and the sample (the gap between the polystyrene and the PE foam), forced convection on the lateral walls and on the superior surface of the PE windshield. The conduction through the windshield is negligible since it has a very low thickness. The base surface of the test box is assumed to be insulated. The model of thermal radiation is applied on the sample of the RC material to be cooled. The sample is 14 x 12 cm and it consists of a substrate material painted with the CHILSKYN^{TM} [7], which is used as RC material, and it has an emissivity of ε_s=0.96 to emit the maximum amount of radiation to outer space. The lateral walls are covered by aluminum foils and in this model are considered diffuse surfaces with an emissivity of ε_w=0.2. Figure 3 shows a schematic diagram of the thermal resistances and the heat transfer phenomenon within the test box.

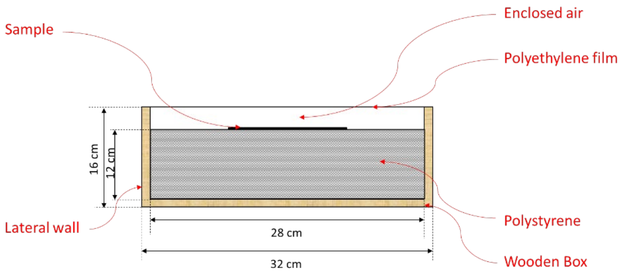

Figure 1. Schematic diagram of the test box.

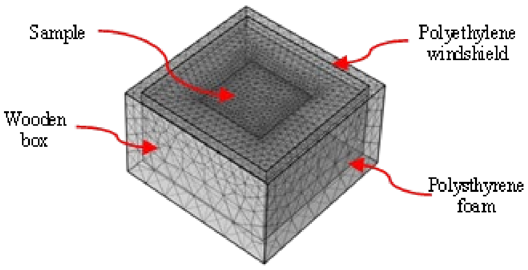

Figure 2. Numerical model of the test box.

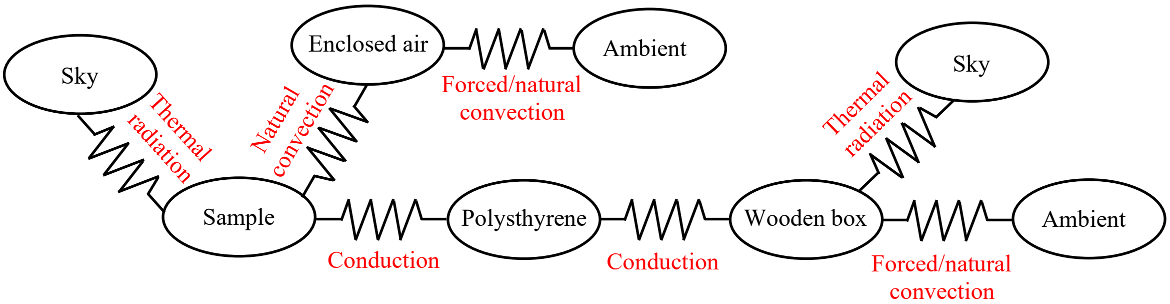

Figure 3: Schematic diagram of the thermal resistance.

4. RESULTS AND DISCUSIONS

4.1. MODEL VALIDATION

To show the accuracy of the model, the numerical results are compared with the results obtained from the experimental test performed on the rooftop of the university of Lleida, Catalonia, Spain. The experimental setup consists of a test box as described in the physical model section. The sample used in the validation of the model is a plate substrate made of copper of dimension 14 x 12 cm and a thickness of 0.5 mm. The substrate is painted with CHILSKYN^{TM} [7] paint, a recently developed commercial product that we use as RC material. For this purpose, only nighttime RC is considered in this study. The temperature evolution in function of time of the RC sample material tested in the experimental set-up is used in the validation. To be more accurate, the ambient temperature and the wind velocity are obtained from the meteorological station of the university of Lleida and are introduced as inputs into the numerical model. The sky temperature is calculated using equation 1 [8]. Figure 4 shows the ambient temperature (T_{amb}), the sky temperature (T_{sky}) calculated using equation 1, and the wind velocity (v_w) used in the model validation and the parametric study in this paper. The 0 hour in the X axis refers to the starting time of the night test.

$$T_{sky} = 0.0552 \cdot T_{amb}{}^{1.5} \tag{1}$$

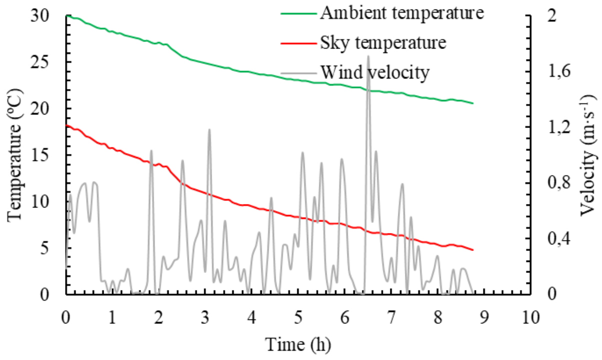

Figure 4: Input parameters of the model.

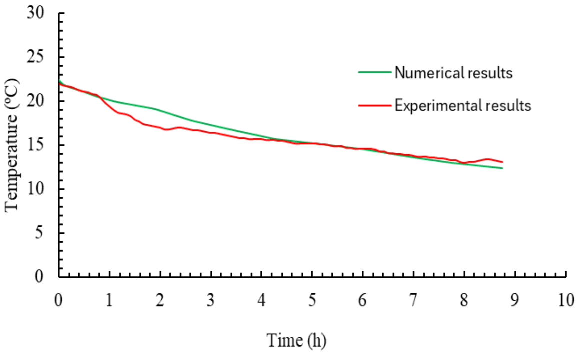

Figure 5: Comparison of the sample temperature between numerical and experimental results.

Figure 5 shows the comparison of the sample's temperature of the numerical model and the results obtained from the experimental test. The temperature of the sample has an initial temperature of T_{ini}=22 ºC, and this value is also taken from the experimental results. It can be seen that the sample temperature predicted by the numerical model agrees well with the sample temperature measured from the experiment, and they have the same evolution with a maximum relative error of 11.42 % and a temperature difference at the end of the cooling process of 0.75 ºC and an error of 5.72 %.

4.2. IMPACT OF THE CLIMATIC CONDITIONS

In this section the impact of the climatic conditions on the temperature evolution of the samples is studied. For this purpose, the ambient temperature and the convective heat transfer coefficient around the test box were studied.

4.2.1. IMPACT OF THE HEAT TRANSFER COEFFICIENT

The impact of the convective heat transfer between the test box and the surrounding air is also considered in this section. For this, the heat transfer coefficient (h_c) varies from 0 to 100 $W \cdot m^{-2} \cdot K^{-1}$ and the boundary conditions of ambient temperature and sky temperature are considered as mentioned in Figure 4. The temperature of the sample in function of time and for various heat transfer coefficients is plotted in Figure 6. The temperature of the sample in all cases studied decreases as the time increases. In the cases of higher heat transfer coefficient (h_c>1 $W \cdot m^{-2} \cdot K^{-1}$) the temperature of the sample evolves in the same way to a final value of ~12.35 ºC. This is because the thermal resistance in the enclosed air space between the PE cover and the sample is the limiting one, and the further reductions of thermal resistance in the free air side when h_c increases are barely affecting the overall thermal resistance between ambient and sample surface. Thus, convection heat gains remain constant. In the other hand, in the case of no heat transfer coefficient or the heat transfer coefficient is h_c=1 $W \cdot m^{-2} \cdot K^{-1}$ the temperature of the sample reaches the values of 10.83 ºC and 11.64 ºC, respectively.

4.2.2. IMPACT OF THE AMBIENT TEMPERATURE

The impact of the ambient temperature on the sample´s thermal behavior is investigated taking into account the variation of the ambient temperature between 20 ºC and 35 ºC and analyzing how the sample's temperature behaves under these conditions. The sky temperature is calculated using equation 1 as function of ambient temperature, and the wind velocity is introduced as input (figure 4). The initial temperature of the samples has a value of T_{ini} = 30 ºC. The sample's temperature evolution over time for the various ambient temperatures under investigation is shown in Figure 7. It can be observed that the temperature of the sample decreases as the time increases. It can also be noticed that as the ambient temperature decreases, the sample's temperature reaches lower values.

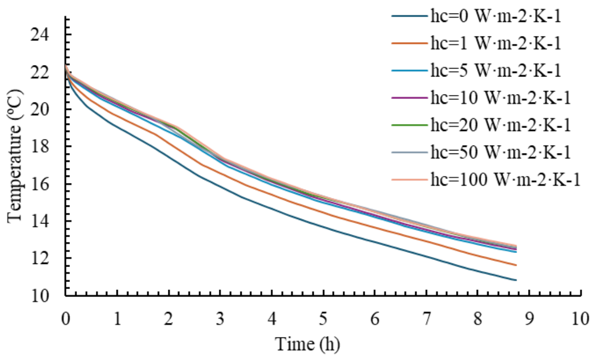

Figure 6: Temperature evolution of the sample in function of time for different heat transfer coefficients.

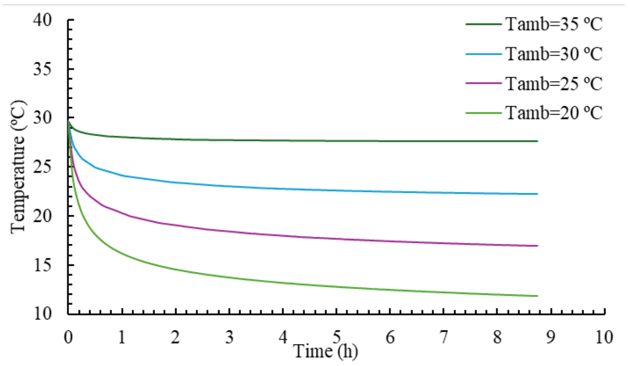

Figure 7: Temperature evolution of the sample in function of time for different ambient temperature.

Table 1. Temperature difference between the sample and the ambient temperature.

Ambient temperature (ºC)	35	30	25	20
Temperature difference (ºC)	7.37	7.8	8.04	8.14

Table 1 presents the temperature difference between the temperature of the sample at the end of the cooling process and the ambient temperature. The temperature difference increases slightly as the ambient temperature decreases, which means that the achieved sub ambient temperature in the sample has a non-lineal relation with ambient temperature.

4.3. IMPACT OF THE SUBSTRATE NATURE

In this section the impact of the substrate material and the substrate thickness is investigated under the same operating conditions.

4.3.1. IMPACT OF THE SUBSTRATE MATERIAL

To show the effect of the substrate material on the thermal behavior of the RC material, three substrate materials are taken into account (cooper, iron and aluminum) with the same thickness of e=0.5 mm. The three simulations have the same climatic conditions of wind velocity, ambient temperature and sky temperature and also the boundary conditions of the test box, as shown in Figure 4 of the validation section.

The temperature evolution of the samples as a function of time for various materials is displayed in Figure 8. As observed, the temperature of the three samples has the same temperature evolution and all the samples have the same temperature of 12.07 ºC at the end of the cooling process and the substrate material does not affect the thermal behavior of the RC material during the nighttime RC. Note that the three substrate materials used are very thin layers of metals, so the resulting thermal resistances and thermal inertia are so low that difference among them is negligible in this case.

4.3.2. IMPACT OF THE SUBSTRATE THICKNESS

The influence of the substrate thickness on the thermal behavior of the RC material is also investigated in this part. For this, the substrate material used is copper with different thicknesses (0.5, 1, 2, 5 and 10 mm).

Figure 9 displays the temperature evolution of the samples over time and for the various thicknesses that were examined. The temperature of the samples decreases as the time increases. It can be seen also that the thickest sample (e=10 mm) has the highest temperature at the end of the night, and its temperature is 14.21 ºC, while the thinnest sample (e=0.5 mm) has the lowest temperature at the end of the cooling process with a temperature of 12.55 ºC. This is because thin surfaces have lower thermal resistance and thermal inertia. Thus, conduction prevails overheat storage, facilitating the cooling process of the sample.

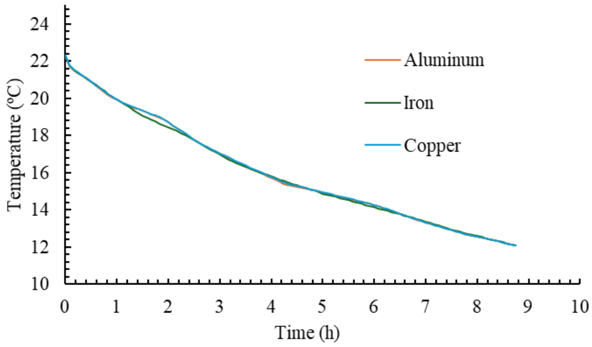

Figure 8: Temperature evolution of the samples in function of time for different substrate materials.

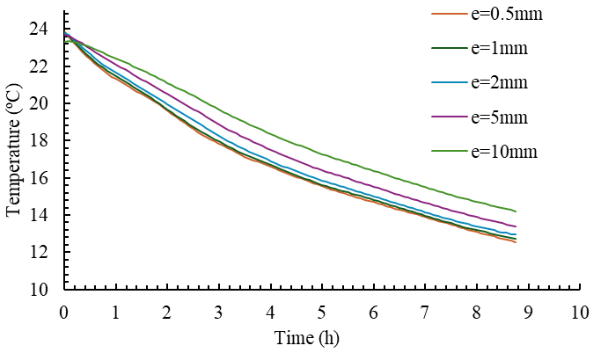

Figure 9: Temperature evolution of the samples in function of time for different substrate thicknesses.

5. CONCLUSIONS

The paper presented a numerical study of a test box used for testing RC material and showed the impact of the climatic conditions on the temperature behavior of the RC sample. The impact of ambient temperature, the ambient air heat transfer coefficient, and the sample's substrate nature and thickness were investigated. The numerical model showed good agreement with the results obtained from the experimental set-up. The conclusions obtained from this study are:

1) The air heat transfer coefficient has an impact on the thermal behavior of the sample. Lower temperatures of the sample are obtained at lower heat transfer coefficients. However, with increasing heat transfer coefficients heat gains remain constant, as the limiting thermal resistance between outside air and sample is in the enclosed air side.
2) A temperature of 10.83 ºC is obtained in the cases of null heat transfer coefficient (h_c=0 W·m^{-2}·K^{-1}) which means that there is no convective heat transfer between ambient air and the test box.
3) The samples temperature is strongly depending on the ambient temperature. As the ambient temperature decreases, the samples temperature decreases also, and at the end of the cooling process, lower temperature of the sample is obtained at lower ambient temperatures. The temperature difference between the ambient temperature and the sample increases slightly as the ambient temperature decreases.
4) For nighttime RC, the substrate material for a thickness of 0.5 mm did not have influence on the behavior of the sample's temperature and all the samples had the same temperature of 12.07 ºC at the end of the cooling process.
5) The thickness of the substrate material had a great influence on the final temperature of the RC material. Thinner substrate results in lower temperature of the sample at the end of the cooling process. In general, the substrate material thickness can influence the RC extent through the relative importance of heat transfer and heat storage.

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REFERENCES

[1] J. Liu et al., «Recent advances in the development of radiative sky cooling inspired from solar thermal harvesting», Nano Energy, vol. 81, p. 105611, mar. 2021, doi: 10.1016/j.nanoen.2020.105611.
[2] J. Kou, Z. Jurado, Z. Chen, S. Fan, y A. J. Minnich, «Daytime RC using near-black infrared emitters», ACS Photonics, p. acsphotonics.6b00991, 2017, doi: 10.1021/acsphotonics.6b00991.
[3] D. Han, B. F. Ng, y M. P. Wan, «Preliminary study of passive RC under Singapore's tropical climate», Sol. Energy Mater. Sol. Cells, vol. 206, p. 110270, mar. 2020, doi: 10.1016/j.solmat.2019.110270.
[4] J. Liu et al., «Sub-ambient RC with wind cover», Renew. Sustain. Energy Rev., vol. 130, p. 109935, sep. 2020, doi: 10.1016/j.rser.2020.109935.
[5] X. Ao, M. Hu, B. Zhao, N. Chen, G. Pei, y C. Zou, «Preliminary experimental study of a specular and a diffuse surface for daytime RC», Sol. Energy Mater. Sol. Cells, vol. 191, pp. 290-296, mar. 2019, doi: 10.1016/j.solmat.2018.11.032.
[6] M. Reda Haddouche et al., «Design strategies for testing daytime and night-time RC materials», 13th National and 4th International Conference in Engineering Thermodynamics, ISBN: 978-84-09-52403-7
[7] PDRC | CHILLSKYN Solutions. ChillSkyn - PDRC n.d. https://www.chillskyn.com (accessed April 10, 2023).
[8] W. C. Swinbank, «Long-wave radiation from clear skies», Division of Meteorological Physics, Aspendale, Australia, (1963), 339-348.