Cooling capacity evaluation of passive radiation cooling materials

Tingsxuan Li¹, Zhilin Xia¹ and Xiaochun Fan²,*

¹ School of materials science and engineering, Wuhan University of technology, Wuhan, Hubei 430070, China
² School of Civil Engineering and Architecture, Wuhan University of Technology, Wuhan 430070, China

*Corresponding author’s e-mail: fxc_free@whut.edu.cn

Abstract: passive radiation cooling technology has aroused widespread interest and research enthusiasm because it can cool objects with zero energy consumption, and even cool to below the ambient temperature. At present, when evaluating the cooling performance of radiation cooling materials, in order to reduce the impact of air convection heat transfer and improve the radiation cooling capacity of materials, test samples are usually put into incubators for insulation. In this paper, the finite element method was used to analyze the influence of the size and material of the common used structural incubator on the radiation cooling capacity of the test sample, as well as the influence of the selection of reference ambient temperature. Results show that the selection of incubator structure, material and ambient temperature has a obvious impact on the evaluation results of material radiation cooling capacity, especially when the ambient heat convection coefficient is low. Therefore, for comparing the test results of different research work, a unified incubator design is needed, including structural size and material selection.

1. Introduction
Passive radiation cooling is a common cooling phenomenon in nature. Its physical principle is [1-3]: objects on the earth's surface will constantly radiate heat energy because their temperature is greater than absolute zero. The peak wavelength of thermal radiation of normal temperature (300K) objects is near 10 microns, which is just in the window (8-14 microns) of the earth's atmosphere. Therefore, part of the object's thermal radiation energy can enter outer space through the atmospheric window, while the outer space temperature (about 4K) and thermal radiation power are very low, which can not feed back the thermal radiation of the object on the earth's surface. As a result, the object on the earth's surface forms a net outward thermal radiation, which continuously reduces its own temperature. When the temperature of the object decreases, a temperature difference is formed between the object and its environment, so as to obtain the energy supplement given by the environment, form a stable heat exchange at a temperature lower than the environment [4-6]. According to this principle, people try to design some materials with better spectral properties to make them have good cooling ability [7-9]. Generally, these materials need to have very low absorptivity in the sunlight band, high enough radiation capacity in the 8-14 micron band of the atmospheric window, and very low absorptivity in the infrared band outside the atmospheric window.

In experiments, the temperature difference between the ambient temperature and the object temperature is usually used to evaluate the radiation cooling ability. In order to reduce the influence of
air convection heat transfer and improve the radiation cooling capacity, the sample is usually placed in an insulation chamber for evaluating the radiation cooling capacity [10-12]. However, there are no clear and unified requirements for the design of insulation chamber, which leads to no comparability between the radiation cooling capacity of samples tested by different research groups. In this paper, the commonly used test cavity structure is simulated by finite element method, and the effects of the size of the test cavity and the absorption capacity of the used material to sunlight on the test sample temperature are evaluated and analyzed. This work hopes to attract the attention of researchers in this field to the design of test cavity and promote the formulation of test cavity design standards.

2. Calculation model and parameters
Here, the finite element method is adopted to simulate based on a cylindrical rotationally symmetric model. The model structure is shown in figure 1. The model consists of PE film, air gap, radiation cooling film (including radiation film and substrate), foam pad and foam chamber. The outer wall of the foam chamber is wrapped with aluminum foil. According to the commonly used test methods in literatures, two kinds of substrates (polymer and copper substrates) are considered in the simulation. The whole test chamber is convective heat exchanged with the external environment through PE film and aluminum foil. The material parameters involved in the test chamber are shown in Table 1.

In the test chamber, PE fresh-keeping film with a thickness of less than 100 microns is usually used, and its absorption of sunlight can be ignored. The air gap is generally 1-2 cm thick, and its absorption of sunlight can also be ignored. Other parameters in the calculation: the foam absorption power density on the inner wall of the air gap is 50 W/m², the absorption power density of the aluminum foil on the outer side wall and the top surface of the foam box is 100 W/m², the ambient temperature is 293.15 K, the convective heat transfer coefficient is 8 W/m²/K, and the radiative power of the radiant film is 80 W/m². The aluminum foil is attached to the foam box surface, and the radiation film is attached to the substrate surface. In the following text, parameter values without special instructions are taken according to the instructions here.

| Structure and performance | Thickness | Radius | Density | Thermal conductivity | Specific heat capacity |
|---------------------------|-----------|--------|---------|----------------------|-----------------------|
| Air domain                | 1cm       | 5cm    | 1.205 kg/m³ | 0.026 W/m/K          | 1005 J/Kg/K           |
| Foam pad                  | 2cm       | 5cm    | 20 kg/m³   | 0.04 W/m/K           | 1500 J/Kg/K           |
| Foam Chamber              | 2cm       | 5cm    | 20 kg/m³   | 0.04 W/m/K           | 1500 J/Kg/K           |
| Radiative sheet on polymer substrate | 1mm     | 5cm    | 1400 kg/m³ | 0.2 W/m/K           | 1200 J/Kg/K           |
| Radiative sheet on copper substrate | 1mm     | 5cm    | 8700 kg/m³ | 400 W/m/K           | 385 J/Kg/K            |
3. Results and discussions
Building cooling and energy saving is one of the most promising application scenarios of passive radiation cooling. Considering that the scale of buildings is usually relatively large, it is unlikely to use insulation cavity when actually using radiation cooling film. Therefore, it is necessary to understand the film’s radiation cooling capacity without incubator. The calculation model without thermal insulation chamber is shown in figure 2. The rotationally symmetric model is also adopted. Compared with figure 1, only the radiant film and the thermal insulation foam pad are retained. In this paper, the radiation cooling capacity is the difference between the ambient temperature and the temperature in the center of the sample. The material has cooling capacity when the difference is positive, and the material does not have cooling capacity when the difference is negative.

![Figure 2 structural diagram of calculation model without incubator](image)

It can be seen from the calculation results of the radiation cooling capacity in figure 3 that the radiation cooling capacity is obviously affected by the convective heat transfer coefficient. The greater the convective heat transfer coefficient, the worse the radiation cooling capacity. The natural convection coefficient of air is generally 5-25 W/m$^2$/K, and the forced convection heat transfer coefficient is generally 20-100 W/m$^2$/K. It can be seen that under forced convection heat transfer, the radiation cooling capacity is poor, and the cooling capacity tends to zero with the increase of convection heat transfer coefficient. Under natural convection heat transfer, the material has good cooling capacity. With the decrease of convection heat transfer coefficient, the cooling capacity can reach 19°C (conditions: net radiation power 80 W/m$^2$, convection coefficient 3 W/m$^2$/K). However, in the case of natural convection heat transfer, if the sample is placed on copper plate, the radiation cooling capacity becomes slightly worse with the decrease of the sample size. This is because copper plate conducts the heat at the sample boundary to the central area, which increases the temperature of the central area. When the polymer material is used as the substrate, due to the poor thermal conductivity of the polymer, the cooling capacity of the sample with a radius greater than 5cm is almost independent of the sample size.

Due to the limitation of experimental sample preparation ability, the sample size is usually small. At the same time, in the actual test scenario, the forced convection heat transfer between the object...
surface and the environment is commonly happened. In order to reduce the influence of convective heat transfer, the test sample is usually placed in the insulation chamber to test its radiation cooling capacity. The calculation model of the insulation chamber is shown in figure 1. It can be seen from the calculation results in figure 4 that when the insulation box is adopted, the convective heat transfer between the outer wall of the insulation box and the environment will still affect the cooling capacity of the radiator. The greater the convective heat transfer coefficient, the worse the radiation cooling capacity. For samples with different sizes, the radiation cooling capacity has no obvious change when the radius is greater than 10cm. The most significant effect in the case of using the insulation chamber is that the radiation cooling capacity of the radiation sample is greatly improved. Under the condition of natural convective heat transfer, the radiation cooling capacity of large-size radiation film can exceed 37 °C. Even in the environment of strong convective heat transfer, the radiation cooling capacity can still exceed 22 °C. Comparing the radiation cooling capacity during the day and at night in figure 4 (a) and figure 4 (b), the difference in cooling capacity is very small when the sample size is greater than 10cm. For small-size samples, the absorption of sunlight by the insulation cavity significantly reduces the sample’s cooling capacity, especially in natural convection environment, the cooling capacity decreases obviously, but it is still larger than the radiation cooling capacity without insulation cavity.

![Figure 4](image1.png)

Figure 4 in the case of test chamber used, the relationship between cooling capacity and ambient convective heat transfer for radiation film on polymer substrate with different radius. At night (a) and in daytime (b).

![Figure 5](image2.png)

Figure 5 in the case of test chamber used, the cooling capacity of radiation film on polymer substrate under different ambient convective heat transfer when different absorptive capacity of aluminum foil (a) and inner foam side wall (b) is considered. the absorption of foam is zero in Figure (a), and the absorption of aluminum foil is zero in Figure (b).
The daytime cooling ability of the radiation cooling film is inhibited by the sunlight absorption of the cavity. It is mainly caused by the sunlight absorption of the aluminum foil and the inner side wall of the foam incubator. From the calculation results in Figure 5, it can be seen that when the absorption power density of aluminum foil or foam wall increases, the cooling ability of radiant film decreases. The smaller the convection heat transfer coefficient, the more obvious the cooling ability decreases. The aluminum foil is located on the outer wall of the insulation chamber, and its absorption effect can be reduced by convective heat exchange with the environment. In the forced convection condition, the change of solar absorption power of aluminum foil will not significantly affect the cooling capacity of the radiation film. Foam absorption is located in the inner side wall of the cavity, and its effect cannot be completely suppressed even in the case of strong convection heat transfer condition. While, foam absorption area is small, and its influence on the radiation cooling ability is not so obvious.

When incubator is used, the theoretical value of the radiation cooling capacity can easily exceed 20 °C. However, it is difficult to obtain such excellent cooling capability in practical testing. The main problem is that the radiation film is usually difficult to obtain 100% solar reflectivity. Therefore, the substrate and pad beneath the radiating film absorb the sunlight passing through the radiation film, resulting in the cooling performance decreasing. As shown in Figure 6 (a), when the absorbed power of the pad reaches 80 W/m², the temperature of the radiation film is higher than the ambient temperature, and the cooling effect is lost. The absorption power of 80 W/m² corresponds to that the radiation film has a transmittance of nearly 10%, so it is important to improve the sunlight reflection of the radiation film, otherwise the radiation film is difficult to obtain the cooling effect during the daytime. In this case, the temperature inside the test chamber was used as the environmental comparison temperature to evaluate the radiation cooling capacity in some articles [13-16]. As can be seen from Figure 6 (b), for the case of 80 W/m² pad absorbing power, although the temperature at the center of the radiation film is greater than the external ambient temperature, it is still less than the temperature near the inner wall of the insulation chamber. Taking the internal ambient temperature as a reference, the radiation film still has the cooling effect, but the radiation cooling capacity reflected using this comparison usually has no practical significance.

4. Conclusion
The affection of the chamber structure and materials on the sample’s radiation cooling capacity are calculated and analysed using the finite element simulation method. The incubator size, the sunlight absorption of aluminium foil and foam will obviously affect the radiation cooling effect of the material. In addition, when evaluating the radiation cooling capacity, using different control ambient temperatures will also obtain different radiation cooling capacity. Therefore, when using the incubator
method to reduce the effect of air convection heat transfer and evaluate the radiation cooling capacity of materials, it is necessary to have unified requirements for the size of incubator, the size of radiation sample and the material of incubator, otherwise the radiation cooling capacity of samples is not comparable. However, in the current literature, the test cavity shape, size, material selection, environmental reference temperature selection and test methods designed by different research groups are different. The unified standard of test cavity design needs to be paid attention to.

In addition, in most cases, the application scenario of radiation cooling materials is not suitable for the use of thermal insulation devices. Therefore, the evaluation method of radiation cooling ability of materials using incubator to reduce the influence of air convection has no universal application significance. Reducing the sensitivity of radiation cooling materials to convective heat transfer is an urgent problem to be solved in the popularization and application of this technology.

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