Numerical calculation of passenger compartment cooling effect under the action of radiative cooling film based on MATLAB

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Abstract. Radiative cooling uses space cold source to cool the object, and the radiative cooling film made by using this principle can be applied to automobiles effectively to save the refrigeration resources of automobiles. However, due to the limitation of economy, time, space and other factors, it is difficult to carry out comprehensive research on the actual film-forming cooling effect. Based on the principle of passive radiative cooling, a set of simulation models is developed, which is applied to the selection of infrared radiation materials for automotive radiative cooling film and the study of the influence of environmental factors on the radiative cooling effect. SiO₂ was finally selected as infrared radiation material. At the same time, the theoretical cooling temperature of the radiative cooling film applied to the passenger compartment of automobiles can reach 6.8℃ under the conditions of 35℃ ambient temperature, 0.99 atmospheric transmittance and 10 heat transfer coefficient, using SiO₂ as infrared radiation material and PE as dispersion substrate. At the same time, the cooling effect of the radiative cooling film is positively correlated with the ambient temperature, atmospheric transmittance to some extent.

1. Introduction
With the booming development of global industrialization and the increasing improvement of people's living standards, the energy crisis has become a huge problem faced by human beings[1], which forces people to find a more efficient and environmentally friendly cooling method compared with the traditional active cooling method.

The temperature of outer space is about 3K, and it is a huge cold source pool that is not limited by space and time[2]. Passive radiative cooling is the radiator through the "8-13μm " atmospheric window, reducing the atmosphere of radiative cooling, radiating heat to outer space, so as to achieve the purpose of cooling itself. The cooling method can spontaneously carry out no energy consumption cooling at any time and any place.

As early as 1975, Catalanotti S. et al had proved the feasibility of radiant refrigeration[3]. Selective radiators made by Berdahl et al. used MgO particles and LiF particles to achieve a cooling effect of 5℃ lower than the ambient temperature[4]. Later, some scientists also studied the cooling effect of
multilayer cooling membranes. In 2014, Raman achieved radiative cooling under direct sunlight by using seven layers of HfO2 and SiO2 with high reflectivity selective radiators to achieve cooling below the ambient temperature of 4.9℃ under direct sunlight[5].

Figure 1. (a) Reported sem image of radiator structure. (b) Infrared emissivity of the radiator at an incident Angle of 5°[5].

Gentle and Smith also achieved daytime cooling by using polymer materials[6]. They used alternating birefringence polymer layers to achieve reflection in the 0.4-1μm band, cooling to approximately 2℃ below the ambient air temperature without any convection protection and with solar power of 1060 W/m².

Therefore, it is important to choose suitable infrared radiation materials. The selective radiators with high solar reflectivity and high infrared transmittance in the "atmospheric window" are made, which is of great significance for cooling down. Therefore, we design a set of calculation models for the theoretical cooling temperature of different infrared radiation materials in different environments, which is applied to the selection of infrared radiation materials and the study of environmental factors on the effect of radiative cooling.

2. Build the computational model

2.1. Analysis of radiative cooling principle and preliminary determination of materials

For passive radiative cooling using an "atmospheric window" of 8-13μm, selective radiators should have 100% emissivity within the "atmospheric window" of 8-13μm. Outside the "atmospheric window", the absorption rate is close to zero. So that the energy of radiation is greater than the energy of absorption, so as to achieve their own cooling.

Figure 2. Comparison of absorption spectra of different materials
Based on this principle, we compare the infrared emissivity spectra of SiO$_2$, ZnO and ideal selective radiators. As can be seen from figure 2, the infrared emissivity of SiO$_2$ reaches its peak value in the range of 8-13 μm and has a large integral area in this region. The outer emissivity is low in this region, while the material emissivity of ZnO is low in the "atmospheric window" region and reaches its peak value at about 24μm. In contrast, SiO$_2$ is close to the requirements of ideal selective radiators. Therefore, SiO$_2$ was selected as the infrared radiation material and PE as the base material of the radiative cooling film for further calculation and research.

2.2. Mathematical modeling

The cooling effect of the cooling film can be calculated by energy balance equations[7], such as equation (1) - (6):

$$ P_{\text{net}} = P_t - P_a - P_{\text{nonrad}} - P_{\text{sun}} $$

$$ P_t = 2\pi \int_0^{\pi/2} \sin \theta \cos \theta d\theta \int_0^\infty U_B (T, \lambda) e_t (\lambda, \theta) d\lambda $$

$$ P_a = 2\pi \int_0^{\pi/2} \sin \theta \cos \theta d\theta \int_0^\infty U_B (T, \lambda) e_a (\lambda, \theta) d\lambda $$

$$ U_B (T, \lambda) = \frac{2hc^2}{\lambda^5 e^{hc/\lambda k_T} - 1} $$

$$ P_{\text{nonrad}} = q(T_a - T_e) $$

$$ P_{\text{sun}} = \int_0^\infty e_t (\lambda, \theta) I_{\text{AM1.5}} (\lambda) d\lambda $$

In equation (1), $P_{\text{net}}$ — Cooling net power density; $P_t$ — The power density of the cooling film; $P_a$ — The power density at which an object absorbs atmospheric radiation; $P_{\text{nonrad}}$ — Conduction and convection heat transfer power density; $P_{\text{sun}}$ — The power density at which an object absorbs solar radiation.

In equation (2)—(6), $e_t$ — Black body emissivity; $e_a$ — Atmospheric emissivity; $U_B$ — Black body radiated power density; $I_{\text{AM1.5}}$ — The U.S. national standard solar spectrum; $q$ — Convective heat transfer coefficient.

According to the above equations, in order to select the infrared radiation material with high radiation power and good cooling effect that can be within "atmospheric window", we set the light apex angle of the radiator as 90 degrees to reduce the complex influence caused by the angle of sunlight exposure. At the same time, the passenger compartment of the car is simplified into a radiation plate in the airflow field. Matlab is used to write a set of programs to calculate the theoretical cooling value and to study the influence of environmental factors on the radiative cooling effect of the radiative cooling film on the passenger compartment of automobiles.

2.3. Program parameter definition and impact analysis

The program first defines the environment parameters:

- $T_{\text{amb}}$ — Environment temperature; $T_{\text{air}}$ — Air temperature; $T_{\text{emprmat}}$ — Radiation plate temperature; $\text{PowerSun} = 1000\text{W/m}^2$ — Solar radiation power; $\text{Zenith} = 90 \times \pi / 180$ — Apex angle of radiation;

- Geometrical parameters of radiation plate: Width = 1.00 — Radiation sheet width; Length = 1.00 — Radiation length; AreaEmit = Width * Length — Radiative cooling plate area;
3. Analysis of numerical results

3.1. Simulation comparison of heat dissipation effect of different materials

According to the above, SiO₂ particles are more in line with the conditions of selective infrared radiation materials that radiate energy outward at the atmospheric window of 8-13 microns. At the same time, most applications of radiative cooling membranes are under daytime light. So in the application in the simulation environment situation of the day, for an ideal selective radiator, ZnO and SiO₂ as selective infrared radiation material, three kinds of materials made of PE as a dispersion medium radiation cooling film at the ambient temperature of 35 ℃, atmospheric transmittance is 0.99, the surface heat transfer coefficient is 10 under the environmental conditions of the theory of cooling temperature calculation data is compared.

![Graphs showing theoretical cooling temperatures of different materials](image)

Figure 3. (a) Theoretical cooling temperatures of ideal selective radiators at different temperatures. (b) Theoretical cooling temperature of ZnO at different temperatures. (c) Theoretical cooling temperature of SiO₂ at different temperatures. The DelTE of the ordinate represents the difference between the amount of energy the object absorbs and the amount of energy it emits during each thermal iteration. When DelTE reaches 0, the temperature reaches equilibrium. Abscissa TempM represents the theoretical value of temperature reduction when the surface temperature of the cooling film reaches equilibrium.

As is shown in figure 3, the ideal selective radiator has the best cooling effect. The cooling temperature of the ideal selective radiator can be as low as -20℃ at 35℃ ambient temperature. In the case of 35℃ ambient temperature, the cooling temperature of SiO₂ can reach as low as -6.8℃ ambient temperature. Although the effect is not as good as the ideal selective radiator, it also has a certain cooling effect and practical significance. ZnO has the worst cooling effect and has no cooling effect at all temperatures. Considering cooling effect and economy, SiO₂ is the best infrared radiation material for this time.
3.2. The influence of ambient temperature on the cooling effect of radiation film

Figure 4. Theoretical cooling temperature of cooling film at different ambient temperatures.

Ambient temperature is a typical factor affecting the radiative heat dissipation of cooling film. For the cooling film made of PE and SiO₂ as infrared radiation material, five typical ambient temperatures, 35℃, 30℃, 25℃, 20℃ and 15℃, were selected. The atmospheric transmittance was set as 0.99, and the heat transfer coefficient was set as 10, and the theoretical cooling temperature was numerically calculated. The calculation results are shown in figure 4.

At 35℃, 30℃, 25℃, 20℃ and 15℃, the theoretical cooling temperature of radiation film reaches the maximum at 35℃, and the cooling temperature is 6.8℃ lower than the ambient temperature. Then, as the ambient temperature decreases, the theoretical cooling temperature also decreases, reaching the minimum when the ambient temperature is 15℃, and the cooling temperature is 6.8℃ lower than the ambient temperature. It can be seen that the ambient temperature is positively correlated with the theoretical cooling temperature of the cooling film to some extent.

3.3. The influence of atmospheric transmissivity on the cooling effect of radiation film

Figure 5. Theoretical cooling temperature of the cooling film under different atmospheric transmittance.
The atmospheric window transmittance was set as 0.99, 0.93, 0.87, 0.81, 0.75 under five different weather conditions, and the theoretical cooling temperature of the radiative cooling film was numerically calculated.

The calculated results are shown in figure 5. When the atmospheric window transmittance is 0.99, the theoretical cooling temperature of the radiative cooling film reaches the highest, and the cooling temperature reaches 6.8°C lower than the ambient temperature. Then, as the atmospheric window transmittance setting decreases, the theoretical cooling temperature of the cooling film also decreases. When the atmospheric window transmittance is set at 0.75, the theoretical cooling temperature reaches the lowest, and the cooling drops to 3.7°C lower than the ambient temperature. It can be seen from figure 5 that in a certain range, the cooling temperature of radiant cooling film theory is positively correlated with atmospheric window transmittance.

4. Conclusion
Based on the results and discussions presented above, the conclusions are obtained as below:

(1) According to the passive radiative cooling theory, the radiative cooling film made of PE as the base and SiO2 as the infrared radiation material applied to the passenger compartment of the automobile has the effect of self-cooling. Under the ambient temperature of 35°C, atmospheric transmittance of 0.99, and heat transfer coefficient of 10, the radiative cooling film can reduce the surface temperature of the passenger compartment to 6.8°C.

(2) The theoretical cooling temperature of radiation film reaches the maximum when the ambient temperature is 35°C and the atmospheric window transmittance is 0.99, respectively, and the cooling temperature is 6.8°C lower than the ambient temperature. The cooling temperature is positively correlated with ambient temperature and atmospheric window transmittance.

(3) The material selection of radiant cooling film and the factors influencing its cooling effect are studied by numerical calculation, which to some extent reduces the constraints of economy, time and space. It is of great significance to make radiative cooling film with cooling effect for automobile, save refrigeration resources for automobile and alleviate energy crisis. The subsequent research can focus on the study of temperature field in vehicles under the action of radiation cooling film and the application of passive radiation cooling film in buildings, textiles and other fields.

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