Effect of Precipitable Water Vapor Amount on Radiative Cooling Performance

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Abstract: A radiative cooler based on aluminum-evaporated polyvinyl-fluoride surface was employed to investigate the effect of precipitable water vapor amount on its radiative cooling performance. A mathematic model of steady heat transfer that considers the spectral radiant distribution of the sky, the transparent cover and the collecting surface was established. The results indicate that the amount of precipitable water vapor shows a remarkable and negative effect on radiative cooling performance of the radiative cooler. Both the temperature difference between the cooler and surroundings and the net radiative cooling power decreases as the precipitable water vapor amount increases. The net radiative cooling power drops by about 41.0% as the the precipitable water vapor amount changes from 1.0 cm to 7.0 cm. Besides, the radiative cooler shows better cooling performance in winter than in summer. The net radiative cooling power in summer of Hefei is about 82.2% of that in winter.

1. Introduction
The sky is a natural cold source for terrestrial bodies. Although the atmosphere weakens heat radiation from the earth to outer space in the vast majority of bands, it has extremely high transmittance in wavelengths between 8 μm and 13 μm, wherein the heat radiation of bodies on the ground are mainly concentrated. The terrestrial object could obtain a cooling power by radiating heat to the cold universe through this so called “atmospheric window”. This phenomenon is “radiative cooling”. S N Bathgate and S. G. Bosi prepared a ZnS transparent cover to act as the wind shield of the radiative cooler. The ZnS cover shows a much better weather resistance and intensity than the traditional polyethylene film cover [1]. M. F. Farahani et al. proposed a two-stage cooling system which mainly comprises a radiative cooler and an indirect evaporative cooler. The results demonstrated that the first stage radiative cooler increases the effectiveness of the indirect evaporative cooler [2]. Fan et al. proposed a multi-layered photonic radiative cooler. The results shows that the cooler could reach a steady-state temperature of about 5 °C below ambient for over one hour where the solar irradiance ranges from 800W/m² to 870W/m² [3]. Gang et al. presented a novel combined solar heating and radiative cooling collector which could act as a solar collector in the daytime and be a radiative cooler at nighttime. The experimental results proved that this combined collector shows good performance in both working modes [4].

There are mainly three greenhouse gases in the atmosphere, that is, carbon dioxide, ozone and water vapour. The content of the first two gases are relatively stable while that of the water vapour varies in a large range depending on the geographical and seasonal characteristics. Therefore, the water vapour amount may exert a significant influence on the performance of radiative cooling. In the
present study, a traditional radiative cooler was employed as the research object. A steady heat transfer mathematic model that considers the spectral radiant distribution of the sky, the transparent cover and the collecting surface was established to investigate the effect of precipitable water vapor amount on radiative cooling performance in different seasons and regions.

2. Description of the radiative cooler
The radiative cooler should possess high spectral emittance in the atmosphere window to take full advantage of high transmittance of this heat transfer path. Additionally, the cooling surface should have low spectral absorptivity in those bands excluding atmospheric window wavelength to reject most radiated heat from the sky and surroundings. The spectral property of ideal radiative cooling surface is shown in Figure 1. The real surface studied in this paper is the traditional aluminum-evaporated polyvinyl-fluoride surface (short for Al-evaporated PVF), and its spectral property is also presented in Figure 1, from which we can see that a relative good agreement was found between the real and ideal radiative cooling surfaces.

![Figure 1. The spectral property of Al-evaporated PVF surface and ideal radiative cooling surface.](image)

The section structure of the radiative cooler is presented in Figure 2. The radiative cooler mainly comprises three components: the radiative cooling surface, the transparent cover and the insulation material. The size of the cooling surface is 0.2 m * 0.2 m * 0.0004 m. A 6μm - thick low-density polyethylene film was employed as the transparent cover in this study, and the insulation material is phenolic resin with a thickness of 0.06m. The radiative cooler was placed horizontally with an unobstructed view of the sky to get the maximum radiative cooling possibility.

3. Mathematic model of heat transfer
In this paper, a steady-state heat transfer model was employed to describe the heat transfer between the radiative cooler and its surroundings. The heat transfer model consists of two equation sets, namely, the heat-balance equation of (i) the transparent cover and (ii) the radiative cooling surface.

3.1. Heat-balance equation of the transparent cover
The heat-balance equation of the transparent cover can be expressed as follows:
The sky temperature is written as follows:

\[ T_s = 0.0552T_a^{1.5} \]  

(2)

The convective and radiation heat-transfer coefficients between the cover and the environment are derived as Eqs. (3) and (4) respectively:

\[ h_a = 2.8 + 3.0u_a \]  

(3)  

\[ h_{sc} = \varepsilon_c \sigma (T_s^2 + T_c^2)(T_s + T_c) \]  

(4)

The heat transfer coefficient between the transparent cover and radiative cooling surface consists of two parts, namely, convection and radiation. The heat transfer coefficient is express as follows:

\[ h_{pc} = \sigma(T_p^2 + T_c^2)(T_p + T_c) \frac{1}{1/\varepsilon_p + 1/\varepsilon_c - 1} + \frac{Nu \cdot k_a}{d_{pc}} \]  

(5)

If \( T_p > T_c \), then the Nusselt number is expressed as follows [5]:

\[ Nu = 1 + 1.14 \left( 1 - \frac{1708 \cdot (\sin 1.8 \beta)^{1.6}}{Ra \cdot \cos \beta} \right) \left[ 1 - \frac{1708}{Ra \cdot \cos \beta} \right] + \left( \frac{Ra \cdot \cos \beta}{5830} \right)^{1/3} - 1 \]  

(6)

where the + exponent indicates that only positive values are used for the terms within the square brackets; in case of negative values, zero is used. If \( T_p < T_c \), then the Nusselt number is expressed as follows [6]:

\[ Nu = 1 + \left[ 0.364 \frac{L_p}{d_{pc}} Ra^{1/4} - 1 \right] \sin \beta \]  

(7)

If \( T_p = T_c \), the Nusselt number is equal to zero.

3.2. Heat-balance equation of the radiative cooling surface

The heat-balance equation of the radiative cooling surface is expressed as follows:

\[ h_{pc}(T_c - T_p) + u_{ap}(T_a - T_p) - Q_{rad, net} = 0 \]  

(8)

The heat transfer coefficient between the cooling surface and environment is written as follows:

\[ u_{ap} = 1 \left( \frac{1}{h_a + \frac{d_b}{k_b}} \right) \]  

(9)

The net radiative cooling power between the cooling surface and sky is expressed as follows:

\[ Q_{rad, net} = Q_{rad, p} - Q_{rad, s} \]  

(10)

where \( Q_{rad, p} \) is derived as follows [7]:

\[ Q_{rad, p} = \int_{0}^{\infty} \left[ \frac{E_{b,\lambda}(T_p) \cdot (1 - \rho_{c,\lambda}) - \varepsilon_{c,\lambda} \cdot E_{b,\lambda}(T_c)}{1/\varepsilon_{p,\lambda} - ((1 - \varepsilon_{p,\lambda}) / \varepsilon_{p,\lambda}) \cdot \rho_{c,\lambda}} \right] \, d\lambda \]  

(11)

and \( Q_{rad, s} \) is calculated as follows [7]:

\[ Q_{rad, s} = \int_{0}^{\infty} \left[ \frac{E_{b,\lambda}(T_s) \cdot (1 - \rho_{c,\lambda}) - \varepsilon_{c,\lambda} \cdot E_{b,\lambda}(T_c)}{1/\varepsilon_{p,\lambda} - ((1 - \varepsilon_{p,\lambda}) / \varepsilon_{p,\lambda}) \cdot \rho_{c,\lambda}} \right] \, d\lambda \]
The spectral emissivity of the atmosphere can be calculated from a simple correlation using the precipitable water vapor amount as the only input parameter for any geographic area and season \[8\]. However, this parameter greatly depends on geographic area and season. For Hefei in summer, the precipitable water vapor amount can be expressed using the following semi-empirical equation \[9\]:

\[ w = \exp(-0.508 + 0.089t_d) \] (13)

The net heating or cooling power of the system can be expressed as follows:

\[ Q_{\text{net}} = Q_{\text{rad, net}} - Q_{\text{ac}} - Q_{\text{ap}} \] (14)

where \( Q_{\text{ac}} = h_{ac}(T_a - T_c) \) and \( Q_{\text{ap}} = u_{ap}(T_a - T_p) \).

4. Results and discussion

4.1. Equilibrium temperature
Firstly, the ambient temperature and wind velocity are fixed at 30 °C and 4.0 m/s. The equilibrium temperature and temperature difference between the radiative cooling surface and surroundings (short for temperature difference) under different precipitable water vapor amounts \( w \) were calculated and shown in Figure 3(a). As the precipitable water vapor amounts increases, the equilibrium temperature increases as well with a decreased variation rate. Specifically, the temperature difference could reach 25 °C when \( w \) is 0.5 cm, while drops sharply to 10.8 °C when \( w \) rise up to 7.0 cm. Therefore, the radiative cooler will exhibit a better performance in drier climate. Besides, \( w \) is only related to the dew point temperature \( t_d \) according to Eq. (14) while \( t_d \) is determined by both the relative humidity and ambient temperature. Therefore the cooling performance deteriorates as the ambient temperature increases when relative humidity is the same. This result could explain why the radiative cooler shows better performance in winter than in summer.

4.2. Cooling power
Likewise, the ambient temperature and wind velocity are fixed at 30 °C and 4.0 m/s. Figure 3(b) presents the variation of cooling power under different precipitable water vapor amounts and cooling surface temperatures. On one hand, the cooling power decreases with a decreased variation velocity as \( w \) increases under the same surface temperature. On the other hand, the cooling power increases linearly as the surface temperature increases under the same \( w \). Besides, the cooling power will be zero when the surface reaches its equilibrium temperature. Additionally, the net radiative cooling power will be obtained when the surface temperature is equal to the ambient temperature, in which case no heat conduction and convection occurs between the surface and surroundings. When \( w \) increases from 0.5 cm to 7.0 cm, the net radiative cooling power drops remarkably by 41.0% from 73.5 W/m\(^2\) to 43.4 W/m\(^2\), indicating that the precipitable water vapor amount has a great and negative influence on radiative cooling performance.
Figure 3. (a) The equilibrium temperature and temperature difference between the radiative cooling surface and surroundings under different precipitable water vapor amounts. (b) Variation of cooling power under different precipitable water vapor amounts and cooling surface temperature.

4.3. Annual radiative cooling performance in Hefei

The precipitable water vapor amount is changeable by seasons. Based on the typical meteorological year (TMY) data provided by EnergyPlus software, the annual cooling performance in Hefei was studied. The nighttime TMY data of Hefei from 20:00 to 4:00 is employed. Figure 4 shows the variation of two key cooling performance indicators of the radiative cooler, namely, equilibrium temperature and net radiative cooling power. The annual average temperature difference $\Delta T_{ap}$ and net radiative cooling power $Q_{rad_net}$ are 16.21°C and 47.10 W/m$^2$, respectively. Due to the dew point temperature is lower in winter than in summer, which causing the same characteristic of precipitable water vapor amount, the cooler exhibits the best performance in winter and the worst in summer. For instance, the maximum temperature difference $\Delta T_{ap}$ and net radiative cooling power $Q_{rad_net}$ occur in December and February with values of 19.4 °C and 50.9 W/m$^2$, respectively. By contrast, the minimum $\Delta T_{ap}$ and $Q_{rad_net}$ occur in July and August, respectively, with values of 12.3 °C and 39.8 W/m$^2$. Moreover, the average net radiative cooling power in summer is 41.6 W/m$^2$, which is about 82.2% of that in winter.

Figure 4. Annual radiative cooling performance of the radiative cooler in Hefei.

5. Conclusions

In the present study, the effect of precipitable water vapor amount on the radiative cooling performance of a traditional radiative cooler was numerically investigated using a mathematic model of steady heat transfer. The results led to the following conclusions:

(1) Precipitable water vapor amount shows a great effect on the performance of the radiative cooler. The smaller the precipitable water vapor amount is, the lower the equilibrium temperature
could reach and the larger the net radiative cooling power would be obtained. Therefore, the radiative cooler exhibits better performance in drier and colder climate.

(2) Better cooling performance is observed in winter than in summer. For Hefei, the average net radiative cooling power in summer is about 82.2% of that in winter.

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