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# Radiative Cooling Technology for Data Center Cooling Systems

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**ABSTRACT**

In order to promote the green, energy-efficient and sustainable development of data centers, this study introduces a hybrid cooling system that incorporates the full-day radiative cooling technology into data centers and couples it within a heat pipe integrated cooling system, which efficiently operates alongside mechanical refrigeration and natural cold sources. The radiative cooling performance and regional adaptability in 12 major cities in China were analyzed using Energy Plus and mathematical modeling. Moreover, a 40-day test was conducted in Hebei to validate the practical operation of the radiative cooling system. The results demonstrated that during the summer, the average maximum net radiative cooling power can reach 40-50 W/m². The study also reveals the potential of combining the radiative cooling system with traditional air conditioning, leading to an average annual energy savings rate of 28% for data centers. The research provides valuable guidance for the design and implementation of radiative cooling systems in data centers.

**Keywords:** data center, radiative cooling, mathematical modeling, cooling system, energy efficiency

**NONMENCLATURE**

| | |
|---|---|
| *Abbreviations* | |
| RC | Radiative Cooling |
| IDC | Internet Data Center |
| P | Power, kW |
| T | Temperature, K |
| PE | Polyethylene |
| *Symbols* | |
| $rad$ | Radiative |
| sun | Solar radiation |
| non-rad | Non-radiative heat transfer |
| conv | Convection |
| cond | Conduction |
| atm | Atmosphere |
| amb | Ambient |

## 1. INTRODUCTION

With the advent of the 5G era, data storage and management have become more and more difficult, and a dedicated facility is needed to process and protect large amounts of data. IDCs (Internet Data Centers) serve as the central facilities for storing, processing, and managing vast volumes of data. Therefore, the demand for IDCs has also increased significantly. [1] According to the "2021-2022 China IDC Industry Development Research Report", it is expected that in 2022, the global IDC market size will exceed US 770 billion, and the growth rate has remained stable in recent years (Fig. 1(a)). According to the report of the IDC Energy-saving Technology Committee of the China Electronic Energy-Saving Technology Association, the power consumption of IDCs in 2021 will account for about 2.6% of the electricity consumed by the whole society, and it is showing an increasing trend year by year (Fig. 1(b)). Among them, the energy consumption of the cooling system is about 40% of the total energy consumption of the IDC. Therefore, studying the energy-saving technology of the IDC cooling system is an important way to reduce the energy consumption of the IDC.

RC (Radiative Cooling) technology based on zero energy consumption can not only meet thermal management needs in a carbon-neutral manner, but also meet the environmental sustainability required by carbon peak. In the 1970s, Catalanotti et al. [2] proposed selective surface daytime RC. The principle of RC is that outer space can be regarded as a cold source with a

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temperature close to 3 K. Objects on the ground transmit heat to outer space through the atmospheric window (8~13 μm). With the rapid development of materials science, major breakthroughs have been made in daytime RC technologies [3]. Shanhui Fan et al. [4] made a RC film with a solar reflectance of 97%. Ronggui Yang et al. [5] created a RC film with a solar reflectance of 96% and a noon cooling power of 93 W/m$^2$.

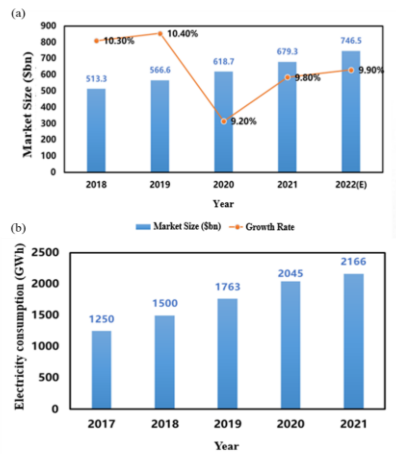


Fig. 1 (a) The global IDC market size and growth rate; (b) Changes in electricity consumption of IDCs in China

In this study, we integrate the RC system with a heat pipe cooling system to efficiently harness natural cold sources for IDC. The RC module incorporates a selective film with high emissivity and low solar absorption. By employing Energy Plus and mathematical models, we simulate the peak cooling power and temperature reduction of the RC system across 12 typical Chinese cities. And we analysis factors that influence performance and regional adaptability. To validate the effectiveness of the RC film, we establish an experiment and conduct a 40-day test. Lastly, we compare the energy-saving benefits with those of traditional IDC cooling methods.

## 2. MATHEMATICAL MODEL AND SIMULATION

### *2.1 Basic principles of radiative cooling*

When solar radiation passes through the atmosphere, it will be absorbed, reflected, and scattered. And when the earth's surface radiates out into space, it will also be absorbed, reflected, and scattered. Although the atmosphere is transparent in the visible band, it is not transparent in the infrared band. The most important transparent band is 8-13 μm, also known as the "atmospheric window." Therefore, the main part of the earth's radiation heat transfer is radiated from this window to the space. The use of materials with the highest emissivity in the atmospheric window can achieve RC without energy consumption. Therefore, RC materials should have two optical properties: minimize the absorption of the solar spectrum and maximum the emission of the atmospheric window. Selective emitters have more potential in daytime RC applications.

### *2.2 Construction of mathematical models*

For a certain RC surface, it is affected by the combination of solar radiation, atmospheric radiation and the environment. Fig. 2 is a simplified schematic diagram of the heat exchange of the RC surface.

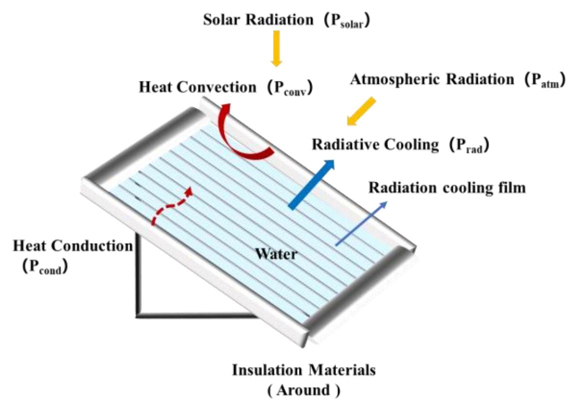


Fig. 2 Simplified schematic diagram of heat exchange on the surface of radiated refrigeration

The following formula is the energy balance relationship on the surface of the radiated refrigeration film, that is, the net radiated refrigeration power $P_{cool}$ can be expressed by the following formula：

$$P_{cool}(T) = P_{rad}(T) - P_{atm}(T_{amb}) - P_{sun} - P_{non-rad} \quad (1)$$

$$P_{non-rad} = P_{conv} + P_{cond} \quad (2)$$

Where $T$ represents the absolute temperature of the RC surface, K; $T_{amb}$ is the ambient temperature, K; $P_{cool}(T)$ is the net RC power of the radiated surface, W/m$^2$; $P_{rad}(T)$ is the surface thermal radiation power, W/m$^2$; $P_{atm}(T_{amb})$ is the atmospheric radiation absorbed by the RC surface, W/m$^2$; $P_{sun}$ is the solar radiation absorbed by the RC surface, W/m$^2$; $P_{non-rad}$ is the RC surface non-radiated heat transfer with the surrounding environment, W/m$^2$, including heat convection $P_{conv}$ and heat conduction $P_{cond}$, W/m$^2$.

#### 2.2.1 Radiative Power of Radiating Surfaces

In the entire wavelength range, the total radiative power per unit area, denoted as $P_{rad}$, which can be represented by the following equation:

$$P_{rad}(T) = \int cos\theta d\Omega \int_0^{\infty} \varepsilon(\lambda,\Omega) E_b(\lambda,T) d\lambda \quad (3)$$

Where $\Omega$ is the three-dimensional angle, $\int d\Omega$ is the angular integral of the hemisphere, $\theta$ is the zenith angle, $\varepsilon(\lambda,\Omega)$ is the surface emissivity, $E_b(\lambda,T)$ is the blackbody spectral radiance, given by Planck's law. The total hemisphere emissivity $\varepsilon_{cooler}$ can be used to simplify $\varepsilon(\lambda,\Omega)$.

$$\bar{\varepsilon}_s = \frac{\int \cos\theta d\Omega \int_0^{\infty} I_{bb}(T_s,\lambda)\varepsilon_s(\lambda,\Omega)d\lambda}{A\sigma T_s^4} \quad (4)$$

Where: A is the effective area of the RC surface facing the sky, $\sigma$ is the Stefan-Boltzmann constant $5.67\times10^{-8}\mathrm{W/(m^2K^4)}$. Hence, the equation (3) can be simplified as:

$$P_{rad}(T) = \varepsilon A\sigma T_s^4 \quad (5)$$

The RC film used in this study was provided by Ningbo Rayleigh Company, with a solar reflectance of 96% and an emissivity of 93%.

2.2.2 Atmospheric Radiative Power

The RC surface absorbs atmospheric radiation mainly from wavelengths beyond the atmospheric window. Utilizing Kirchhoff's law and substituting emissivity for absorptivity, the $P_{rad}(T)$ is expressed as:

$$\mathrm{P_{atm}(T_{amb})} = 2\pi\int_0^{\frac{\pi}{2}}\int_0^{\infty} \varepsilon(\lambda)\varepsilon_{\mathrm{atm}}(\lambda,\theta)\mathrm{E_b}(\lambda,\mathrm{T_{amb}})\ d\lambda\cos\theta d\theta \quad (6)$$

The atmospheric spectral emissivity is influenced by factors such as angle, humidity, cloud cover, geographical location, and season. So the atmospheric spectral emissivity can be simplified using an empirical model of equivalent atmospheric emissivity [6].

## 3. RADIATIVE COOLING PERFORMANCE TEST BENCH

### *3.1 Experimental Methods and Equipment*

The properties of RC, along with weather parameters and system characteristics, collectively influence $P_{cool}(T)$. Typically, the maximum net RC power $P_{coolmax}$ and the achievable temperature reduction $\mathrm{Ta-Tmin}$ are employed to assess the practical performance of RC materials.

When the temperature of the RC thin film's surface approaches the ambient temperature, the cooling loss due to non-radiative heat transfer can be neglected. So the energy balance equation is as follows:

$$P_{coolmax} = P_{rad} - P_{atm} - P_{sun} \quad (7)$$

Where $P_{coolmax}$ represents the cooling power when the temperature of the RC surface equals $T_{amb}$.

When $P_{cool}(T)$ is zero, the surface temperature is $T_{\min}$ The energy balance equation is as follows:

$$P_{\mathrm{rad}}(T_{\min}) - P_{\mathrm{sun}} - P_{\mathrm{atm}}(T_{\mathrm{a}}) - P_{\text{non-rad}} = 0 \quad (8)$$

The experimental setup should minimize the effects of thermal conduction and convection. The RC testing module is illustrated in Fig. 3(a). Initially, the testing apparatus comprises a cube made of insulating polystyrene foam. At the upper center is a rectangular air gap. From bottom to top, the layers consist of an electric heating element, a copper plate and a RC film. To mitigate cooling losses caused by non-radiative heat transfer, the top is covered with a polyethylene (PE) film acting as a convection shield. The copper plate conducts heat, while the electric heating element is connected to a programmable power supply (Fig. 3(c)) to provide controlled heat input. This maintains the radiative surface temperature at the $T_{amb}$, facilitating the $P_{coolmax}$. As depicted in Fig. 3(b), seven T-type thermocouples are distributed between the RC film and the copper plate.

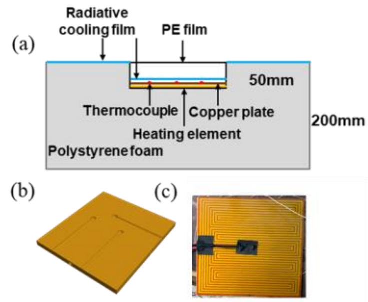


Fig. 3 (a) RC test module; (b) Copper sheet; (c) Electric heating sheet

This experiment enables real-time monitoring of the environment while measuring the maximum achievable temperature reduction $\mathrm{Ta-Tmin}$ and maximum net RC power $P_{coolmax}$. The $P_{coolmax}$ is determined by the 'thermal feedback method', employing a Proportional-Integral-Derivative (PID) control algorithm.

### *3.2 Experimental Testing*

The RC test experiment setup is illustrated in Fig. 4. The experimental testing period spanned from June 30 to August 10, 2023. The entire setup was positioned above an elevated structure outdoors in Hebei. Both the $T_{amb}$ and the radiative surface temperature were fed into PID program. This program was connected to a DC power supply, which adjusted the power delivered to the electric heating element to maintain the RC film temperature at the $T_{amb}$.

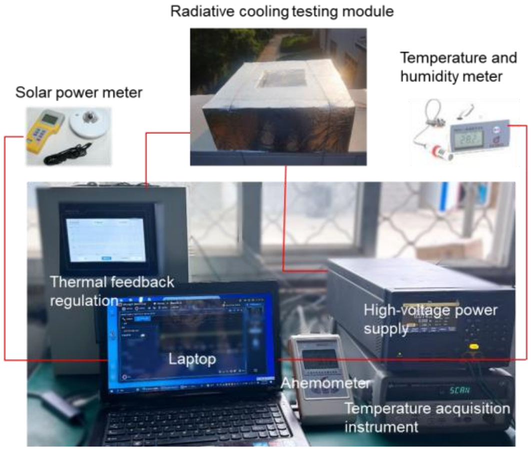


Fig. 4 RC test bench

## 4. RESULTS AND DISCUSSION

### *4.1 Simulation Results and Analysis*

#### 4.1.1 Maximum Net Radiative Cooling Power

Through the calculation, the annual hourly variation diagram of the $P_{coolmax}$ of 12 cities in China is shown in Fig. 5, including Lanzhou, Urumqi, Lhasa, Xi'an, Shijiazhuang, Beijing, Changchun, Harbin, Chengdu, Changsha, Guiyang and Haikou. It can be seen that the performance of the RC system is better in the northern regions. For example, in Urumqi, the annual average $P_{coolmax}$ can reach 83.9 W/m$^2$. These areas are relatively dry and the $T_{amb}$ is low. In the southeast coastal area, the climate is hot and humid, and the energy saving effect of the system is limited.

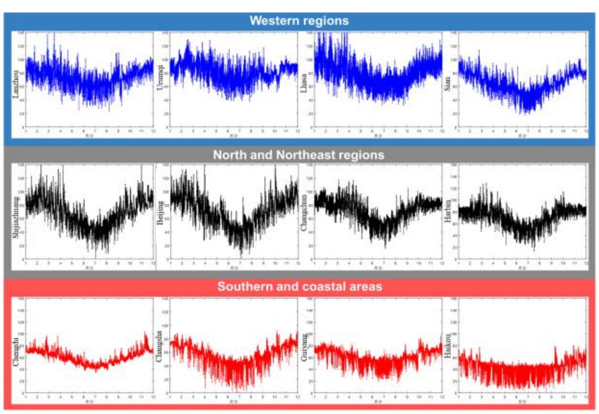


Fig. 5 Annual Pcoolmax in 12 Chinese cities

#### 4.1.2 Reduced temperature

By comparing and analyzing the maximum temperature that can be reduced in 12 typical cities in China, Fig. 6 shows the year-by-hour change graph of the temperature $\mathrm{Ta}-\mathrm{Tmin}$ in different cities. The conclusion is the same as above. The annual average $\mathrm{Ta}-\mathrm{Tmin}$ in Beijing can reach 19.2°C. The RC effect of southern cities is generally lower than that of northern cities. This also provides data reference and site selection suggestions for practical engineering applications.

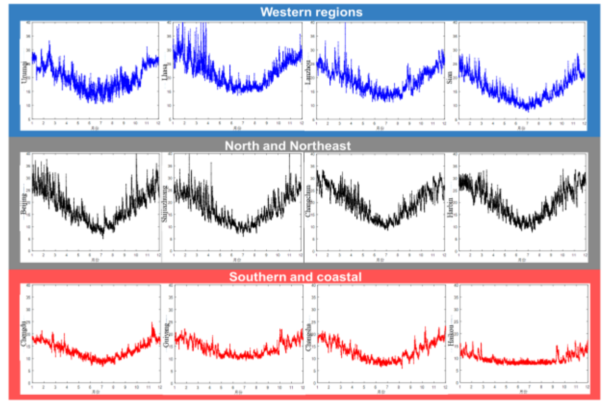


Fig. 6 Annual temperature Ta-Tmin in 12 Chinese cities

### *4.2 Experimental Results and Analysis*

The data on July 9, 2023 is more classic, as shown in Fig. 7(a), the average $P_{coolmax}$ is 48.03 W/m$^2$. And the data on July 16 is more typical during the test. The average $\mathrm{Ta}-\mathrm{Tmin}$ is 4.00 °C, as shown in Fig. 7(b). Fig. 7(c), (d) show the environmental parameters on July 9 and July 16: solar radiation power, ambient temperature, wind speed and relative humidity.

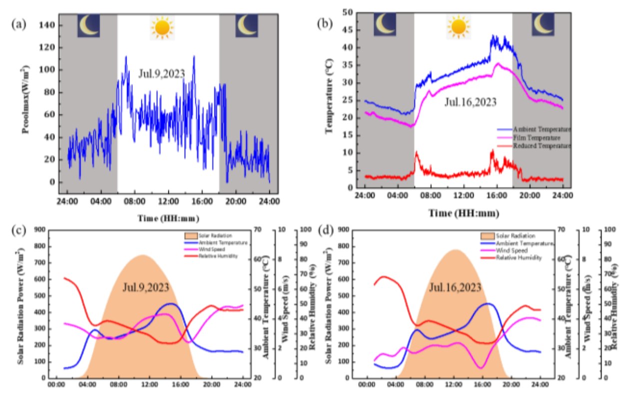


Fig. 7 (a) Pcoolmax *on July 9; (b) Ta-Tmin on July 16; Environmental parameters* on (c) July 9; (d) July 16

It can be concluded that when the solar radiation is strong at noon, the surface temperature of the RC is close to the ambient temperature, and the RC power is low. At night, the surface temperature of RC is lower than the $T_{amb}$. Through the comparison of experimental data, it can be found that the greater the relative humidity of the environment, the worse the effect of RC. And RC effect has a strong correlation with weather.

### *4.3 Cooling System Design for IDCs*

This study proposes a combined heat pipe cooling system that integrates RC. The schematic diagram of the overall cooling system is shown in Fig. 8, which is applied throughout the year in IDC. The RC system serves as a supplementary cooling system, directly cooling the condenser to enhance cooling efficiency. The heat pipe cycle and vapor compression refrigeration cycle operate relatively independently, allowing for seamless and smooth transitions. During transitional seasons, the heat pipe cycle, vapor compression refrigeration cycle, and RC cycle operate efficiently together, maximizing the utilization of natural cold sources.

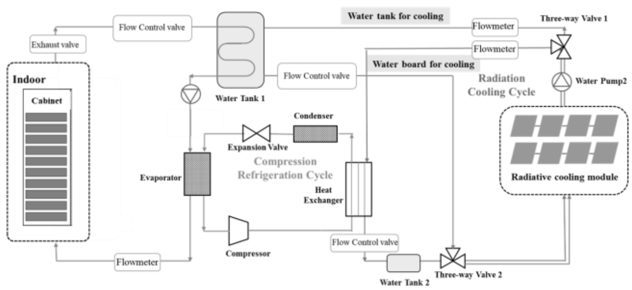


Fig. 8 Schematic diagram of RC system

### *4.4 Conclusions Energy Saving Potential Analysis*

If the RC system is combined with traditional air conditioning system and applied to a small-scale IDC in Beijing, the average annual energy savings rate of the IDC can reach 28% according to simulations.

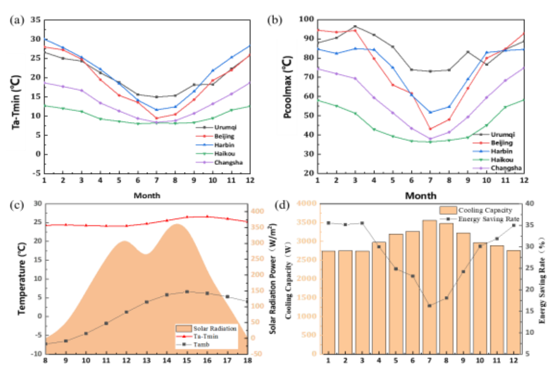


Fig. 9 (a)Ta-Tmin; (b)Pcoolmax of 5 cities; (c) Beijing winter daytime weather; (d) Simulation trend of cooling load and energy saving rate of IDCs

## 5. CONCLUSIONS

(a) This study proposes a composite refrigeration system that applies RC technology to IDCs. The system is coupled to a heat pipe cooling system that applies efficiently natural cooling sources. The RC module uses a RC film that has an emissivity as high as 93% and a solar absorption coefficient as low as 4%.

(b) This study uses Energy Plus and mathematical modeling to calculate $P_{coolmax}$ and $\mathrm{Ta-Tmin}$ of 12 typical cities in China. And we analyze the factors affecting cooling performance and the adaptability of different regions. The results show that the RC power is higher in relatively dry and low temperature areas.

(c) This study designs a test bench for testing the RC film performance in Hebei, and the test was carried out for 40 days in summer. The results show that the average $P_{coolmax}$ is 48.03 W/m$^2$, and the average $\mathrm{Ta-Tmin}$ is 4.00°C. Finally, if the RC system is combined with the traditional air conditioning system, the annual average energy saving rate of the IDC can reach 28%.

Therefore, this study provides a new idea for the development of green energy-saving cooling technology for IDCs in the future.

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