Thermal analysis in daytime radiative cooling

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Abstract. Radiative cooling is a well-researched cooling technique which is based on the ability of terrestrial surfaces to dissipate heat to the cold outer space. Past research on radiative cooling mostly failed to present sub-ambient temperature under direct sun due to the limited solar reflectance and emissivity in the atmospheric window. The nanostructures developed in recent years have successfully achieved sub-ambient feature during daytime. This paper mainly presents and analyses the experiment and simulation/calculation in the related thermal analysis in daytime radiative cooling. The main purpose is to provide some feasible tools, techniques in testing its thermal performance. It emphasizes the importance of objective and critical evaluation about different cooling performance results reported in papers since the results are significantly influenced by settings in both simulation and experiment.

1. Introduction

Among all the cooling technologies for building and outdoor environment, material-related radiative cooling is of great potential since it can work without consuming extra energy or heating the nearby air. It is commonly believed that the ideal radiative cooling material should have: (a) Extreme high reflectivity in solar wavelength, mainly in 0.3-2.5 μm; (b) near unity emissivity in the atmospheric window range, 8-13 μm [1], as is shown in Figure 1. Previous research mainly aimed at discovering natural or creating composite materials having the satisfying optical properties. The incapability to control the optical spectrum precisely significantly constraints the performance of the cooler.

Figure 1. Spectral Irradiance and ideal emissivity spectrum in 0.25-20μm

In recent years, as the nanofabrication technologies mature, the structure of materials can be modified at nanoscale, leading to the possibility to further increase the spectral reflectivity and emissivity. Some multilayer planar photonic structures [2-5], 2D/3D photonic devices [6, 7], metamaterials [8, 9], polymer [10-14] and paints [15] have been developed and are reported to have the satisfying optical properties. Among these materials, most of them are demonstrated to be able to reach sub-ambient temperature under direct sun. Their cooling performance is indicated by the sub-
ambient temperature or the cooling power of the cooler. Since these 2 indicators are extracted from simulation/calculation or experiment result, their reliability can be significantly influenced by the choice of simulation tool, accuracy of the tool selected, the season, climate of the experiment, peak solar radiation during the experiment, the insulation property of the apparatus, whether the apparatus is prevented from convection or direct solar radiation, and so on.

This paper aims to present and analyse thermal analysis including simulation and experiment concerning daytime radiative cooling. How the calculation or simulation tool works, the key factors influencing the experiment result and the possible explanation of why some experiment disagrees with the theoretical analysis are also reported and discussed.

2. Fundamentals of radiative cooling

The cooling flux of a radiative cooler, \( P_{\text{cool}} \) (W/m\(^2\)), is a function of the emitted longwave radiation by the cooler, \( P_{\text{rad}} \) (W/m\(^2\)); the absorbed solar radiation, \( P_{\text{solar}} \) (W/m\(^2\)); the absorbed ambient radiation, \( P_{\text{ambient}} \) (W/m\(^2\)); and the convective and conduction heat gains/losses, \( P_{\text{con}} \) (W/m\(^2\)):

\[
P_{\text{cool}} = P_{\text{rad}} - P_{\text{solar}} - P_{\text{ambient}} - P_{\text{con}}
\]

(1)

\( P_{\text{rad}} \) is a function of the temperature and the spectral emissivity of the material:

\[
P_{\text{rad}} = \int_{\lambda_0}^{\lambda_\infty} I_{BB}(T_m, \lambda) \epsilon(\lambda) d\lambda
\]

(2)

where \( I_{BB} \) is the black body radiation spectrum based on Planck’s law which is a function of material’s surface temperature \( T_m \) and wavelength \( \lambda \). \( \epsilon(\lambda) \) is the spectral emissivity of the material. \( P_{\text{solar}} \) is calculated through the integral of the solar spectrum and material spectral absorptance:

\[
P_{\text{solar}} = \int_{\lambda_0}^{\lambda_{25}} SS(\lambda) A(\lambda) d\lambda
\]

(3)

where \( SS \) is the solar spectrum derived from ASTM G173, which is shown in Figure 1(a). \( A(\lambda) \) is the spectral absorptance of the material. Absorption of ambient radiation \( P_{\text{ambient}} \) can be written as:

\[
P_{\text{ambient}} = \int_{\lambda_{25}}^{\lambda_{45}} I_{BB}(T_{\text{air}}, \lambda) e_{am}(\lambda) A(\lambda) d\lambda
\]

(4)

where \( T_{\text{air}} \) is the ambient air temperature; \( e_{am} \) is the atmospheric spectral emissivity. The ambient radiation for a typical tropic city obtained in MODTRAN 6 [16] is shown in Figure 1(b) as an example. The conduction and convection heat gain of the material can be calculated using the following equation:

\[
P_{\text{con}} = c \cdot (T_{\text{air}} - T_m) + \alpha \cdot (T_{\text{air}} - T_m)
\]

(5)

where \( \alpha \) and \( c \) are the convection coefficient and conduction coefficient.

3. Theoretical analysis

The theoretical analysis is based on fundamental equation (1). Environment related inputs are solar radiation, ambient radiation, ambient air temperature, wind speed and the two radiation spectrums in short and long wavelengths while material related inputs are heat capacity, mass, spectral reflectance and emissivity and area of the sample. With these input parameters determined, the cooling power and the temperature of the cooler can be directly calculated.

COMSOL is a common software used as the heat transfer simulation tool. In [2], it is used to quantify the combined non-radiative heat transfer coefficient. A thin radiator, surrounding air and the polystyrene block are objects included in the simulation. After this coefficient is extracted, it is subsequently used in the theoretical model (Equation for calculating the net cooling power of the radiative cooler). The predicted steady-state temperature is 4.2 °C below ambient which agrees well with the experiment. The atmospheric transmission here is obtained from MODTRAN 5.

Direct calculation is used in a big amount of the papers. When a net positive power outflow exists when the temperature of the surface equals that of the ambient, the device becomes a daytime cooling surface. The calculation in [5] is conducted not only for coolers, but also for two additional cases with idealized emissivity, one is of unity emissivity beyond 4.5μm and zero elsewhere, while the other one only has unity emissivity in atmospheric window. It has raised a doubt that whether emissivity or absorption outside the main atmospheric window is detrimental. It is turned out that if parasitic conduction and convection exist, expanding the emissive bandwidth can be beneficial to the cooling performance. The theoretical analysis here plays a crucial role in identifying the optimal emissivity spectrum. Besides, the predicted steady-state temperature by calculation is 8.7 °C below ambient.
under direct sun which agrees well with the experiment. Similar calculation is done by [17]. Two comparative materials, SiC (a broadband absorber) and SiO$_2$ (absorbing mainly in atmospheric window), are tested as emitters. The same conclusion is drawn in [5], indicating the better performance of the broadband emitter in the real environment. But the predicted sum-ambient performance is not observed in the experiment. The author reports the influence of relatively high humidity and cloudy sky in Shanghai as explanation of the disagreement.

The theoretical analysis in [4] is quite similar to that of [5]. By calculation, it draws the conclusion that in order to reach the limit on radiative cooling, ultra-low parasitic heat loss is required and solar irradiance needs to be suppressed. For the structure proposed in [18], it is reported that cooling power is 85.5W/m$^2$ according to calculation. But it lacks further description of the other parameters like whether conduction and convection are considered and what value of solar radiation it uses for calculation. They make the assumption that temperature of the structure was always the same as that of the ambient, in other words, the conduction and convection heat transfer are neglected, leading to the uncertainty of their simulation result.

The theoretical estimation of cooling power in [15] extracted the sky’s hemispherical spectral radiance from MODTRAN 6 Web Application. They also reported that humidity and total precipitable water heavily influences the magnitude of cooling power. Therefore, the resolution of meteorological data should be as high as possible. A small error of 2mm in the total precipitable water data can change the cooling power by 5W/m$^2$.

4. Experiment
The performance of coolers cannot be compared directly because the cooling power depends significantly on experiment design, season, local climate and meteorological variables, see Table 1.

4.1 Measured Index
In most of the experiments, temperature of both the radiative cooler and ambient air is the directly measured index for evaluating the cooling performance [2, 4, 5, 17]. Since the temperature of the cooler differs with that of the ambient in most cases, convection and heat conduction are inevitable. Since these heat exchanges vary with boundary conditions and stochastic environmental parameters such as wind speed, the resulted temperature of the cooler cannot be compared directly.

In [12], a feedback-controlled system is implemented to keep the cooler temperature the same as the ambient temperature and accurately records the true radiative cooling power. It keeps the temperature difference between ambient and cooler less than 0.2$^\circ$C over the whole experiment period. The uncertainty of the measurement due to conductive and convective heat exchange between ambient air and the cooler is therefore substantially eliminated. By doing like this the cooler is able to be exposed directly to surrounding air without the necessity of a convective cover.

4.2 Has a convective cover or insulation
Convective heat transfer is one part of the non-radiative heat exchange and it can influence the cooling performance significantly due to the existence of temperature difference between the ambient air and the device. If the device is of sub-ambient temperature, the ambient air will be continuously heating the surface. That is why in most of the experiment settings, a convective shield is used to cover the top surface of the device, as is shown in Table 1. Such a cover can significantly prevent the heat gain due to convection since it blocks most of the air circulation. In [5], [9] and [11], authors have proved the huge difference of cooling performance caused by the difference of convective heat transfer coefficient. Polyethylene film is usually used as the convective shield due to its high transmittance in almost all wavelengths [2, 3, 5, 10, 12, 15, 17, 19]. ZnSe is used in [4] but it is of much higher cost.

Heat transfer by conduction is the other part of the non-radiative heat exchange and influences the cooling performance as well. Similar to the prevention of convection, various of insulations are used to prevent the heat conduction to surrounding objects. Polystyrene is the most common material used for insulation [2, 12, 15, 17, 19]. Some also use aerogel blanket [5], double-walled acrylic enclosure [3, 10] and vacuum [4].
4.3 Has a sunshade or not

The solar radiation is composed by direct part and diffuse part. The intensity magnitude of these two parts differ a lot. According to a field measurement in [15], the direct normal solar radiation is over 1000 W/m² while the diffuse radiation is only around 70 W/m². That means the direct solar radiation makes up the majority of the solar radiation concerning energy intensity. But in some researches, in order to get remarkable cooling performance, this direct radiation is blocked by a sunshade. Like in [4], by adding a sun shade to block the direct sun, they got a deep-freezing cooling performance. But this achievement cannot be directly compared to other daytime radiative cooling devices.

4.4 Season, climate and meteorological condition

Parameters significantly influenced by season, climate and meteorological condition are solar radiation, ambient radiation, ambient air temperature and wind speed. The amount of solar radiation is impacted by latitude, altitude, solar elevation angle, quantity of clouds, tilt angle of the apparatus, etc. The intensity of ambient radiation is influenced by latitude, altitude, humidity, aerosol contents, temperature of the atmosphere, zenith angle, etc. Wind speed is directly related to terrain and the geographical location, for example, whether there is sea or desert nearby. Influencing factors to air temperature are well-researched. It fluctuates due to the change of solar radiation and radiant surface heat.

Apparently, the cooling experiment in summer is more challenging that other seasons because the increased average and peak solar radiation due to the increase of solar elevation angle and the range of azimuthal angle. For example at Stanford, the solar elevation angle could be 70° in summer while being below 40° in winter [4]. The climate and meteorological condition of where the experiment is conducted also impacts the result a lot. For example, the experiment of [17] was conducted in Shanghai, a city of humid subtropical climate. The experiment was conducted in a cloudy day. The structure did not get sub-ambient as was predicted by the calculation. The relatively high humidity and partly cloudy sky are the possible reasons for this disagreement. The similar result is observed in [3]. They conducted the experiment in Okayama, Japan. Compared to their theoretical prediction, the cooling performance of the structure is deteriorated due to the high humidity in the experiment. They also calculated the equilibrium temperature of the device as a function of the precipitable water vapor (PMV). They found that the device temperature at PMV=20 mm is 2.0°C higher than that at PMV=1 mm. It is concluded that in warm regions with high PMV, the cooling performance can be much lower since the 2nd atmospheric window is mostly lost. Hence, to achieve daytime radiative cooling, cooling structures in such area should present maximized emissivity only in 8-13 μm.

The research team from Columbia University has developed a hierarchically porous polymer coating for radiative cooling [15]. They have conducted experiments in places of different climate and meteorological conditions, using the same material and have got different results. In Phoenix with clear sky, warm air and low humidity, they achieved a sub-ambient temperature drop of 6°C. In New York, a sub-ambient temperature of 5°C was observed in a cold afternoon. In the tropical and coastal region of Chattogram, under a hazy and foggy winter sky, a 3°C temperature drop from ambient was reported. According to their estimation of the noon-time cooling power of the material during peak summer, it can be around 99 W/m² in midlatitude arid desert like Southwestern USA while being around 26 W/m² in subtropical humid place like South Asia.
| Reference No | Experiment measured index in experiment | Has a convective cover or not | Has a sunshade or not | How the apparatus is insulated | Season and climate and weather of the experiment | Solar radiation | Performance of the cooler in experiment | Simulation | Heat transfer simulation tool | Atmosphere simulation tool | Performance of the cooler in simulation | Agreement between experiment and simulation |
|--------------|------------------------------------------|-----------------------------|---------------------|--------------------------------|---------------------------------------------|----------------|--------------------------------------|------------|-----------------------------|-----------------------------|------------------------------------------|-----------------------------------------------|
|              | Temperature of ambient air and the cooler | Yes, PE film | No | By a polystyrene polysteryl | Mid December in Stanford, California | 37°C | 4.3°C below ambient during the measured period and 4.9°C below ambient when solar radiation exceeds 850W/m² | COMSOL | MODTRAN 5 | MODTRAN 5 | 4.2°C below ambient is anticipated during the measured period | Simulation in COMSOL agrees quite well with the experiment |
|              | Temperature of ambient air and the cooler | Yes, ZnSe with anti-reflection coating | No | By a vacuum chamber | Winter in Stanford, California | Temperature reduction from the ambient air during a 24-hour day-night cycle, maximal reduction of 42°C when solar radiation gets to its peak | Calculation only | Calculation only | Calculation only | 60°C below ambient air when the emitter is in ideal situation | Experiment agree well with the theory, and some outliers may be related to invisible thin cloud coverage |
|              | Temperature of ambient air and the cooler | Transparent wind convection shield and transparent PE cover | No | Insulation extruded polyvynyl (XPS) frame covered by Al film | September in Shanghai, China, cloudy | Temperature of the cooler is 3-10°C higher than the ambient temperature in daytime | Calculation only | Calculation only | Calculation only | 5°C-11.5°C below ambient air temperature is anticipated | The theoretically predicted cooling to temperature below ambient is not observed under direct solar radiation. |
|              | Temperature of ambient air and the cooler | Yes, PE film | No | A low thermal conductivity aerogel blanket | Pasadena, California Season is not reported | Average temperature reduction from the ambient air under direct sun | Calculation only | Calculation only | Calculation only | Average 8.7°C temperature reduction from the ambient air under direct sun | Calculation is in good agreement with the measurement |
|              | True radiative cooling power | wind fence at surroundings | No | Foam | Clear autumn days in Cave Creek, Arizona (585m altitude) | Average radiative cooling power = 110 W/m² | Not reported | Not reported | MODTRAN 6 | Not reported | The predicted cooling power values are consistent with measured values |
|              | Temperature of ambient air and the cooler | No, does not have any convection shield | No | Styrofoam | 3 experiments: New York, Chatogram (thick haze and fog) and Phoenix (clear sky with low humidity) | Greater than 700W/m² | Not reported | Not reported | Not reported | The plate temperatures for various flow rates are predicted. |
|              | Temperature of ambient air, water inlets and outlets, the plate heat exchangers | Yes, PE film | No | A double-walled acrylae enclosure | October 2015 in California, USA | The panel with no water flowing through it has approximately 7°C below the ambient air temperature | Not reported | Not reported | Not reported | The device temperature is 1.3°C cooler than the ambient air |
|              | Temperature of ambient air and the cooler | Yes, PE film | No | Acrylic chamber | Cloudy early summer day in Okayama, Japan | On average the device is 2.8°C warmer than the ambient |

| Table 1. Experiment and simulation/calculation for thermal analysis |

| Reference No | Experiment measured index in experiment | Has a convective cover or not | Has a sunshade or not | How the apparatus is insulated | Season and climate and weather of the experiment | Solar radiation | Performance of the cooler in experiment | Simulation | Heat transfer simulation tool | Atmosphere simulation tool | Performance of the cooler in simulation | Agreement between experiment and simulation |
|--------------|------------------------------------------|-----------------------------|---------------------|--------------------------------|---------------------------------------------|----------------|--------------------------------------|------------|-----------------------------|-----------------------------|------------------------------------------|-----------------------------------------------|
|              | Temperature of ambient air and the cooler | Yes, PE film | No | By a polystyrene polysteryl | Mid December in Stanford, California | 37°C | 4.3°C below ambient during the measured period and 4.9°C below ambient when solar radiation exceeds 850W/m² | COMSOL | MODTRAN 5 | MODTRAN 5 | 4.2°C below ambient is anticipated during the measured period | Simulation in COMSOL agrees quite well with the experiment |
|              | Temperature of ambient air and the cooler | Yes, ZnSe with anti-reflection coating | No | By a vacuum chamber | Winter in Stanford, California | Temperature reduction from the ambient air during a 24-hour day-night cycle, maximal reduction of 42°C when solar radiation gets to its peak | Calculation only | Calculation only | Calculation only | 60°C below ambient air when the emitter is in ideal situation | Experiment agree well with the theory, and some outliers may be related to invisible thin cloud coverage |
|              | Temperature of ambient air and the cooler | Transparent wind convection shield and transparent PE cover | No | Insulation extruded polyvynyl (XPS) frame covered by Al film | September in Shanghai, China, cloudy | Temperature of the cooler is 3-10°C higher than the ambient temperature in daytime | Calculation only | Calculation only | Calculation only | 5°C-11.5°C below ambient air temperature is anticipated | The theoretically predicted cooling to temperature below ambient is not observed under direct solar radiation. |
|              | True radiative cooling power | wind fence at surroundings | No | A low thermal conductivity aerogel blanket | Pasadena, California Season is not reported | Average temperature reduction from the ambient air under direct sun | Calculation only | Calculation only | Calculation only | Average 8.7°C temperature reduction from the ambient air under direct sun | Calculation is in good agreement with the measurement |
|              | Temperature of ambient air and the cooler | No, does not have any convection shield | No | Foam | Clear autumn days in Cave Creek, Arizona (585m altitude) | Average radiative cooling power = 110 W/m² | Not reported | Not reported | MODTRAN 6 | Not reported | The predicted cooling power values are consistent with measured values |
|              | Temperature of ambient air, water inlets and outlets, the plate heat exchangers | Yes, PE film | No | A double-walled acrylae enclosure | October 2015 in California, USA | Greater than 700W/m² | Not reported | Not reported | Not reported | The plate temperatures for various flow rates are predicted. |
|              | Temperature of ambient air and the cooler | Yes, PE film | No | Acrylic chamber | Cloudy early summer day in Okayama, Japan | On average the device is 2.8°C warmer than the ambient | Not reported | Not reported | Not reported | The device temperature is 1.3°C cooler than the ambient air | They did not achieve the sub-ambient performance in the experiment as is expected in the calculation |
5. Conclusion

Thermal performance evaluation is an essential part in researching daytime radiative cooling. It includes experimental and theoretical analysis. In experiment, the performance of cooler is significantly influenced by experiment settings like which index is measured, whether there is convective cover, insulation or sunshade. The season, climate and meteorological condition also matter a lot by significantly influencing solar radiation, ambient radiation, ambient air temperature and wind speed. For theoretical analysis, COMSOL is the commonly used software and plenty of researches use calculation directly. The performance of different coolers cannot be compared directly. By analysing the discrepancies between experiment and simulation or calculation, we can get some clues about the limitation of daytime radiative cooling in some specific climate areas, for example areas of high humidity. Also, for future performance prediction, possible error can be evaluated by analysing the current discrepancy, like the error caused by meteorological data.

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