University of Virginia Net-Zero Residence Initiative 2022 Project Energy Generation Group Final Design Report

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1. Introduction

Over the past few decades, the global temperature has been steadily rising. In order to escape the severe heat, many people use electronic air conditioning in their homes and office buildings. The issue is that these air conditioners produce greenhouse gases. They also take the hot air from a room and send it outside, replacing it with colder air. This causes large urban areas to become dangerously hot at times. In 2018, approximately 17% of the world's electricity use was from air conditioners and other cooling devices (Dong et al., 2021). Many developing countries in the tropics are expected to greatly increase their demand for air conditioning, causing the total electricity consumption of air conditioners to triple by 2050. Certain estimates believe that cooling services will increase the global temperature by 0.5º C by 2100. This is why it is important to find ways of cooling buildings that do not produce greenhouse gases.

Passive Daytime Radiative Cooling (PDRC) is the process of cooling buildings that receive direct sunlight without emitting greenhouse gases or requiring electricity. One way is to use specialized materials that reflect most of the solar energy it comes into contact with, absorbing very little. The atmosphere allows light at wavelengths between 8-13 micrometers to pass through it and escape back into space. An ideal material would be one that reflects almost all sunlight it comes into contact with and emits light between 8-13 μm. This can cool buildings without using electricity and without producing any greenhouse gases.

2. Objectives

The main objective of this project is to research different ways of cooling buildings using Passive Daytime Radiative Cooling over traditional air conditioners. The goal is to compare different materials that are currently being used for PDRC and determine the advantages and disadvantages of each material. The net cooling power of a material is determined using the equation:

$$P_{cool}(T) = P_{rad}(T) - P_{atm}(T_{amb}) - P_{sun} - P_{cond+conv} \tag{1}$$

T is the material's surface temperature while T_{amb} is the ambient air temperature. $P_{rad}(T)$ is the power radiated out of the surface, $P_{atm}(T_{amb})$ is the power absorbed by the surface due to atmospheric thermal radiation, P_{sun} is the power absorbed by the surface from the sun and $P_{cond+conv}$ is the total power lost due to conduction and convection. In order to maximize the P_{cool}, you must maximize the P_{rad} value while minimizing the P_{atm}, P_{sun} and $P_{cond+conv}$ values. A surface must reflect almost all sunlight to minimize the P_{sun}. In order to minimize the P_{atm} value, the surface must only emit light with wavelengths between 8-13 μm while reflecting light of all other wavelengths. In order to minimize $P_{cond+conv}$, you need to insulate the surface to minimize the amount of heat it absorbs from the air and external surfaces. This will minimize the non-radiative heat coefficient. You can calculate these parameters using the following equations:

$$P_{rad}(T) = A\int d\Omega cos\theta \int_{0}^{\infty} d\lambda I_{BB}(T, \lambda)\varepsilon(\lambda, \theta) \tag{2}$$

$$P_{atm}(T_{amb}) = A\int d\Omega cos\theta \int_{0}^{\infty} d\lambda I_{BB}(T_{amb}, \lambda)\varepsilon(\lambda, \theta)\varepsilon_{atm}(\lambda, \theta) \tag{3}$$

$$P_{sun} = A\int_{0}^{\infty} d\lambda\varepsilon(\lambda, \theta_{sun})I_{AM1.5}(\lambda) \tag{4}$$

$$P_{cond+conv}(T, T_{amb}) = Ah_{c}(T_{amb} - T) \tag{5}$$

where $I_{BB}(T, \lambda) = \frac{2hc^{2}}{\lambda^{5}(e^{hc/(\lambda\kappa_{B}T)} - 1)}$ (h=6.626e-34 m^2kg/s, κ_B=1.381e-23 m^2kg/s^2K and c=2.998m/s) is the formula for calculating the spectral irritants of the surface. This equation can be simplified to

$$I_{BB}(T,\lambda) = \frac{1.1910232e{-}16}{\lambda^{5}(e^{1.986429e-25/(\lambda*1.381e-23*T)}-1)} \tag{6}$$

Also, $\varepsilon_{atm}(\lambda, \theta) = 1 - t(\lambda)^{\sec(\Theta)}$ is the atmospheric emissivity of the material where t is the atmospheric transmittance based on wavelength and θ is a constant value of 30º. Since the angle of the material relative to the ground will be fixed, the values of $\int d\Omega cos\theta$ in equations 2 & 3 will be equal to 1.

Since this project is theoretical, it is not possible to calculate a non-radiative heat coefficient (h_c) which makes it impossible to calculate the $P_{cond+conv}$ value. Therefore, that value will be assumed to be negligible.

3. Background

There have been multiple attempts to make a material with these ideal properties. In 2014, Raman et. al. designed a material made out of seven alternating layers of HfO_2 and SiO_2. This material was able to reflect 97% of all sunlight that it came into contact with. This meant that it absorbed very little heat from the sun. The material also selectively emitted in the atmospheric transparency window. This allowed the material to be 4.9º C below the ambient air temperature when it was exposed to direct sunlight. The material also had a 12.5 µm thick clear polyethylene film that protected it from the wind. Since the experiment was performed at 37.4º N, the material was tilted 30º towards the south in order to increase the amount of sunlight that it comes into contact with. These factors allowed the material to have a total cooling power of nearly 40.1 Wm^{-2}. However, the material had a non-radiative heat coefficient (h_c) of 6.9 $Wm^{-2}K^{-1}$. As shown in equation 5, this will increase the value of $P_{cond+conv}$. From equation 1, as $P_{cond+conv}$ increases, the net cooling power decreases. The group who made the material believed that if they could decrease h_c to 0, the material would be able to lower its temperature to 19.5º C below the ambient air temperature.

A material with similar properties was made in 2021 by Wang et. al. Their material reflected 95% of the sunlight that contacted it. In addition, 98% of the energy emitted by their material was emitted in the atmospheric transmissivity window. This allowed the material to cool itself by ~8.2ºC below the ambient air temperature when it is not exposed to direct sunlight and 6-8.9ºC below the ambient temperature when it is exposed to direct sunlight. This allowed their material to have a net cooling power of 85 Wm^{-2} when exposed to direct sunlight. Their material was also made out of multiple layers and materials. The first layer was a polymethyl methacrylate (PMMA) film that consisted of small hexagonally shaped holes that were 5 μm wide. Then they had 200 nm spheres of SiO_2 randomly penetrate the film. The spheres quickly evaporated leaving behind randomly placed pores. This meant that the film had symmetrical pores that were 5 μm wide and randomly placed pores that were 200 nm wide. The purpose of the 5 μm pores is to scatter any light in the ultra violet, visible and infrared light ranges. The 200 nm pores allowed the material to scatter light with shorter wavelengths more easily by reducing the scattering distance through the material. This greatly reduces the materials transmissivity which prevents more sunlight from penetrating the material and entering the building the material is covering. These are just two different materials that have been made that do an effective job at passive daytime radiative cooling.

The city of Doha Qatar has painted some of their roads blue in order to decrease the ambient air temperature throughout the city. The government believes this can reduce the surface temperature of their roads by 12ºC. The government painted a 1 mm thick coat that is designed to absorb less solar radiation than traditional asphalt. The material they used is supposed to be highly reflective in the UV range. Doha is not the only city using this strategy. Other cities like Los Angeles and Tokyo are also planning on building a similar style of road in order to decrease their urban temperature.

4. Results & Analysis

The main goal of this project was to use equation 1 in order to maximize the cooling power of a material. In order to do so, you must maximize the P_{rad} value while minimizing the P_{atm}, P_{sun} and $P_{cond+conv}$ values. Assuming the material is facing the sun at a fixed angle, the P_{sun} value will only be dependent on the latitude of the material. Since this is a theoretical model, MODTRAN was to calculate the atmospheric transmittance on a clear summer day in a mid-latitude range.

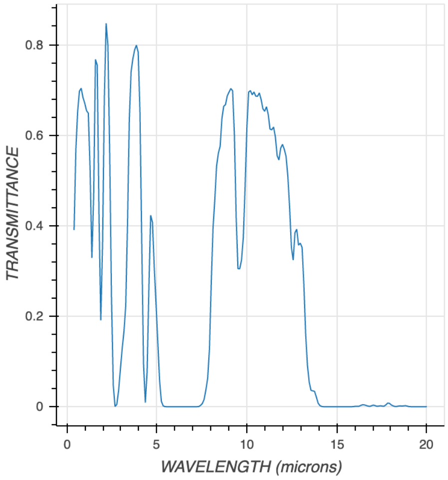

Figure 1: Plot of atmospheric transmittance depending on wavelength

Using the data from MODTRAN, the integral of the atmospheric window was approximated to be 2.4957*10^-6. This value multiplied by the material's surface area will give you the value of P_{sun}. That value was also used to approximate the average transmissivity of the atmospheric transmissivity window to be .4991. After this, equation 6 was used to calculate the intensity of the radiation that was emitted by the surface based on the wavelength of the radiation (figure 2).

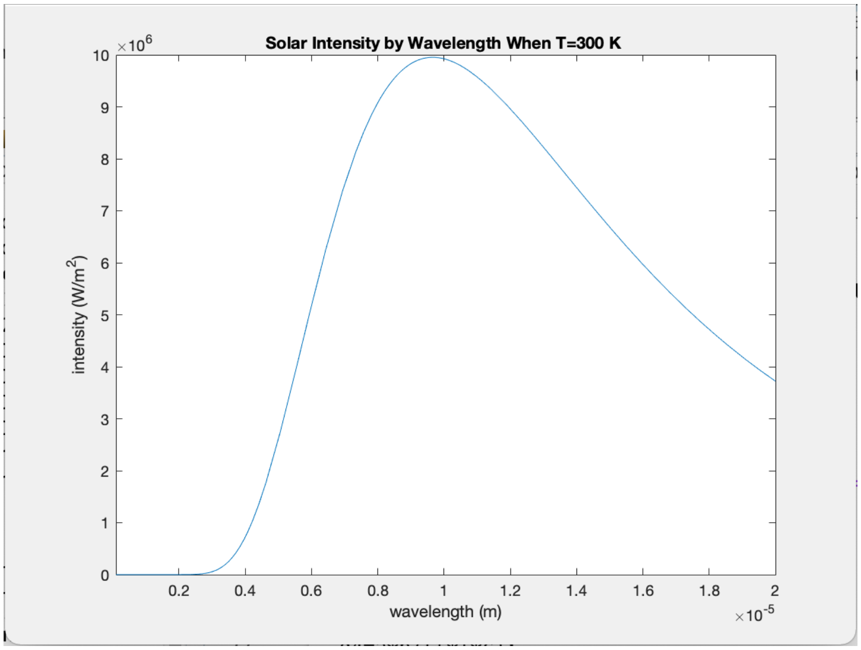

Figure 2: Plot of solar intensity based on wavelength when T=300 K

This shows the intensity of the heat that is being emitted from the surface. The integral of this function can determine the cooling power over a range. The value of the integral will calculate the power that is radiated by the surface in a particular range of wavelengths. The integral from 8-13µm determined that the net cooling power of a surface at 300K in the atmospheric transmissivity window is 47.1 W/m^2. It also calculated the cooling power of wavelengths below this window (.2-8µm) to be 20.5067 W/m^2 and the cooling power of wavelengths above the window (13-20µm)n to be 40.2608 W/m^2. From this data, it was determined that the peak intensity of the material occurs when emitting radiation with a wavelength of 9.68318 µm. To determine the net cooling power, the amount of radiation blocked by the atmosphere also needs to be determined. Since the average atmospheric transmissivity from 8-13µm was determined to be .4991, the total net cooling power of a material emitting radiation in this range is 47.1*.4991 = 23.51 W/m^2.

Even though the atmospheric transmissivity has large peaks at 2.163 µm and 3.904 µm, the thermal emissivity of the surface is very low at these points. This decreases their potential cooling power. Also, these peaks occur at very small windows. The average atmospheric transmissivity in this range was calculated to be .2503. This makes net cooling power in this range to be .2503*20.5067 = 5.1345 W/m^2. For wavelengths above 13 µm, the atmospheric transmissivity is nearly 0 meaning the net cooling power in this range is also around 0 W/m^2.

From HITRAN, water has 2 main spikes at 2.536-2.901µm and 5.020-7.581µm while CO_2 has 2 main spikes at 4.184-4.376µm and 13.812-16.181µm. These intervals are where water and CO_2 molecules absorb radiation and prevent it from exiting the atmosphere. All four of these spikes occur outside the atmospheric transmission window. This means that if your material is emitting radiation between 8-13 µm, it will not be prevented from leaving the atmosphere by either water or CO_2.

Figure 3: Plot of the absorbability of Water by wavenumber (W=1/λ, W=wavenumber in cm^{-1}, λ=wavelength in cm)

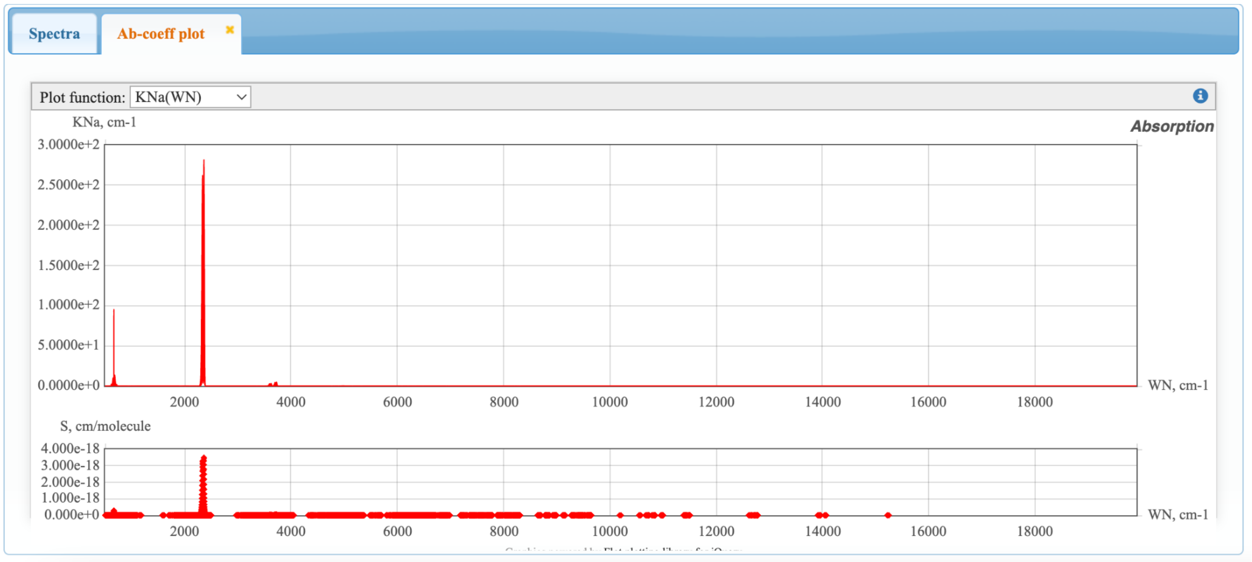

Figure 4: Plot of the absorbability of CO_2 by wavenumber (W=1/λ, W=wavenumber in cm^{-1}, λ=wavelength in cm)

5. Future Work

Another aspect to focus on inorder to achieve passive daytime radiative cooling is decreasing the non-radiative heat coefficient. This project was unable to focus on this aspect since it is a theoretical model. Large amounts of solar energy enter buildings through their glazing systems. Depending on the climate, nearly half of the energy consumed by a building's cooling system can be attributed to removing solar energy that passed through the windows. Minimizing the overall heat transfer coefficient (h) of a building's glazing system can greatly reduce the amount of energy needed to cool the building. The goal is to develop a material that minimizes the transmittance levels of ultraviolet and infrared light while maintaining a relatively high level of transmittance in the visible light range so people can still see out the windows. In cooler climates, it is important to increase the level of reflectivity in the glass. This will prevent the outdoor summer heat from entering the building and prevent the indoor winter heat from escaping. However, in warmer climates, the glass may become too hot to dissipate heat from inside back into the surrounding environment. Therefore, the glass should have high levels of emissivity in the atmospheric window, radiating heat back into outer space. The glazing system should also have very low emissivity outside the atmospheric window. Using these restrictions can decrease a building's annual air conditioner energy consumption by 40.9-63.4% (Yi et al., 2021). Another way to increase a materials cooling power is to constantly change the angle of the material relative to the ground and the direction the material is pointed in so that the material is receiving the most direct sunlight it can. This might seem counterintuitive, but the more direct sunlight that a material comes into contact with, the greater its cooling potential.

6. Conclusion

One way to combat climate change is to reduce the amount of solar energy that is absorbed by surfaces on the Earth. It is also important to decrease the amount of heat that is absorbed by the atmosphere. One way to achieve this is to have surfaces that receive direct sunlight radiate light with wavelengths in the infrared atmospheric transparency window

(8-13µm). The surface must also reflect light that is coming from The Sun. Light particles from The Sun have wavelengths between 0.3-2.5 µm. Therefore, the material needs to be highly reflective to light in this range. Multiple materials have been made that reflect >95% of sunlight while having high infrared thermal emissivity over the atmospheric transparency window. These materials have been successful in arid environments, but they are less successful in humid regions because the transmissivity of the atmosphere decreases as humidity increases. In addition, many of these materials are very expensive to produce. This project showed that passive daytime radiative cooling is very achievable when using the correct material and location. The best way to achieve passive daytime radiative cooling is by using a well insulated material that reflects over 95% of the sunlight it comes into contact with while emitting primarily in the atmospheric transmissivity window. Passive daytime radiative cooling is more achievable in an arid environment that receives a lot of sunlight. Not only can passive daytime radiative cooling decrease your need for air conditioning, it can also decrease the threat of global warming.

7. References

Abraham |, M. (2019, August 27). *Blue Roads in Doha: An Innovative Way to Combat Rising Temperatures | EcoMENA*. https://www.ecomena.org/blue-roads-doha/

Çengel, Y. A., & Ghajar, A. J. (2020). *Heat and mass transfer : fundamentals & applications*. Mcgraw-Hill Education.

Dong, Y., Coleman, M., & Miller, S. A. (2021). Greenhouse Gas Emissions from Air Conditioning and Refrigeration Service Expansion in Developing Countries. *Annual Review of Environment and Resources*, *46*(1). https://doi.org/10.1146/annurev-environ-012220-034103

Folger, B. (2021). *This new technology could help cool people down—without electricity* [Review of *This new technology could help cool people down—without electricity*].

HITRAN on the Web. (n.d.). Hitran.iao.ru. Retrieved August 1, 2022, from https://hitran.iao.ru/

MODTRAN®. (n.d.). Modtran.spectral.com. Retrieved July 27, 2022, from http://modtran.spectral.com/

Raman, A. P., Anoma, M. A., Zhu, L., Rephaeli, E., & Fan, S. (2014). Passive radiative cooling below ambient air temperature under direct sunlight. *Nature*, *515*(7528), 540–544. https://doi.org/10.1038/nature13883

Roxana Family. (2018, August 28). *Analysis of Sustainable Materials for Radiative Cooling Potential of Building Surfaces* [Review of *Analysis of Sustainable Materials for Radiative Cooling Potential of Building Surfaces*]. Ozyegin University.

Wang, T., Wu, Y., Shi, L., Hu, X., Chen, M., & Wu, L. (2021). A structural polymer for highly efficient all-day passive radiative cooling. *Nature Communications*, *12*(1), 365. https://doi.org/10.1038/s41467-020-20646-7

Yi, Z., lv, Y., Xu, D., Xu, J., Qian, H., Zhao, D., & Yang, R. (2021). Energy saving analysis of a transparent radiative cooling film for buildings with roof glazing. *Energy and Built Environment*, *2*(2), 214–222. https://doi.org/10.1016/j.enbenv.2020.07.003

Yin, X., Yang, R., Tan, G., & Fan, S. (2020). Terrestrial radiative cooling: Using the cold universe as a renewable and sustainable energy source. *Science*, *370*(6518), 786–791. https://doi.org/10.1126/science.abb0971

8. Appendix

Matlab code:

```
a=6.626069*10^-34;

b=2.9979*10^8;

c=1.38065*10^-23;

d=2*a*b^2;

e=2.7182818;

t=300; %surface temperature

syms x
```

```
g=a*b/(t*x*c);

f=d/(x^5*(e^g-1)); %function of intensity by wavelength (x)

f2=diff(f,x);

up=20*10^-6;

low=.1*10^-6;

step=1*10^-9;

fplot(f,[low up])

xlabel('wavelength (m)')

ylabel('intensity (W/m^2)')

title('Solar Intensity by Wavelength When T=300 K ')

h=vpaintegral(f,x,8*10^-6,13*10^-6)

j=vpaintegral(f,x,0.2*10^-6,8*10^-6)

k=vpaintegral(f,x,13*10^-6,20*10^-6)

w1=2.536*10^-6;

w2=2.901*10^-6;

w3=5.02*10^-6;

w4=7.581*10^-6;

c1=4.184*10^-6;

c2=4.376*10^-6;
```

```
c3=13.812*10^-6;

c4=16.181*10^-6;

wint1=vpaintegral(f,x,w1,w2);

wint2=vpaintegral(f,x,w3,w4);

cint1=vpaintegral(f,x,c1,c2);

cint2=vpaintegral(f,x,c3,c4);
```