Chapter 1

Introduction

This thesis centers on the modeling of Passive Daytime Radiative Cooling Devices (PDRCs) utilizing the COMSOL Multiphysics™ software. PDRCs exhibit a unique capability to dissipate blackbody radiation, transferring energy to the cold reservoir of outer space without requiring electrical input. Consequently, PDRCs hold the promise of addressing two significant challenges: the energy crisis and global warming.

1.1 Cooling is Critical

Over the years, cooling has become more critical to humans due to global warming, rapid population growth and industrial development. Various methods exist for cooling buildings, ranging from traditional practices such as shading and solar orientation to the use of electric fans. The most advanced approach is air conditioning (AC), encompassing systems that enhance indoor thermal comfort and air quality. While mechanical cooling techniques date back to the 19th century, widespread adoption of air conditioning began in the 1950s, driven by improved performance, affordability, and economic prosperity, primarily in the United States. Modern air conditioning systems vary widely in size and cost, catering to individual rooms or entire buildings, with electricity being the predominant power source. Urban areas, both in industrialized nations and emerging economies, predominantly house the majority of cooling systems in use today.

Global sales of air conditioners (ACs) have exhibited consistent growth in recent years. Over the period from 1990 to 2016, annual AC sales experienced a nearly fourfold increase, reaching 135 million units. In 2016, China emerged as the leading market in terms of AC capacity sales, totaling nearly 390 gigawatts (53 million units).

The growing demand for cooling is significantly influencing power systems, primarily due to the reliance on electricity-driven fans or air conditioners to meet cooling requirements. The escalating demand for air conditioning, in particular, not only elevates overall electricity consumption but also contributes to higher peak electricity loads. Additionally, the emission of greenhouse gases (GHGs) from ACs occurs through refrigerant leakage or improper disposal. It's noteworthy that these refrigerants are potent GHGs with adverse implications

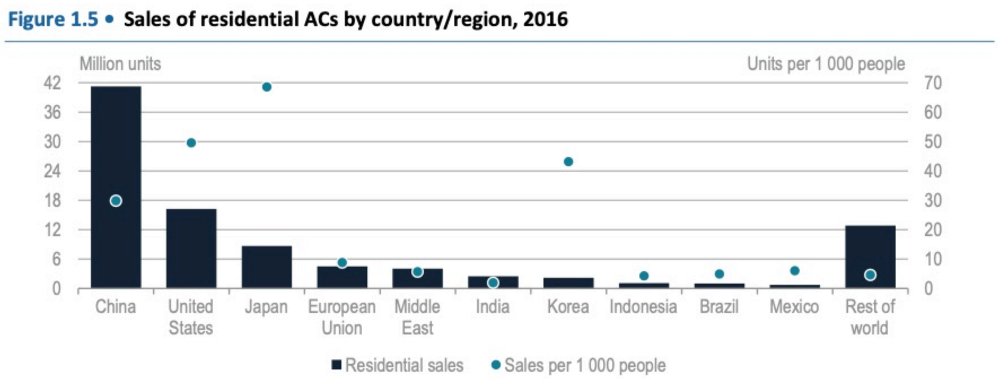

Figure 1.1: Sales of Residential ACs by Country or Region, 2016

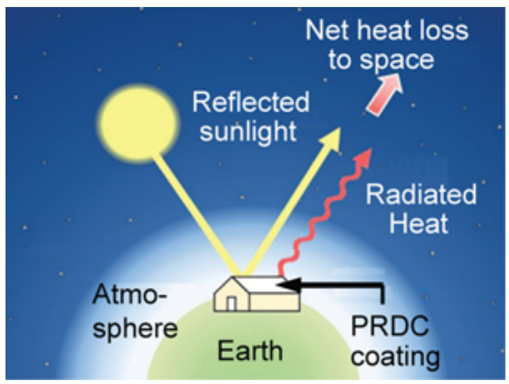

Figure 1.2: Schematic for Radiative Cooling

for climate change.

Improving the efficiency of air conditioning systems (ACs) is pivotal in mitigating peak electricity demand, thereby resulting in decreased emissions and associated financial implications. Endeavors focused on enhancing cooling efficiency necessitate a thorough assessment of the comparative costs linked to diverse cooling technologies.

1.2 Radiative Cooling

Objects with temperatures above absolute zero emit blackbody radiation across all wavelengths. Radiative passive cooling occurs when objects emit more blackbody radiation than they absorb, resulting in a temperature reduction below the ambient level. The surplus emitted heat is transferred to outer space through thermal radiation, leveraging the substantial temperature contrast between Earth (approximately 300 K) and outer space (approximately 3 K). This process efficiently exchanges heat with the infinite cold reservoir of deep space, achieving cooling without any energy consumption.

Passive radiative cooling can be realized during the daytime, necessitating precise tuning

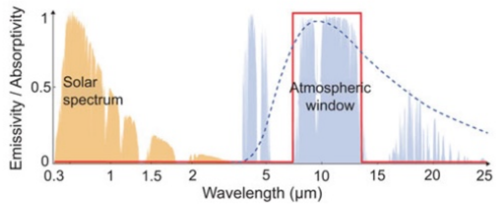

Figure 1.3: Ideal Optical Properties of a Radiative Cooling Surface

of optical properties across a broad spectrum of wavelengths, from ultraviolet to mid-infrared. As a result, achieving effective passive radiative cooling imposes stringent requirements on materials and structures to mitigate solar heating:

1. 0% absorptivity/α (100% reflectance/R) in the solar spectrum (0.3–2.5 μm), so the surface is not heated by sunlight in daytime at all.

2. Emittance (ε) of 1 in the so-called long-wavelength infrared (LWIR) transmission window of the atmosphere ($\lambda = 8$–$13\ \mu m$), where the atmosphere is partially transparent, since there is limited infrared absorption by gas molecules.

3. ε of 0 in other mid-infrared wavelengths (e.g., 5–8 μm and >13 μm). This is because the atmosphere is not transparent in these ranges.

1.3 Previous Project Work and Project Goals

Research on PDRCs has been an ongoing project in the Hudgings lab. This thesis aims to build upon the work of Paul McKinley (class of 2022) and Genevieve diBari (class of 2023). McKinley laid the groundwork by developing the fabrication process for PDRCs, a process I plan to replicate after completing the modeling of various PDRC iterations on COMSOL. DiBari contributed by modeling PDRCs in Python and enhancing the initial outdoor testing setup. For my thesis, the goal is to model different PDRC structures using COMSOL, exploring materials that could enhance the optical properties of an ideal PDRC device. This includes stacking materials of varying thicknesses and refractive indices on current PDRC models in the Hudgings lab to increase reflectivity (R). If time permits, promising PDRC models (with high R and/or emissivity in the atmospheric window) will be fabricated after the modeling phase.

Chapter 2

The Physics Behind PDRCs

A Passive Daytime Radiative Cooling (PDRC) device operates by absorbing a lower amount of blackbody radiation than it emits, thereby facilitating electricity-free cooling, even in daylight conditions. Consequently, one of the pivotal attributes of a PDRC device is the imperative for an absorptivity (α) as close to 0% or, conversely, a reflectivity (R) of 100% within the solar spectrum (ranging from 0.3 to 2.5 micrometers). This specification ensures that the device's surface remains entirely unaffected by solar heating during daylight hours.

To enhance the effectiveness of PDRC, it becomes essential to accurately measure and optimize this reflectivity (R) within the solar spectrum. One approach for achieving this goal is to perceive light as an electromagnetic wave, and from this perspective, derive a quantifiable means to measure R through the renowned *Fresnel equations*.

The Fresnel equations are mathematical expressions that delineate the proportion of incident energy that is either transmitted or reflected at the interface of two materials with differing refractive indices. This concept aligns precisely with our objectives, as we plan to stack plane surfaces featuring distinct reflective properties and refractive indices. This chapter serves as an exploration of the theoretical framework underpinning the derivation of R via the Fresnel Equations, delving into associated phenomena such as total internal reflection. Additionally, we explore the practical application of these principles to PDRC devices.

2.1 Fresnel Equations

Consider a light ray incident at point P upon a planar interface, leading to the generation of both reflected and refracted rays. It is noteworthy that the refractive index at the interface for both the incident and reflected rays (n_1) differs from the refractive index associated with the refracted ray (n_2). The plane of incidence lies within the x-z plane and is defined by both the surface normal and the incident ray.

In the context of each ray, the direction of wave propagation ($\vec{\mathbf{k}}$), can be established by the vector cross product of the electric field ($\vec{\mathbf{E}}$), and magnetic field ($\vec{\mathbf{B}}$) vectors, expressed as $\vec{\mathbf{E}} \times \vec{\mathbf{B}}$. This relationship can be conveniently determined using the right-hand rule, offering