Improving solar thermal receiver performance
via spectral and directional selectivity

by

Lee A. Weinstein

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Abstract

Adoption of renewable energy technologies has accelerated rapidly in recent years due to growing energy demand and concerns over climate change. Among renewable energy sources, solar energy conversion systems are particularly promising due to the abundance of solar energy reaching Earth. Despite its abundance, the solar resource is dilute, so solar energy must be collected efficiently in order for it to meet an appreciable portion of demand.

The efficiency of solar energy conversion systems can be improved by taking advantage of the spectral and directional properties of sunlight. Spectral properties refer to the distribution of wavelengths associated with solar photons, with most solar energy arriving as photons with wavelengths from 300 – 2500 nm. Spectral selectivity entails absorbing these solar photons while suppressing losses associated with infrared photons at longer wavelengths. Directional properties refer to the incident vector of sunlight, which spans a small solid angle due to the sun’s distance from Earth. Directional selectivity entails absorbing radiation from the direction of the sun while suppressing losses to other directions.

This thesis explores the theoretical limits of performance enhancement via spectral and directional selectivity, as well as practical devices designed to take advantage of those effects. Limits to spectral selectivity are investigated by applying the Kramers-Kronig relations to spectrally selective absorbers. Limits to directional selectivity are studied via geometrical limits, and are compared to the limits of concentrating sunlight. Two silica aerogel based solar receivers are presented as practical devices utilizing spectral selectivity. A solar thermal aerogel receiver is predicted to achieve similar performance to state of the art vacuum tube receivers, and a hybrid aerogel receiver that collects electricity from photovoltaic cells and heat is shown to potentially achieve higher efficiency than photovoltaics or a thermal receiver alone. A macroscale reflective cavity is demonstrated as a method for achieving directional selectivity in solar absorbers, and can be used to improve the performance of both solar thermal systems and photovoltaic cells.

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# Table of Contents

Acknowledgements ................................................................................................................................. 5

Table of Contents .................................................................................................................................. 7

List of Figures ........................................................................................................................................ 10

Chapter 1 Introduction ........................................................................................................................... 13

1.1 Background on CSP ......................................................................................................................... 15

1.1.1 Concentrator ............................................................................................................................. 16

1.1.2 Receiver ..................................................................................................................................... 17

1.1.3 Heat transfer fluid ...................................................................................................................... 18

1.1.4 Thermal energy storage ............................................................................................................. 18

1.1.5 Heat engine ............................................................................................................................... 19

1.2 Efficiency ....................................................................................................................................... 19

1.3 Understanding spectral and directional properties of sunlight ....................................................... 27

1.3.1 Wavelength and spectral selectivity ......................................................................................... 28

1.3.2 Direction and directional selectivity ......................................................................................... 30

1.4 Thesis Outline ................................................................................................................................. 32

Chapter 2 Limits to Spectral and Directional Selectivity ..................................................................... 33

2.1 Kirchhoff’s radiation law .................................................................................................................. 33

2.2 Limits to solar concentration and energy conversion ....................................................................... 34

2.2.1 Maximum solar concentration ratio ......................................................................................... 34

2.2.2 Maximum solar energy conversion efficiency ......................................................................... 37

2.3 Limits to spectral selectivity ............................................................................................................ 38

2.3.1 Spectral selectivity with a step function emittance profile .................................................... 39

2.3.2 Spectral selectivity considering the Kramers-Kronig relations ............................................ 44

2.4 Limits to directional selectivity ....................................................................................................... 56

2.4.1 Theoretical equivalence of directional selectivity and concentration ................................... 56

2.4.2 Practical limits to concentration ............................................................................................... 57
5.2.4  Experiment results and discussion ................................................................. 121
5.2.5  Effect on receiver efficiency ........................................................................... 124
5.3  Reflective cavity for PV applications ................................................................. 126
      5.3.1  Hemi-ellipsoidal optical cavity for a PV receiver ........................................ 127
      5.3.2  Absorption enhancement for thin-film PV .................................................. 132
Chapter 6 Summary and future directions ............................................................... 137
      6.1  Summary ......................................................................................................... 137
      6.2  Future directions ............................................................................................ 138
Appendix A: Strengths and weaknesses of STAR components ................................ 141
Bibliography ............................................................................................................. 142
List of Figures

Figure 1.1 Photos of two CSP plants ........................................................................................................ 14
Figure 1.2 Illustrated components of a conventional CSP system .......................................................... 15
Figure 1.3 Illustrations and photos of CSP plant configurations ............................................................. 18
Figure 1.4 Efficiency, as given by Eq. (1.20), of two idealized CSP systems ........................................... 26
Figure 1.5 Spectral irradiance as a function of wavelength for different solar spectra ........................... 29
Figure 1.6 Sample emittance spectra of various spectrally selective absorbers .................................. 31
Figure 2.1 System efficiency $\eta$ as a function of operating temperature $T_H$ ........................................ 38
Figure 2.2 Contour plot of the ideal transition wavelength $\lambda_{\text{step}}$ .................................................. 41
Figure 2.3 Contour plot of the receiver efficiency $\eta_{\text{rec}}$ achieved with an absorber with a step function emittance profile ........................................................................................................................................ 42
Figure 2.4 Contour plot of the system efficiency $\eta$ achieved with an absorber with a step function emittance profile ........................................................................................................................................ 43
Figure 2.5 Physical example to show how the Kramers-Kronig relations lead to causality for reflection from a surface ........................................................................................................................................... 46
Figure 2.6 (a) reflectance profile given by Eq. (2.32) for the case of $\Delta \omega/\omega * = 0.2$ and $R_{\text{low}} = 0.01$ and (b) imaginary portion of the index of refraction $k$ which would required of an intrinsic absorber material to achieve this reflectance profile .......................................................................................................................................................... 49
Figure 2.7 (a) reflectance profile given by Eq. (2.32) for various parameters ........................................... 50
Figure 2.8 (a) reflectance profile given by Eq. (2.33) for the case of $n = 4$, and (b) corresponding phase shift profile as calculated by Eq. (2.29) .................................................................................................................. 51
Figure 2.9 (a) reflectance profile given by Eq. (2.34) for the case of $= 25$ and $b = 3$, and (b) corresponding $k$ profile ......................................................................................................................................................... 52
Figure 2.10 Minimum value of $b$ for a given $a$ for reflectance profiles given by Eq. (2.34) ............... 53
Figure 2.11 Receiver efficiency $\eta_{\text{rec}}$ as a function of the parameter $a$ used to generate an absorber reflectance profile as given by Eq. (2.34), with $b$ taken from the curve shown in Figure 2.10 ........... 55
Figure 2.12 (a) Peak receiver efficiency achievable by a passive, intrinsic absorber with a reflectance profile given by Eq. (2.34) as a function of operating temperature $T$ and concentration ratio $C$. (b) The difference in achievable receiver efficiency between a passive, intrinsic absorber and an absorber with an ideal step function reflectance profile ........................................................................................................................................................................... 55
Figure 2.13 Achievable concentration ratio for sunlight on earth as a function of error angle ............. 58
Figure 2.14 Emittance as a function of incidence angle for an ideal and non-ideal directionally selective surface ........................................................................................................................................................................................................ 60
Figure 2.15 Total hemispherical emittance of a directionally selective surface as a function of emittance lower bound and angular transition from high to low emittance ............................................................ 61
Figure 2.16 Total hemispherical emittance of a directionally selective surface as a function of emittance lower bound and angular transition from high to low emittance ............................................................ 62
Figure 2.17 Product of receiver and optical efficiency as a function of receiver temperature for a sample concentrating system and three sample directionally selective surfaces (DSS)............................................... 63
Figure 3.1 Performance of fabricated transparent aerogel samples from Bhatia, et al. [101].................. 67
Figure 3.2 Cross section diagram of proposed Solar Thermal Aerogel Receiver (STAR) ...................... 69
Figure 3.3 Hybrid Electric And Thermal Solar (HEATS) receiver concept ........................................... 72
Figure 3.4 Contour plot of STAR receiver efficiency as a function of aerogel solar weighted transmittance and effective thermal conductivity ..............................................................................................................76
Figure 3.5 Performance of a fabricated SSLP coating from Cao, et al. [137] ........................................ 80
Figure 3.6 Effective spectrally selective light pipe transmittance in the PV band and absorptance in the thermal bands as a function of SSLP fin tilt angle from Monte Carlo ray tracing simulations. ..................... 82
Figure 3.7 Contour plots showing HEATS receiver performance with varying SSLP coating properties. 84
Figure 3.8 Contour plots of HEATS receiver electric efficiency [%] as a function of aerogel solar weighted transmittance through 10 mm and effective thermal conductivity through 10 mm .............. 85
Figure 4.1 Cross section diagram of proposed Solar Thermal Aerogel Receiver (STAR) ...................... 87
Figure 4.2 Diagram of receiver efficiency measurement concept .......................................................... 88
Figure 4.3 Photographs of fabricated STAR prototype test platform ..................................................... 91
Figure 4.4 Photograph of constructed receiver platform ........................................................................ 92
Figure 4.5 Absorber piping loop for STAR prototype ............................................................................. 93
Figure 4.6 Thermopiles (left) and thermocouples (right) attached to one end of the absorbing section of the receiver pipes. ....................................................................................................................... 95
Figure 4.7 Photographs of the flux gauges which are used to measure the flux incident on the receiver aperture ................................................................................................................................. 96
Figure 4.8 Removable section of the receiver platform ........................................................................... 98
Figure 4.9 LFR concentrating optics array ............................................................................................. 100
Figure 4.10 Motor and linkage mechanism to track LFR mirrors over the course of a day ...................... 101
Figure 4.11 Auxiliary equipment for the STAR prototype setup ............................................................. 104
Figure 4.12 Indoor auxiliary system equipment ....................................................................................... 106
Figure 4.13 Experimentally measured receiver efficiency ........................................................................ 108
Figure 5.1 Operating principle of specularly reflective cavity to achieve directional selectivity .......... 110
Figure 5.2 a) Simulated cavity geometry b) Different outcomes for rays emitted from the absorber ...... 113
Figure 5.3 Experimental procedure for measuring the effective emittance of an absorber within an optical cavity. .......................................................... 114
Figure 5.4 Photos of experimental setup. ................................................................................................................................. 116
Figure 5.5 Diagram of virtual aperture concept ......................................................................................................................... 116
Figure 5.6 Effective emittance as a function of cavity size ratio predicted by ray tracing simulations. ........................................ 117
Figure 5.7 Effective emittance as a function of acceptance angle predicted by ray tracing simulations. 118
Figure 5.8 Effective emittance as a function of normalized height misalignment predicted by ray tracing simulations. ................................................................. 119
Figure 5.9 Effective emittance as a function of normalized radial misalignment predicted by ray tracing simulations. 120
Figure 5.10 Measured effective emittance of near black absorber with cavity using prototype system as a function of absorber temperature. ......................................................................................................................... 121
Figure 5.11 Measured effective emittance of near black absorber with cavity using prototype system as a function of aperture acceptance angle. ......................................................................................................... 122
Figure 5.12 Measured effective emittance of near black absorber with cavity using prototype system as a function of absorber height misalignment. ........................................................................................................ 123
Figure 5.13 Measured effective emittance of near black absorber with cavity using prototype system as a function of absorber radial misalignment. .................................................................................................. 124
Figure 5.14 Receiver efficiency as a function of absorber temperature for various absorbers. .................................................. 125
Figure 5.15 Diagram of the PV cell cavity enhancement concept ................................................................................................................. 128
Figure 5.16 Diagram of cavity with the PV cell taken as horizontal. ................................................................................................. 130
Figure 5.17 Effective absorptance of a cell within a cavity as a function of the cell tilt angle. ......................................................... 131
Figure 5.18 Fraction of rays which absorbed by the cell ("absorbed"), absorbed by the cavity ("mirror losses") and lost through the aperture ("aperture losses") as a function of cavity size ratio. .......................... 131
Figure 5.19 (a) The schematic of simulated planar, 2D grooved, and 3D INP solar cells. (b) Effective absorptance of cell within a cavity as a function of cell absorptance (solid blue curve) with cell performance in absence of cavity for comparison (dotted black curve). (c) Spectral absorptance of a 5 μm thick planar silicon cell with and without the cavity. (d) Spectral absorptance for 5 μm silicon cells within a cavity and without a cavity. ......................................................................................................................... 133
Figure 5.20 (a) Photo-generated current density and (b) efficiency as a function of cell thickness for planar (red), 2D grooved (green) and 3D INP (blue) surfaces both with (solid curves with pentagrams) and without the cavity (dashed curves with open circles). ......................................................................................... 135
Chapter 1

Introduction

Renewable energy is critical to meeting the growing energy demands of humanity. Energy demand is growing at an accelerating rate as the global population increases and a higher proportion of the population is lifted out of poverty into a high energy consumption lifestyle [1]. Renewable energy sources will play a critical role for two reasons: global warming and finite reserves of conventional sources. Conventional fossil fuel sources release carbon dioxide into the atmosphere when burned to release energy, which has led to an increased greenhouse effect, rising temperatures, and a host of detrimental environmental effects [2]. Even if sequestration efforts allow the burning of more fossil fuels without the addition of more greenhouse gasses into the atmosphere, fossil fuel reserves are finite [3]. Unless we can reduce the global energy demand or find extra-terrestrial sources of conventional fuel, humanity must adopt a switch to renewable energy sources.

Among renewable energy sources, solar power is a promising option. Solar power is the most abundant energy source on Earth, with over $10^3$ TW (three to four orders of magnitude greater than global energy demand) continuously supplied to the Earth by the sun [4]. Compared to other renewable sources, solar energy has widespread availability – it has some dependence on latitude and climate [5], but it is not limited to certain geographical features. A challenge in utilizing solar energy is that it is dilute: the solar flux that reaches the Earth’s surface is about 1 kW/m$^2$ [5]. For comparison, the average 2016 model automobile in the United States had an engine power of 170 kW [6], so a collection area well in excess of 170 square meters would be required to power such a car by solar energy at full throttle.

There is a substantial amount of solar energy reaching Earth, but it is infeasible to collect all of it. Looking at the specific case of the United States, a reasonable estimate of the upper bound of the area that could be used to collect solar energy is the total constructed ground area (the area of roads, parking lots, and roofs) which is currently about $10^{11}$ m$^2$ [7]. The average annual solar radiation in the US is around 1600 kWh/m$^2$/year [8]. In order to meet the United States' annual energy demand of $2.8 \times 10^{13}$ kWh [9], that collected solar energy would need to be converted to useful energy (electricity, powering vehicles, etc.) at an efficiency of 17.5%. This efficiency is fairly high compared to solar conversion systems used in practice today [10,11], and in order to meet energy demands with a smaller footprint the collected solar energy would need to be converted at even higher efficiencies. This initial exercise also ignores a big

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Figure 1.1 Photos of two CSP plants: a) Solana Generating Station, a parabolic trough collector plant in Phoenix, Arizona (original photo by James Loomis) and b) Solar Two, a "power tower" plant near Barstow, California. Reprinted with permission from reference [15]. Copyright 2015 Elsevier.

The challenge associated with utilizing solar energy: the temporal availability of the solar resource. Solar energy is not available at night and the effects of weather can lead to variability and uncertainty [5]. The solution to this challenge is storage; if extra energy is collected during periods of high solar insolation, the excess energy can be made available for dispatch after the sun sets or is covered by clouds.

Photovoltaics (PV) are the most deployed solar energy technology, making up about 98% of the installed global solar capacity [12]. The basic working principle of a PV cell is that incident solar photons excite electrons into the conduction band of a semiconductor PN junction, leaving a hole in the valence band. These excited electrons can be collected to do electrical work as they travel back to the valence band to rejoin the holes. PV addresses the efficiency challenge fairly well, with many commercial PV technologies achieving efficiencies from 15-20% [13]. For meeting the storage challenge, batteries can be used to store the electricity generated from PV, but this solution is too expensive to be adopted on a large scale using current technologies [14].

The second most common solar technology is concentrating solar power (CSP), which makes up the other 2% of deployed solar capacity [12]. Photos of two operating CSP plants, a parabolic trough collector plant and a central receiver (or "power tower"), are shown in Figure 1.1. In a CSP system, solar energy is concentrated onto an absorber which collects the solar energy as high temperature thermal energy [11]. This thermal energy is then delivered to a heat engine to be converted to electricity. Because of the intermediate thermal step in CSP, it is sometimes referred to as “solar thermal,” and both nomenclatures will be used in this thesis. CSP systems can achieve good efficiencies: peak efficiencies can be as high as
25%, but average efficiencies tend to be slightly lower than PV at around 15% [11]. There is less deployed CSP capacity than PV because CSP systems are more expensive on a generation capacity basis [16]. Despite the higher generation capacity cost, CSP is still an important technology because it is cheaper to store thermal energy than electricity, so it is less expensive to integrate storage into a CSP plant [17].

1.1 Background on CSP

This thesis covers both PV and CSP related technologies, but since it focuses on CSP, more background information will be provided on the working principles of CSP plants. As previously mentioned, there are five steps to a conventional CSP system (illustrated in Figure 1.2):

1. Concentration: sunlight incident on a large concentrator is redirected to a much smaller receiver
2. Absorption: sunlight incident on the receiver is converted to thermal energy by an absorber
3. Transfer: thermal energy is carried away from the absorber by a heat transfer fluid (HTF)
4. Storage: thermal energy can be stored in a thermal energy storage (TES) tank for later use
5. Generation: the HTF delivers thermal energy to a heat engine which generates electricity

It is worth noting that there are many uses for thermal energy and solar thermal systems are not limited to electricity generation [18], however this thesis focuses on technologies which generate electricity. Transfer, the third step on this list, is not strictly necessary for CSP systems (e.g., the absorber can be
directly coupled to the heat engine), however all currently operating utility-scale CSP plants use heat transfer fluids. Storage, the fourth step on this list, is optional for CSP systems, however it is one of the primary advantages compared to other renewable electricity technologies, and as such is an important step to mention. These five steps will be explained briefly in this introductory section.

1.1.1 Concentrator

There are a number of concentrator configurations which are commonly used in CSP systems. The first step of concentrating sunlight from a concentrator to a receiver is not necessary for all solar thermal applications; however, for electricity generation it is almost always a requirement [19]. CSP systems require concentration to be efficient, as otherwise system losses would be dominated by the large receiver areas at the high temperatures required to drive a heat engine efficiently. The level of concentration can be characterized by the concentration ratio, which is the ratio of the collector aperture area (the large mirror area intercepting sunlight) to the receiver aperture area (the small receiver area where the sunlight is redirected). Because concentration is required, CSP can only use the direct portion of sunlight (diffuse sunlight cannot be concentrated easily) which limits the best locations for CSP plants to areas with high average annual direct normal irradiation [20]. Due to the solar progression across the sky (daily in the east-west direction and both daily and seasonally in the north-south direction) two-axis tracking is required to maintain a concentrator normal to the sun. With two-axis tracking, sunlight can be focused approximately to a point ("point-focus"). While the sun has both east-west and north-south movement, most of its daily movement is in the east-west direction. If one only tracks a collector in the east-west direction, sunlight can be focused approximately to a line ("line-focus"). Both line-focus and point-focus collectors can be found in commercial use [21]. Point-focus systems can achieve higher concentration ratios (~1,000×) [22], but the required two-axis solar tracking is more complex and more expensive to implement. Line-focus systems have lower concentration ratios (~80× based on tube receiver diameter, or ~30× based on tube receiver circumference or for flat receivers) but use simpler, less expensive one-axis solar tracking.

Another distinction between different types of concentrators is whether the collecting surface is continuous or made up of discrete facets. Collectors with continuous surfaces can achieve higher concentration ratios, as there is no sunlight lost between facets, and tracking is simpler since only one surface needs to be actuated. When using a continuous surface, the focal axis should always intersect both the receiver and the sun, so the receiver is typically mounted with the reflector in one assembly, limiting the receiver size. Collectors with discrete facets can cover a greater area since the receivers can be stationary, as they do not need to be tracked with the reflecting surfaces. Additionally, wind loading is typically a smaller concern for discrete facets since they can be kept closer to the ground. The stationary
receivers in this case are still elevated so wind loading should be considered, but they are less susceptible to damage than reflector elements.

The four combinations of these two distinctions (point-focus vs. line-focus and continuous surface vs. discrete facets) result in the four primary collectors for CSP systems: Parabolic trough collectors (PTC), linear Fresnel reflectors (LFR) [23,24], parabolic dish reflectors, and heliostat fields, which are all shown in Figure 1.3. In a parabolic trough collector, a long, curved, trough-shaped mirror tracks the sun from east to west and concentrates sunlight on a pipe at the focus of the curved mirror, with the whole assembly rotating together [25]. In a linear Fresnel reflector, long mirrors tracking the sun from east to west reflect sunlight onto a fixed, raised receiver. The “Fresnel” in this collector’s name originates from the many reflector elements approximating a continuous curve, as in a Fresnel lens. With a parabolic dish, the sun is tracked on both axes across the sky, and sunlight is focused on a receiver which moves with the dish, such that it is always on-axis with the sun [26]. In a heliostat field, individual mirrors track the sun across the sky to reflect sunlight to a central, raised receiver [27]. Thus, PTCs and LFRs are line-focus systems, while parabolic dish reflectors and heliostat fields are point-focus, and PTCs and parabolic dishes use continuous surfaces, while LFRs and heliostat fields use discrete facets. It should be noted that parabolic dish systems sometimes have discrete reflector facets which form the overall parabolic shape, but since these facets are fixed in position relative to each other, they can be effectively considered a continuous reflective surface. While these characteristics in principle only determine the collector of the CSP system, in practice the collector type determines many of the operating conditions of the overall system.

This connection between collector type and plant operating conditions is a result of the collector being paramount in determining the receiver concentration ratio and the overall plant size. As an example, parabolic dish plants are almost ubiquitously referred to as dish Stirling systems, due to how commonly they are paired with a Stirling engine to convert heat to electricity [26]. Similarly, plants which use a heliostat field as the collector are often called power tower or central receiver systems, referring to the large tower where sunlight is focused at the center of the field.

1.1.2 Receiver

The receiver is the portion of a CSP system where the concentrated sunlight from the concentrator is focused. The receiver always has an absorber (where sunlight is converted to thermal energy), often has piping which carries a heat transfer fluid to deliver the thermal energy to storage or the heat engine, and can also include transmitting or reflecting optics. The purpose of the receiver is to efficiently convert sunlight to thermal energy. Improving the performance of the receiver is the focus of this thesis, and as such it will be explored in more depth in later sections.
1.1.3 Heat transfer fluid

After solar energy is absorbed and converted to thermal energy, it is delivered to what is known as a heat transfer fluid (HTF). Thermal energy is typically transferred to the HTF through convection, but this heat transfer could also be accomplished in less traditional ways (e.g. radiation [29] or conduction [30]). The multi-functional HTF needs to collect, transport, and exchange heat obtained from solar radiation and is therefore an important part of a CSP system [31].

The HTF often sets the operating temperature of a CSP plant. As an example, the most commonly used HTF in parabolic trough plants is a eutectic mixture of biphenyl and diphenyl oxide (sold commercially as Therminol VP-1 or Dowtherm A), which is stable to about 400 °C [32]. Parabolic trough plants must thus limit their operating temperature to 400 °C even if higher efficiencies could be achieved at higher temperatures. Some power tower plants use molten salts stable to 600 °C as the HTF in order to operate at higher temperatures [33], but molten salt is incompatible with PTC plants due to challenges associated with the high freezing temperature of the molten salts [34].

1.1.4 Thermal energy storage

To generate electricity on demand despite solar transients (such as clouds passing overhead or the sun setting) storage is required. Storage is very valuable for renewable energy technologies, as storage makes
them more reliable, more amendable to integration in the grid, and in the case of solar power allows electricity production to be shifted to meet peak demand [35,36]. The most appropriate storage mechanism for use with CSP is thermal energy storage (TES) due to the intermediate thermal step already present in CSP systems [37,38]. Plants with solar multiples greater than unity, defined as the ratio of insolation to the receiver at the design point to the nominal heat input of the heat engine, can use the extra solar energy collected during peak sunlight hours to charge a TES system, and discharge the TES later to produce electricity when the sun is no longer shining.

Thermal energy storage is one of the main advantages of CSP, because TES is significantly cheaper than other energy storage technologies (e.g., batteries) and is not compatible with other intermittent renewable energy technologies such as photovoltaic cells and wind turbines. There are some grid-level energy storage technologies that are economically competitive with TES, such as pumped hydro and compressed air, however these exceptions are geographically limited [39]. For intermittent renewable sources, the value of their generated electricity decreases at high grid penetration [40]. If storage is included, e.g., CSP with TES, then the generated electricity maintains a high value even in the high renewable penetration scenario. Jorgenson et. al. found that in certain deployment scenarios, electricity from CSP with storage could be more than twice as valuable as electricity from PV to the utility provider [41].

1.1.5 Heat engine

The heat engine is the system in a CSP plant which converts the collected thermal energy to electricity. This is traditionally achieved via a thermodynamic cycle converting the heat to mechanical energy, which is used to drive a generator and produce electricity [42]. For use with CSP, a cycle needs to work in the appropriate temperature range and have a reasonably high conversion efficiency. Existing CSP plants almost exclusively use steam-Rankine engines, however other cycles such as supercritical carbon dioxide and combined Brayton-Rankine cycles have been proposed if higher operating temperatures can be reached in CSP systems [42]. Some direct heat to electricity conversion approaches such as thermoelectrics, thermophotovoltaics, and thermionics have also been proposed, although they primarily exist at the research stage [43].

1.2 Efficiency

Improving performance with respect to solar energy systems typically refers to one of two things: levelized cost of energy (LCOE, also referred to as levelized cost of electricity or levelized energy cost) or efficiency. LCOE, which is the amount of money that a plant would need to charge per unit of electricity generated (typically reported in €/kWh or $/MWh) in order to operate profitably is ultimately more important for adoption [44]. While LCOE is more important in practice, efficiency is a strong driver
of LCOE and efficiency is easier to evaluate in the academic setting, so it is more common in the scientific literature. Efficiency is the primary metric of interest for this thesis.

Various efficiencies are reported in the field of solar energy, so it is important to define them. For any system with the purpose of generating electricity, we can define an electric efficiency $\eta_{elec}$, which is the ratio of electrical power output $P$ to incident solar power $Q_{solar}$:

$$\eta_{elec} = \frac{P}{Q_{solar}}$$  \hspace{1cm} (1.1)

Some CSP systems provide heat rather than electricity, and in this case a thermal efficiency $\eta_{therm}$ can be reported, which is the ratio of useful heat output $Q_{out}$ to incident solar power:

$$\eta_{therm} = \frac{Q_{out}}{Q_{solar}}$$  \hspace{1cm} (1.2)

Some hybridized solar systems deliver both electricity and heat as outputs, by combining a PV and a thermal receiver [45]. If the heat is intended for electricity generation, then electric efficiency still applies, and can be calculated by summing the direct electricity output from PV and the electricity generated from the heat output. Other efficiencies have been proposed to characterize hybrid systems as well. One example is energetic efficiency $\eta_{energ}$, which is the ratio of useful energy output (thermal energy and electrical energy) divided by incident solar power:

$$\eta_{energ} = \frac{P + Q_{out}}{Q_{solar}}$$  \hspace{1cm} (1.3)

This approach significantly overvalues heat compared to electricity so it is not necessarily a fair way to compare hybrid systems to other systems. Operating at low temperature would easily lead to high energetic efficiency, so, for example, a rooftop hot water heater system would beat any PV cell by this metric.

Another proposed metric for hybrid systems is exergetic efficiency $\eta_{exerg}$, which is the ratio of exergy output (work potential) divided by incident solar power:

$$\eta_{exerg} = \frac{P + Q_{out} \left(1 - \frac{T_C}{T_H}\right)}{Q_{solar}}$$  \hspace{1cm} (1.4)

where $T_C$ is temperature that heat is rejected to in the relevant thermal cycle (typically close to the
ambient temperature) and $T_H$ is the temperature of the thermal energy delivered by the receiver. This treatment gives more value to heat at higher temperature, which is appropriate since heat at higher temperature is more valuable. Pros and cons of this metric as compared to electric efficiency for a hybrid receiver will be discussed in more detail in chapter 3 of this thesis, which investigates a particular implementation of a hybrid receiver.

These system efficiency values are often treated instantaneously, but a more in-depth analysis can provide a time averaged value (e.g., over the course of a day or year) [42]. Annual average values are the most relevant to LCOE for an actual deployed plant, but design point efficiencies (i.e., the efficiency at a particular day and time) are quicker and simpler to calculate so they are still frequently used.

It is often useful to break up overall system efficiencies into sub-efficiencies. The relevant sub-efficiencies vary for different types of solar energy systems. PV cells have a few properties which can be thought of as sub-efficiencies: absorption – the ratio of photons absorbed by a PV cell to photons incident on that PV cell, internal quantum efficiency (IQE) – the ratio of electron-hole pairs generated to photons absorbed by the cell, and external quantum efficiency (EQE) – the ratio of electron-hole pairs generated to photons incident on the cell [46]. However, calculating overall efficiency from these “sub-efficiencies” is not a trivial calculation, so when characterizing PV cells system efficiency is often treated as a lone value. An exception is that in concentrating PV systems, efficiency can be split into the optical efficiency of the concentrator and the PV efficiency.

CSP is easier to break up into sub-efficiencies: there is an efficiency associated with each of the five steps in a CSP plant (concentration, absorption, transfer, storage and generation). Overall system efficiency can be calculated by multiplying all of the sub-efficiencies together, given that they are of the same form (e.g., all energetic efficiencies, or all exergetic efficiencies).

Optical efficiency $\eta_{opt}$ is the ratio of solar power reaching the receiver $Q_{rec}$ to solar power incident on the concentrating optics:

$$\eta_{opt} = \frac{Q_{rec}}{Q_{solar}}$$

Another important characteristic related to optical efficiency and the concentrating optics is the geometric concentration ratio $C$:

$$C = \frac{A_{conc}}{A_{rec}}$$
where $A_{\text{conc}}$ is the concentrator area and $A_{\text{rec}}$ is the receiver area. It is important to specify which area is used as concentrator area in calculating optical efficiency or concentration ratio, as different values are used in different contexts. It is common to use the reflector area, as reflector area is the primary driver of overall system cost, but land area or projected reflector area are often used as well. Additionally, it is important to distinguish which receiver area is used when the projected area and surface area differ (e.g., in the case of a tubular receiver). For the purposes of calculating receiver efficiency, as in Eq. (1.8) below, surface area should be used, since thermal losses depend on surface area and not projected area. In addition to geometric concentration ratio, the flux concentration ratio $C_{\text{flux}}$ might also be specified for a system, which is the ratio of the average incident flux at the receiver $q_{\text{rec}}$ to the direct normal irradiance $G_{DNI}$ reaching the collector:

$$C_{\text{flux}} = \frac{q_{\text{rec}}}{G_{DNI}} = C_{\eta_{\text{opt}}}$$

In the context of a CSP plant, receiver efficiency $\eta_{\text{rec}}$ is the useful heat output from the receiver $Q_{\text{rec,out}}$ divided by the solar power incident on the receiver [11]. A simple expression for receiver efficiency is:

$$\eta_{\text{rec}} = \frac{Q_{\text{rec,out}}}{q_{\text{rec}} A_{\text{rec}}} = \tau \alpha - \frac{h (T_{H,\text{abs}} - T_{\text{amb}}) + \varepsilon \sigma (T_{H,\text{abs}}^4 - T_{\text{amb}}^4)}{C G_{DNI} \eta_{\text{opt}}}$$

where $\tau$ is the transmittance of any transmitting optics in the receiver (e.g., a glass cover), $\alpha$ is the absorptance of the receiver’s absorbing surface, $h$ is the convection coefficient between the absorber surface and the environment, $T_{H,\text{abs}}$ is the elevated absorber temperature, $T_{\text{amb}}$ is the ambient environmental temperature, $\varepsilon$ is the emittance of the absorber surface, and $\sigma$ is the Stefan-Boltzmann constant. The first term $\tau \alpha$ is the portion of incident solar radiation which can successfully be absorbed as solar energy, while the second term consists of thermal losses from the receiver normalized by the incident irradiance.

In CSP receivers it is common for radiation losses to dominate over convective losses. This can be either because the receiver includes an evacuated design so the absorber is not in contact with the environment, or because the receiver operates at high enough temperatures that the radiation term, which goes as temperature to the fourth power, dominates the convection term, which goes linearly with temperature. Thus receiver efficiency can often be expressed without the convection loss term [11]:

22
As can be seen from (1.9), receiver efficiency is a strong function of operating temperature: radiative losses increase with the absorber temperature to the fourth power. Since the losses are scaled by the incident irradiance on the receiver, high efficiency can be achieved even at high temperature for sufficiently high concentration ratios. This is how dish and power tower systems are able to operate efficiently at high temperatures. If receiver efficiency is expressed in exergetic form $\eta_{\text{rec,x}}$, it is instead the ratio of exergy output from the receiver to solar power incident on the receiver:

$$
\eta_{\text{rec,x}} = \frac{Q_{\text{rec,out}}(1 - T_{C}/T_{H,\text{rec}})}{q_{\text{rec}}A_{\text{rec}}} = \left( \tau a - \frac{\varepsilon \sigma (T_{H,\text{abs}}^4 - T_{\text{amb}}^4)}{C_{G_{\text{DNI}}}\eta_{\text{opt}}} \right) \left( 1 - \frac{T_{C}}{T_{H,\text{rec}}} \right)
$$

(1.10)

where $T_{H,\text{rec}}$ is the temperature of the thermal energy delivered by the receiver, which is not necessarily the same as the absorber temperature. In practice $T_{H,\text{rec}}$ will be lower than $T_{H,\text{abs}}$, although how much lower depends on the receiver and overall system design.

Transfer efficiency $\eta_{\text{xfer}}$ refers to the ratio of heat delivered to storage $Q_{\text{stor,in}}$ and the heat engine to heat collected by the receiver. In energetic form the transfer efficiency is given by:

$$
\eta_{\text{xfer}} = \frac{Q_{\text{stor,in}}}{Q_{\text{rec,out}}}
$$

(1.11)

As a temperature gradient is required to drive the heat transfer processes involved in transporting the thermal energy through a CSP system, it is arguably more relevant to use an exergetic transfer efficiency [47]. This can be given by:

$$
\eta_{\text{xfer,x}} = \frac{Q_{\text{stor,in}}(1 - T_{C}/T_{H,\text{stor,in}})}{Q_{\text{out,rec}}(1 - T_{C}/T_{H,\text{rec}})}
$$

(1.12)

where $T_{H,\text{stor,in}}$ is the temperature of heat input to the storage.

Storage efficiency $\eta_{\text{stor}}$ refers to the ratio of thermal energy that can be dispatched from storage $Q_{\text{stor,out}}$ to thermal energy originally delivered to storage. In energetic form the transfer efficiency is given by:

$$
\eta_{\text{stor}} = \frac{Q_{\text{stor,out}}}{Q_{\text{stor,in}}}
$$

(1.13)
With some thermal storage technologies, the heat recovered can be at a different temperature than the heat input. In these cases, exergetic storage efficiency can be given by:

$$\eta_{\text{stor},x} = \frac{Q_{\text{stor,out}} (1 - T_c / T_{H,\text{stor,out}})}{Q_{\text{stor,in}} (1 - T_c / T_{H,\text{stor,in}})}$$  \hspace{1cm} (1.14)

In practice, both transfer and storage efficiencies close to unity have been achieved through diligent system design [48,49], so it is common to ignore the associated losses in academic studies.

Finally, the heat engine efficiency \(\eta_{HE}\) is the electrical power output \(P\) from the generator divided by the heat input to the heat engine \(Q_{HE}\):

$$\eta_{HE} = \frac{P}{Q_{HE}}$$  \hspace{1cm} (1.15)

The maximum achievable efficiency is the Carnot efficiency \(\eta_{\text{Carnot}}\), which would be achieved for a cycle where each step is thermodynamically reversible:

$$\eta_{\text{Carnot}} = 1 - \frac{T_c}{T_{H,\text{HE}}}$$  \hspace{1cm} (1.16)

where \(T_c\) is the temperature at which heat is rejected from the heat engine and \(T_{H,\text{HE}}\) is the temperature at which heat is delivered to the heat engine. In the ideal case, \(Q_{HE} = Q_{\text{stor,out}}\) and \(T_{H,\text{HE}} = T_{H,\text{stor,out}}\), however there could be additional transfer losses between storage and the heat engine. The Carnot efficiency cannot be achieved in practice, and a more realistic heat engine efficiency is given by the Chambadal-Novikov efficiency \(\eta_{CN}\), for a heat engine with irreversible heat transfer processes operating at maximum power output [50]:

$$\eta_{CN} = 1 - \sqrt{\frac{T_c}{T_{H,\text{HE}}}}$$  \hspace{1cm} (1.17)

The Chambadal-Novikov efficiency matches the efficiencies achieved in operating power plants with much better accuracy than the Carnot efficiency, and is therefore a reasonable estimate to use for heat engine efficiency in practice [50].
For both the Carnot and Chambadal-Novikov efficiencies, heat engine efficiency increases with increasing operating temperature. For this reason, many efforts to improve CSP performance aim to operate at higher temperature. Operating at higher temperatures allows for the possibility of improved performance, but also introduces many challenges. Whenever operating temperature is increased, all the relevant components and materials must be stable at the elevated temperature, and the increased losses associated with the higher operating temperature must be addressed.

Heat engine efficiency can also be reported in terms of exergy, in which case it denotes the ratio of electricity output to exergy input. In the case of Carnot efficiency, the exergetic efficiency is unity. The exergetic Chambadal-Novikov efficiency \( \eta_{CN,x} \) is given by:

\[
\eta_{CN,x} = \frac{1 - \frac{T_C}{T_{H,HE}}}{1 - \frac{T_C}{T_{H,HE}}} \tag{1.18}
\]

As previously mentioned, overall system efficiency \( \eta \) can be calculated as the product of all the sub-efficiencies (if the Chambadal-Novikov efficiency is assumed for heat engine efficiency):

\[
\eta = \eta_{opt} \eta_{rec} \eta_{xfer} \eta_{stor} \eta_{HE}
\]

\[
= \left( \eta_{opt} \tau \alpha - \frac{h(T_{H,abs} - T_{amb}) + \epsilon \sigma(T_{H,abs}^4 - T_{amb}^4)}{C G_{DNI}} \right) \frac{Q_{stor,out}}{Q_{rec,out}} \left( 1 - \frac{T_C}{\sqrt{T_{H,HE}}} \right) \tag{1.19}
\]

This result uses the Chambadal-Novikov efficiency, and assumes that transfer losses from storage to the heat engine are insignificant. Using the expressions for exergetic sub-efficiencies instead of energetic sub-efficiencies yields the same equation for overall efficiency, as one would expect.

A simpler version of CSP plant efficiency is given by the product of optical efficiency, receiver efficiency considering only radiative losses, and the Chambadal-Novikov heat engine efficiency, assuming no temperature drop between the absorber and heat engine:

\[
\eta = \left( \eta_{opt} \tau \alpha - \frac{\epsilon \sigma(T_H^4 - T_{amb}^4)}{C G_{DNI}} \right) \left( 1 - \frac{T_C}{\sqrt{T_H}} \right) \tag{1.20}
\]

Since convection losses are typically small compared to radiation losses, transfer and storage efficiencies are usually close to unity, temperature drops between the different sub-systems are usually small, and Chambadal-Novikov is a reasonable estimate for real heat engine efficiencies, the calculated efficiency values from this expression should be reasonably accurate. Thus, Eq. (1.20) offers a simple way to
investigate the effects of different system parameters on overall system efficiency. For a particular system with prescribed concentration ratio, optical efficiency, and receiver properties, maximizing efficiency becomes a simple optimization of temperature in theory, but in practice each subcomponent needs to be compatible with the chosen operating temperature.

The efficiencies of two example systems, as given by Eq. (1.20), are plotted as a function of operating temperature in Figure 1.4. The two example systems are an idealized power tower ($\eta_{opt} = 0.6$, $\tau = \alpha = \epsilon = 1$, $C = 1000$) and an idealized parabolic trough collector ($\eta_{opt} = 0.8$, $\tau = \alpha = 0.95$, $\epsilon = 0.1$, $C = 30$). In both cases, $G_{DNI}$ is taken as 1000 W/m$^2$ and it is assumed that $T_{amb} = T_C = 300$ K. At low temperatures, the PTC achieves higher efficiencies than the power tower as it has a higher optical efficiency and its strategy of minimizing losses through low emittance is effective. At temperatures above 1000 K the power tower performs better even with the lower optical efficiency, as its high concentration is much more effective at reducing the relative thermal losses from the receiver. It should be noted that this simple example is valuable for recognizing broad trends, but the specific numbers recovered do not
accurately reflect operating plants. For example, the idealized PTC achieves a peak efficiency of slightly above 25% at 600 °C, when in practice PTC plants are limited to an operating temperature of 400 °C due to their thermal oil. Likewise, the idealized power tower plant is predicted to maximize efficiency at an operating temperature of 800 °C, which is incompatible with the steam Rankine engines typically used in these plants in practice.

1.3 Understanding spectral and directional properties of sunlight

In order to improve the performance of systems designed to collect solar energy, it is important to understand the nature of solar energy. Solar energy is thermal radiation emitted by the sun, which can be approximated as a blackbody with a surface temperature of 5800 K [5]. In order to reach the Earth’s surface, this radiation travels through space and through Earth’s atmosphere. Radiation in general can be characterized by a few properties: wavelength, intensity and direction. In the case of solar energy, each of these properties offer a route to improved performance. In fact, intensity has already been discussed: increasing intensity through concentration leads to higher receiver efficiency for CSP systems, as explained in section 1.2 above. Utilizing the spectral and directional properties of solar radiation to improve receiver performance will be discussed in the following sections.

Central to both spectral and directional selectivity is Kirchhoff’s law of thermal radiation, which states that for a given surface at a fixed operating temperature the absorptance in a particular direction θ∗ for a specific wavelength λ∗ must be equal to its emittance for that same direction and wavelength [51]:

\[ \alpha_{\lambda,\theta}(\lambda^*, \theta^*) = \epsilon_{\lambda,\theta}(\lambda^*, \theta^*) \]  

(1.21)

Kirchhoff’s law arises as a consequence of the second law of thermodynamics. The derivation of the law and its relevance to the limits of spectral and directional selectivity will be discussed in more detail in chapter 2 of this thesis. To calculate overall absorptance and emittance of a surface (e.g., for use in Eq. (1.9) to determine receiver efficiency), the spectral and directional properties must be integrated over all wavelengths and incidence angles. As an example, the total-hemispherical emittance ε can be calculated from the spectral, directional emittance \( \epsilon_{\lambda,\theta} \) by [51]:

\[ \epsilon(T) = \frac{2}{\sigma T^4} \int_0^{\pi/2} \int_0^\infty \epsilon_{\lambda,\theta}(\lambda, \theta) E_{bb\lambda}(T, \lambda) \sin \theta \cos \theta \, d\lambda \, d\theta \]  

(1.22)

assuming an isotropic surface (with no variation due to azimuthal angle), with \( \theta \) denoting incidence angle and where \( E_{bb\lambda} \) is the spectral blackbody emissive power, which will be discussed in more detail in the following section. Total-hemispherical absorptance is calculated in a similar way, except with the spectral
blackbody emissive power being replaced by incident radiative intensity [51]. In this thesis, solar absorptance is the property of interest, which is absorptance with solar spectral irradiance being used as the incident radiative intensity.

1.3.1 Wavelength and spectral selectivity

As previously mentioned, the origin of sunlight is thermal radiation: the sun is at a high temperature, and thus radiates energy outward in all directions. One characteristic of thermal radiation is that it spans a wide range of wavelengths, and the spectrum for a blackbody (an object which absorbs all radiation incident on it) is given by Planck’s law. The spectral blackbody emissive power $E_{b\lambda}$ for a body at temperature $T$ is [51]:

$$E_{b\lambda}(T, \lambda) = \frac{2\pi h c_0^2}{n^2 \lambda^5 (e^{h c_0/n\lambda k_B T} - 1)}$$ (1.23)

where $\lambda$ is the wavelength of interest, $h$ is the Planck constant, $c_0$ is the speed of light in a vacuum, $n$ is the index of refraction of the medium the blackbody is emitting into, and $k_B$ is the Boltzmann constant.

Solar radiation can be approximated as thermal radiation from a blackbody at 5800 K, and in this approximation 98% of the solar spectral power is contained between 250 nm and 4 µm. The true solar spectrum that reaches the Earth’s surface differs from the blackbody approximation primarily due to atmospheric absorption. Standard solar spectra are published in tables by organizations such as ASTM International [52]. The most commonly used spectrum is AM 1.5G, where “AM 1.5” refers to the solar spectrum after passing through 1.5 air masses (i.e., at an incidence angle of 48° through the atmosphere) and “G” denotes the global value, including radiation from the entire sky. The other spectrum of interest in this thesis is AM 1.5D+C, where “D+C” denotes the direct and circumsolar value, only including radiation within 2.5° of the center of the sun. AM 1.5D+C is more relevant for concentrating applications, which cannot collect the diffuse portion of incident solar radiation. These different spectra are plotted for comparison in Figure 1.5. As can be seen from the figure the three spectra are similar, so analyses using the 5800 K blackbody approximation should still yield accurate results.

Converting sunlight to electricity with PV cells is inherently spectral in nature, since only photons with energy above the bandgap of the PV semiconductor material can promote an electron from the valence band to the conduction band. There are two spectral losses in PV cells: photons with energy below the bandgap are unusable, and electrons with energy above the bandgap quickly thermalize to band edge, so photons with energy above the bandgap only contribute energy equal to the bandgap. These spectral losses are the biggest factors in the Shockley-Queisser limit, which sets the limit for the conversion
Figure 1.5 Spectral irradiance as a function of wavelength for different solar spectra: air mass 1.5 global irradiance (AM 1.5G, red curve), air mass 1.5 direct & circumsolar irradiance (AM 1.5D+C, orange curve), and irradiance of a blackbody at 5800 K, scaled to approximate an air mass 1.5 intensity (dotted black curve).

efficiency of single bandgap PV cell [53]. Choosing a semiconductor material with an appropriate bandgap energy is critical to achieving high efficiency in PV cells, which is a consequence of the solar spectrum.

Spectral effects are important in CSP systems because absorber temperatures are much lower than the surface temperature of the sun. This difference leads to significantly different spectra for solar radiation versus the emitted radiation from the absorber in a CSP receiver. The small overlap in these two spectra can be leveraged to improve receiver performance by finding (or designing) an absorber surface with high absorptance over the solar spectrum, but low emittance in the mid-infrared spectrum. This difference in absorptance and emittance as a function of wavelength is known as spectral selectivity. To calculate the effective solar absorptance $\alpha$ of a surface from its spectral emittance properties (assuming no variation with incidence angle), an integral is performed over all wavelengths [51]:

$$\alpha = \frac{1}{G} \int_0^\infty \varepsilon(\lambda)G(\lambda)d\lambda$$  \hspace{1cm} (1.24)
where $G$ is total solar irradiance, $G_\lambda$ is spectral solar irradiance, and $\varepsilon_\lambda$ is the emittance of the surface, which in the case of a spectrally selective surface varies with wavelength.

Similarly, to calculate the total emittance of a surface $\varepsilon$, which is a function of the surface temperature $T$ as well as the surface’s radiative properties, an integral is performed over all wavelengths:

$$\varepsilon(T) = \frac{1}{\sigma T^4} \int_0^\infty \varepsilon_\lambda(\lambda) E_{b\lambda}(T, \lambda) d\lambda$$  \hspace{1cm} (1.25)$$

where $\sigma$ is the Stefan-Boltzmann constant and $E_{b\lambda}$ is the blackbody emissive power (given by Eq. (1.23)).

Spectral selectivity is a widely pursued strategy for improving CSP receiver performance, and as such there are many examples of spectrally selective surfaces that have been fabricated and measured. Specific absorber structures for achieving spectral selectivity include ceramic-metal composites ("cermets"), semiconductor metal tandems, multi-layer thin-film structures, structured surfaces, and photonic crystals [11,54]. The spectral emittance curves for a number of different spectrally selective solar absorber surfaces are shown in Figure 1.6, along with a non-selective black paint for comparison. Each of the spectrally selective surfaces has high absorptance in the solar spectrum, but low emittance in the longer IR wavelengths. It is common for these spectrally selective surfaces to achieve solar absorptances of around 95% with effective emittances of less than 15% at 400 °C, the typical operating temperature of the PTC systems with which these absorbers are paired. There are limited demonstrations of spectrally selective absorbers that are stable at higher temperatures in air, which would be necessary for use in power tower systems.

### 1.3.2 Direction and directional selectivity

Despite its true size, the sun looks small due to its great distance from Earth. When viewed from Earth's surface, the sun appears as a circle with a half angle of about 0.27 degrees [5]. Thus, the solid angle that the sun subtends in the terrestrial sky is roughly $6.9 \times 10^{-5}$ steradians, approximately 1/46000 of the total sky. Solar radiation arriving on Earth’s surface from this nearly uniform direction gives an opportunity for improved performance via directional selectivity. Directional selectivity refers to a solar receiver that absorbs radiation over a small range of incidence angles while minimizing emitted radiation at other angles.
Figure 1.6 Sample emittance spectra of various spectrally selective absorbers. All follow the same trend of high emittance in the solar spectrum and low emittance in IR. Sunselect (solid curve) is a commercial cermet coating [55]. A number of coatings resulting from university research are also plotted: a SiO2/Cr/SiO2/Al thin-film coating (dashed curve) [56], a nickel nanop pyramid structured surface (dash-dotted curve) [57], and a tantalum photonic crystal coating (dotted curve) [58]. A commercial black paint, Pyromark 2500, is plotted along with the spectrally selective absorbers for comparison [59].

Directional selectivity can be utilized in both PV and CSP systems. In PV systems, one form of losses is radiative recombination loss, which can occur when an excited electron rejoins a hole leading to an emitted photon. If that photon escapes the PV cell rather than being reabsorbed, its energy is lost. Directional selectivity can reduce radiative recombination losses by reducing the angular range over which photons can escape. Examples of previous work investigating directional selectivity for improving PV performance include directional filters, micro-concentrators, and optical cavities [60–64].

In CSP systems, directional selectivity can be used to improve receiver efficiency. Similar to calculating solar absorptance of a spectrally selective surface by integrating over wavelength, the solar absorptance of a directionally selective absorber (which does not vary with wavelength) is calculated by integrating over incidence angle θ (in the azimuthally symmetric case) [51]:

\[
\alpha = \frac{2}{\sin^2 \theta_{\text{max}}} \int_0^{\theta_{\text{max}}} \epsilon_{\theta}(\theta) \sin \theta \cos \theta \, d\theta
\]

(1.26)

where \( \epsilon_{\theta} \) is the directionally dependent emittance (and therefore absorptance) of the surface, and \( \theta_{\text{max}} \) is
the maximum incidence angle of solar radiation striking the absorber. Here $\theta_{max}$ would be 0.27 degrees for a surface normal to incident unconcentrated solar radiation, and it would be larger for concentrated solar radiation. The interplay between concentration and directional selectivity will be discussed in more detail in chapter 2 of this thesis. Total hemispherical emittance is calculated by integrating over all incidence angles:

$$\epsilon = 2 \int_0^{\pi/2} \epsilon_\theta(\theta) \sin \theta \cos \theta d\theta$$

(1.27)

If the receiver has high absorptance at angles near normal incidence, but high reflectance at large incidence angles, a high solar absorptance can be maintained while achieving a low total hemispherical emittance. In this way, directional selectivity can improve receiver efficiency, as seen from Eq. (1.9) in the case of high absorptance and low emittance. Strategies proposed for achieving spectral selectivity in CSP systems include photonic crystals and grooved surfaces [65,66].

1.4 Thesis Outline

This thesis primarily addresses two methods for improving the performance of solar receivers: spectral selectivity and directional selectivity. In chapter 2, the theoretical limits of improvement via spectral and directional selectivity are investigated. For the case of spectral selectivity, the Kramers-Kronig relations are applied to an interface in order to determine the sharpest spectral drop in reflectance allowed for a homogeneous medium. For directional selectivity, a geometric approach is used to define maximum achievable performance, and it is compared to concentration. Chapter 3 introduces silica aerogel, a spectrally selective material, and two solar receiver designs which are enabled through the use of silica aerogel. A method for modeling the performance of aerogel based solar receivers is presented, and is subsequently used to calculate the achievable efficiencies of the aerogel based solar receiver designs. Chapter 4 covers the design and fabrication of a prototype test system for measuring the performance of a solar thermal aerogel receiver, along with preliminary results collected from the system. Chapter 5 describes a reflective macroscale cavity for directional selectivity. Modeling results show the performance enhancement achievable with such a cavity for both PV and solar thermal receivers, and experimental results for the solar thermal case are presented. Chapter 6 summarizes what has been accomplished in this thesis and offers directions for future work in spectral and directional selectivity.
Chapter 2

Limits to Spectral and Directional Selectivity

In attempting to improve performance of a solar receiver through spectral and directional selectivity, it is helpful to understand the limits to possible improvement. This chapter will first cover Kirchoff’s radiation law, which is integral to understanding the ultimate limit to radiative selectivity, followed by an explanation of the geometrical concentration limit of sunlight on Earth, and the highest achievable efficiency for terrestrial solar energy conversion. Next, an approach for determining the limit to spectral selectivity will be introduced, and will be used to explore the best achievable spectral selectivity for a passive, intrinsic CSP absorber. Lastly, this chapter will detail the equivalence of directional selectivity and concentrating sunlight, and will investigate the level of directional selectivity necessary to outperform existing systems using high concentration.

2.1 Kirchhoff’s radiation law

Ultimately, limits for energy conversion systems are set by the laws of thermodynamics. One such limit setting law that is relevant for systems involving radiative heat transfer is Kirchhoff’s radiation law (sometimes called Kirchhoff’s law of thermal radiation). Kirchhoff’s radiation law is critically important for both spectral and directional selectivity, and states that emittance $\varepsilon$ and absorptance $\alpha$ of a surface (at a given temperature) for a specific wavelength $\lambda^*$ in a specific direction $\theta^*$ must be equal [51]:

$$\varepsilon_{\lambda,\theta}(\lambda^*, \theta^*) = \alpha_{\lambda,\theta}(\lambda^*, \theta^*)$$  \hspace{1cm} (2.1)

Kirchhoff’s radiation law is a consequence of the second law of thermodynamics, which forbids heat flowing up a temperature gradient (i.e., from a colder to a hotter object). We can derive Kirchhoff’s radiation law with a thought experiment [67]: imagine we have a surface facing a blackbody cavity at a temperature $T_0$, with the surface and cavity separated by an optical filter. The equilibrium temperature of the surface must be $T_0$, otherwise if the surface was introduced at the temperature $T_0$, heat would need to flow from a colder to hotter object in order for the surface to reach its equilibrium temperature.

Now suppose the optical filter perfectly reflects radiation at all wavelengths except for $\lambda^*$, which it transmits. If the surface has a higher emittance than absorptance at that wavelength ($\varepsilon(\lambda^*) > \alpha(\lambda^*)$), then
the surface would emit more radiation through the filter to the cavity than it would absorb, and it would cool to a temperature below that of the cavity. Similarly, if the filter reflected all directions except for one particular direction $\theta^*$, a disparity in emittance and absorptance of the surface for that direction ($\epsilon(\theta^*) \neq \alpha(\theta^*)$) would also lead to the surface changing temperature from $T_0$ despite only being thermally exposed to that cavity at $T_0$. In order to prevent the possibility of a surface spontaneously reaching a temperature which is higher or lower than an object it is exposed to, its radiative properties must follow Kirchoff's law.

2.2 Limits to solar concentration and energy conversion

This chapter explores the limits of efficiency, so for this chapter we will take the case where optical efficiency is unity (as are transfer and storage efficiencies) and the heat engine efficiency is taken as the Carnot limit. Radiation is the only thermodynamically required thermal loss from the receiver in order to absorb solar radiation, so it is the only receiver loss we will consider for now. Thus, the system efficiency $\eta$ is given by:

$$\eta = \left( \alpha - \frac{\varepsilon \sigma (T_H^4 - T_{\text{amb}}^4)}{C G_{\text{DNI}}} \right) \left( 1 - \frac{T_C}{T_H} \right)$$

In this simplified approach, overall efficiency is primarily determined by the operating temperature and the parameters which influence receiver efficiency: absorptance, emittance and concentration ratio.

2.2.1 Maximum solar concentration ratio

The simplest approach to finding a limit for CSP system efficiency is to maximize concentration ratio [11]. It is not intuitively obvious that there should be a limit to maximizing solar concentration ratio: one might expect that if a solar concentrator has a large aperture and an arbitrarily small outlet, an arbitrarily high concentration ratio can be achieved. However carrying out this situation would break the second law of thermodynamics, and is therefore impossible [68].

The quickest way to prove that arbitrarily high concentration ratios are impossible is to consider the scenario where solar radiation incident on Earth is concentrated to a very high value, say 1,000,000x, and directed towards a black absorber which is insulated on the back side. The absorber would eventually reach a stagnation temperature $T_{\text{stag}}$ where the absorbed power is balanced by emitted radiation losses from the absorber, given by $\sigma T_{\text{stag}}^4$ where $\sigma$ is the Stefan-Boltzmann constant. Thus, $T_{\text{stag}}$ can be calculated from:
As an example, taking \( C = 1,000,000 \) and \( G_{DNI} = 1000 \text{ W/m}^2 \), we calculate that \( T_{stag} \approx 11,500 \text{ K} \), almost twice the temperature of the Sun. This is impossible, as it would require heat (in the form of radiation) to flow from a colder object (the Sun) to a hotter object (the absorber). The highest temperature that we expect the absorber to reach is the temperature of the Sun, so we can rearrange (2.3) for the highest thermodynamically allowed concentration ratio \( C_{max} \):

\[
C_{max} = \frac{\sigma T_{sun}^4}{G_{DNI}}
\]  

(2.4)

In using this approach, we should take \( G_{DNI} \) based on the AM0 spectrum, rather than the typical AM1.5 spectrum, since considering atmospheric absorption would lead to the absorber temperature being lower than the surface temperature of the Sun. Taking \( G_{DNI} = 1370 \text{ W/m}^2 \) \[52\] and \( T_{sun} = 5800 \text{ K} \), we estimate that \( C_{max} = 47,000 \). Therefore, from a thermodynamic argument, solar concentration ratios greater than \( \approx 47,000 \) are impossible on Earth, as it could lead to a net flow of heat from the Sun to an absorber at a higher temperature.

There are also geometrical explanations for why there is a limit to the achievable solar concentration ratio on Earth. The field of non-imaging optics explores the geometry of solar concentrators in detail, and revolves around the concept of conservation of etendue \[69\]. Etendue is a property of radiation and is the product of the area and subtended solid angle of the radiation. Intuitively, etendue measures how spread out a radiation source is - both spatially and angularly. Refraction and specular reflection conserve etendue, while diffuse reflection increases etendue (since it increases the angular spread of reflected light), so at best etendue can be kept constant through an optical system, but it cannot be decreased. Since etendue measures the spread of radiation, conservation of etendue sets a geometric limit on concentrating light.

Conservation of etendue requires that an optical element (such as a solar concentrator) which accepts light over an area \( A_{in} \) up to an incidence angle \( \theta_{in} \) and redirects that light to an output with area \( A_{out} \) over an angle \( \theta_{out} \) follow the equation \[69\]:

\[
A_{in} \sin^2 \theta_{in} = A_{out} \sin^2 \theta_{out}
\]  

(2.5)

35
In the case of a concentrator, the geometric concentration ratio $C$ is given by the ratio of the input area to the output area:

$$C = \frac{A_{in}}{A_{out}} = \frac{\sin^2 \theta_{out}}{\sin^2 \theta_{in}}$$  \hspace{1cm} (2.6)

To maximize concentration, $\sin^2 \theta_{out}$ should be maximized, and the maximum value of 1 is achieved when an output angle of $\theta_{out} = 90^\circ$ is used. $\sin^2 \theta_{in}$ should be minimized, but in order to accept all incident sunlight the acceptance angle $\theta_{in}$ must be at least the divergence half angle of solar radiation on Earth $\theta_{sun}$. Nominally, $\theta_{sun}$ can be calculated by taking the inverse tangent of the radius of the Sun ($6.96 \times 10^8$ m) divided by the distance between the Earth and Sun ($1.52 \times 10^{11}$ m), which yields a value of approximately 4.58 mrad, or about 0.26°. Using this value for the solar divergence angle yield a maximum concentration ratio $C_{max} = 1/\sin^2 \theta_{sun} \approx 48,000$. It should be noted that this geometric argument also sets the limit of concentration to the radiative flux at the surface of the Sun, since a perfect concentrator would be able to recover the etendue state of solar radiation at the Sun’s surface.

Using either a direct thermodynamics argument or using a geometric argument, we calculate the maximum achievable solar concentration ratio on Earth to be in the range of 47,000 - 48,000. When considering atmospheric effects on the apparent solar divergence angle, it is common to take a slightly lower value of 45,000 - 46,000 [70], however this is a largely academic distinction, as demonstrated concentration ratios still fall short of even this reduced value [26]. The exception is for concentrators which use high index of refraction secondary concentrators, since the forms of Eqns. (2.5) and (2.6) when considering the index of refraction $n$ through which the radiation travels are:

$$A_{in} n_{in} \sin^2 \theta_{in} = A_{out} n_{out} \sin^2 \theta_{out}$$  \hspace{1cm} (2.7)

$$C = \frac{n_{out}^2 \sin^2 \theta_{out}}{n_{in}^2 \sin^2 \theta_{in}}$$  \hspace{1cm} (2.8)

While impressively high concentration ratios of 60,000× have been demonstrated using high index secondary concentrators [71], such concentrators are not beneficial for improving the efficiency of CSP systems. Radiative losses from a CSP receiver also scale as $n^2$, so any benefit gained by increased concentration ratio is cancelled out by increased radiative thermal losses. Thus, for the purposes of terrestrial CSP systems, the maximum achievable solar concentration ratio is approximately 46,000×.
2.2.2 Maximum solar energy conversion efficiency

Maximizing the concentration ratio of solar radiation incident on our solar collector, assuming we have perfect concentrating optics, and treating the Sun as a blackbody at $T_{sun}$, then the highest incident flux we can achieve is $\sigma T_{sun}^4$. Given this incident flux, the equation for system efficiency becomes

$$\eta = \left( \alpha - \frac{\epsilon(T_H^4 - T_{amb}^4)}{T_{sun}^4} \right) \left( 1 - \frac{T_C}{T_H} \right)$$  \hspace{1cm} (2.9)$$

Since we expect that the operating temperature of our system $T_H$ is much greater than the ambient temperature $T_{amb}$, we can make the approximation $T_H^4 - T_{amb}^4 \approx T_H^4$, and the expression simplifies to:

$$\eta = \left( \alpha - \frac{\epsilon T_H^4}{T_{sun}^4} \right) \left( 1 - \frac{T_C}{T_H} \right)$$  \hspace{1cm} (2.10)$$

The heat rejection temperature $T_C$ depends on ambient conditions and a representative value of 300 K can be used for our calculations. Thus, the only parameters we need to set are absorptance $\alpha$, emittance $\epsilon$, and operating temperature $T_H$. In principle, we would like to maximize absorptance and minimize emittance, however we are constrained by Kirchhoff’s law. For maximum concentration, solar radiation is incident on the absorber from all angles, so there is no capacity for directional selectivity. Additionally, if the incident solar spectrum is modeled as a blackbody at $T_{sun}$, there is no improvement to be gained by spectral selectivity. This is because, due to Planck’s law (Eq. (1.23)), a blackbody at a higher temperature will emit more radiation at every wavelength. So as long as $T_H < T_{sun}$ (which it must be for a system efficiency above 0), then there is more incident solar radiation to be absorbed than blackbody radiation that would be emitted from the absorber, and performance is maximized by choosing $\alpha = \epsilon = 1$ for all wavelengths. It should be noted that if the real solar spectrum were used rather than a blackbody at $T_{sun}$, a slight improvement could be achieved with the use of spectral selectivity. The true solar spectrum has dips at some wavelengths where the ideal absorber would have low emittance. For the case we are considering here, the expression for efficiency now simplifies to:

$$\eta = \left( 1 - \frac{T_H^4}{T_{sun}^4} \right) \left( 1 - \frac{T_C}{T_H} \right)$$  \hspace{1cm} (2.11)$$

Taking $T_{sun} = 5800$ K and $T_C = 300$ K, efficiency is plotted as a function of $T_H$ in Figure 2.1. A maximum efficiency of about 85% is achieved for an operating temperature of approximately 2500 K. This efficiency limit of 85% is much higher than any system efficiency which has been achieved in
Figure 2.1 System efficiency $\eta$ as a function of operating temperature $T_H$ for a CSP system operating under the maximum solar concentration ratio with a heat engine efficiency of Carnot, as given by Eq. (2.11).

practice, but it still sets a useful target for other specific strategies (beyond just solar concentration) to aspire to.

It is worth noting that the limit derived above only applies for solar-thermal energy conversion, where solar radiation is first converted to thermal energy and then work is extracted via a heat engine. In a more general approach performed by Landsberg leads to the derivation of an efficiency limit given by [72]:

$$\eta = 1 - \frac{4}{3} \frac{T_C}{T_{sun}} + \frac{1}{3} \left( \frac{T_C}{T_{sun}} \right)^4$$

Using $T_C = 300$ K and $T_{sun} = 5800$ K yields an efficiency limit of 93.1%. Thus, solar conversion efficiency could be pushed even higher if different strategies were pursued. For the case of solar thermal energy conversion, however, the relevant limit is given by Eq. (2.11).

### 2.3 Limits to spectral selectivity

Spectral selectivity is an effective method for improving receiver efficiency and is commonly used in systems with operating temperatures $\leq 400$ °C, since there are many spectrally selective surfaces available that are stable at those temperatures. Spectral selectivity reduces the effective emittance $\epsilon$ of the absorber
while maintaining a high effective absorptance $\alpha$. This improves the receiver efficiency $\eta_{\text{rec}}$, as can be seen from the equation for receiver efficiency $\eta_{\text{rec}}$, Eq. (1.9), which is reprinted here for convenience:

$$\eta_{\text{rec}} = \tau \alpha - \frac{\epsilon \sigma (T_{\text{H,abs}}^4 - T_{\text{amb}}^4)}{CG_{\text{DNI,\ell, opt}}}$$  \hspace{1cm} (2.13)

2.3.1 Spectral selectivity with a step function emittance profile

To determine the optimal emittance profile of a spectrally selective surface, it is more useful to recast the equation for receiver efficiency as an integral over all wavelengths, rather than using the effective radiative properties $\alpha$ and $\epsilon$ [11,54]:

$$\eta_{\text{rec}} = \frac{1}{CG_{\text{DNI,\ell, opt}}} \int_0^\infty \epsilon_\lambda(\lambda) [\tau CG_{\text{DNI,\ell, opt}}(\lambda) \eta_{\text{opt}} - E_{b\lambda}(T, \lambda)] d\lambda$$  \hspace{1cm} (2.14)

where properties subscripted with $\lambda$ denote spectral values, and $E_{b\lambda}$ is the spectral blackbody emissive power (given by Planck’s law, Eq. (1.23)). Because the emittance and absorptance must be equal for a particular wavelength due to Kirchhoff’s radiation law, the same value affects absorbed and emitted radiation at each wavelength, which is why there is only a single instance of $\epsilon_\lambda(\lambda)$ in the integrand of Eq. (2.14). The term in the integrand in square brackets is the incident solar radiation, which can potentially be absorbed, minus the spectral blackbody emissive power at the receiver’s operating temperature, which can potentially be emitted as radiative thermal losses. For wavelengths where the term in square brackets is greater than 0, emittance should be large to maximize receiver efficiency, whereas for wavelengths where it is less than 0, emittance should be small to maximize receiver efficiency. Since emittance can vary from 0 to 1, the ideal emittance profile of a spectrally selective surface is therefore given by:

$$\epsilon_\lambda(\lambda) = \begin{cases} 1 & \text{if } [\tau CG_{\text{DNI,\ell, opt}}(\lambda) \eta_{\text{opt}} - E_{b\lambda}(T, \lambda)] > 0 \\ 0 & \text{if } [\tau CG_{\text{DNI,\ell, opt}}(\lambda) \eta_{\text{opt}} - E_{b\lambda}(T, \lambda)] < 0 \end{cases}$$  \hspace{1cm} (2.15)

When considering the true solar spectrum, this can lead to complicated emittance profiles that start at 1 for short wavelengths, then step between 1 and 0 near the tail of the solar spectrum where atmospheric absorption bands lead to values of 0 for $G_{\text{DNI,\ell}}$ at some wavelengths, before finally dropping to 0 at longer wavelengths where the solar spectrum effectively goes to zero [11]. If the solar spectrum is modeled as a blackbody at a temperature of 5800 K (that is, $G_{\text{DNI,\ell}}(\lambda) \equiv E_{b\lambda}(T = 5800 \text{ K}, \lambda)$), the ideal profile will have a single transition from an emittance of 1 at short wavelengths to an emittance of 0 at long wavelengths [73]. This ideal transition wavelength is a function of the parameters in Eq. (2.15):
transmittance of any receiver optics \( \tau \), concentration ratio \( C \), concentrating optics efficiency \( \eta_{\text{opt}} \), and operating temperature \( T \). If we define the total incident power on the receiver (per unit area) \( q_{\text{rec}} \) by:

\[
q_{\text{rec}} = \int_{0}^{\infty} \tau C G_{\text{DNI}, \lambda}(\lambda) \eta_{\text{opt}} d\lambda = \int_{0}^{\infty} \tau C k E_{b \lambda}(T_{\text{sun}} = 5800 \, \text{K}, \lambda) \eta_{\text{opt}} d\lambda
\]  
(2.16)

and take the solar spectrum as the blackbody spectrum at 5800 K, that is \( G_{\text{DNI}, \lambda}(\lambda) = k E_{b \lambda}(T_{\text{sun}} = 5800 \, \text{K}, \lambda) \) where \( k \) is some scaling factor, we can find \( k \) as a function of other system parameters (by using \( \sigma T^4 = \int_{0}^{\infty} E_{b \lambda}(T, \lambda) d\lambda \)):

\[
k = \frac{q_{\text{rec}}}{T C \eta_{\text{opt}} \sigma T_{\text{sun}}^4}
\]  
(2.17)

We can find the ideal transition wavelength \( \lambda_{\text{step}} \) by setting the spectral blackbody emissive power (at the operating temperature of the receiver) equal to the incident solar spectral power.

\[
E_{b \lambda}(T, \lambda_{\text{step}}) = \tau C G_{\text{DNI}, \lambda}(\lambda_{\text{step}}) \eta_{\text{opt}} = \frac{q_{\text{rec}}}{\sigma T_{\text{sun}}^4} E_{b \lambda}(T_{\text{sun}}, \lambda_{\text{step}})
\]  
(2.18)

Plugging in the expression for \( E_{b \lambda} \) given by Planck's law (Eq. (1.23)) and simplifying yields:

\[
\frac{1}{(e^{\frac{h c_0}{n \lambda_{\text{step}}} k \beta T} - 1)} = \frac{q_{\text{rec}}}{\sigma T_{\text{sun}}^4 (e^{\frac{h c_0}{n \lambda_{\text{step}}} k \beta T_{\text{sun}}} - 1)}
\]  
(2.19)

For wavelengths and temperatures we are concerned with, \( e^{\frac{h c_0}{n \lambda_{\text{step}}} k \beta T} \gg 1 \) (using \( \lambda = 2 \, \mu\text{m} \) and \( T = 1000 \, \text{K} \) yields \( e^{\frac{h c_0}{n \lambda_{\text{step}}} k \beta T} = 1331 \), so we can make the approximation \( e^{\frac{h c_0}{n \lambda_{\text{step}}} k \beta T} - 1 \approx e^{\frac{h c_0}{n \lambda_{\text{step}}} k \beta T} \) and maintain reasonable accuracy except for very high operating temperatures (above 2000 K). This approximation and further algebra yields:

\[
\lambda_{\text{step}} = \frac{h c_0 (T - T_{\text{sun}})}{n k \beta T_{\text{sun}} \ln \left( \frac{q_{\text{rec}}}{\sigma T_{\text{sun}}^4} \right)}
\]  
(2.20)

This ideal transition wavelength is plotted in Figure 2.2 as a function of \( T \) and \( q_{\text{rec}} \). At high operating temperatures and low incident solar fluxes, the ideal transition wavelength shifts to shorter values, as the incident solar spectrum and the emitted blackbody spectrum have more overlap. For low operating temperatures and high incident solar fluxes the ideal transition wavelength shifts to longer values, and the ideal absorber effectively becomes black, as the incident solar power is much greater than the emitted...
Ideal transition wavelength $\lambda_{step}$ in $\mu$m for a spectrally selective absorber as a function of incident solar radiation on the receiver $q_{rec}$ and the receiver operating temperature $T$. Incident flux is reported in kW/m$^2$ so that it also corresponds to flux concentration ratio $C_{flux}$, assuming a DNI of 1000 W/m$^2$. These results use Eq. (2.20) which assumes that the solar spectrum is proportional to the spectrum from a blackbody at 5800 K.

blackbody radiation. It's worth noting that for the parameters typical of deployed CSP systems which use spectral selectivity ($q_{rec} \approx 20,000$ W/m$^2$ and $T \approx 700$ K) the ideal transition wavelength is around 2 - 2.5 $\mu$m, and most spectrally selective surfaces have a transition from high to low absorptance around this value [11, 54, 73].

The primary purpose to calculating the ideal transition wavelength $\lambda_{step}$ is to improve the efficiency of a system which uses a spectrally selective absorber. We can calculate the receiver efficiency achieved by such a spectrally selective absorber by plugging in its emittance profile, given in Eq. (2.15), into the expression for receiver efficiency, given in Eq. (2.14). If we take the ideal case where $\tau = \eta_{opt} = 1$, the resulting receiver efficiency when using the optimal emittance profile is given by:

$$\eta_{rec} = \frac{1}{q_{rec}} \int_0^{\lambda_{step}} \left[ \frac{q_{rec}}{\sigma T_{sun}^4} E_{b\lambda}(T_{sun}, \lambda) - E_{b\lambda}(T, \lambda) \right] d\lambda$$

(2.21)

This receiver efficiency is plotted as a function of $q_{rec}$ and $T$ in Figure 2.3. As one would expect, receiver efficiency increases with incident solar radiation (i.e., with concentration ratio) and decreases for higher operating temperatures. In general, the receiver efficiencies when using these idealized parameters and
Figure 2.3 Contour plot of the receiver efficiency $\eta_{\text{rec}}$ achieved with an absorber with a step function emittance profile for varying operating temperature $T$ and solar radiation incident on the receiver $q_{\text{rec}}$. These results use Eq. (2.20) which assumes that the solar spectrum is proportional to the spectrum from a blackbody at 5800 K.

ideal step function spectrally selective absorber are high: the operating space that real plants occupy correspond to receiver efficiencies above 95%.

We can further calculate full system efficiency $\eta$ if we make an assumption about the efficiency of the heat engine which converts the heat output from the receiver to electricity. In the ideal case, the heat engine efficiency is given by the Carnot limit, in which case full system efficiency is given by:

$$\eta = \eta_{\text{rec}} \left( 1 - \frac{T_c}{T_H} \right)$$  \hspace{1cm} (2.22)

where the temperature of heat input to the heat engine $T_H$ can be taken as the receiver operating temperature $T$, as it is reasonable to assume a negligible temperature drop from the receiver to the heat engine. This full system efficiency is plotted in Figure 2.4 for varying $q_{\text{rec}}$ and $T$, assuming a heat engine rejection temperature of $T_c = 300$ K. System efficiency increases with incident solar radiation, and at each incident solar radiation level there is an operating temperature which leads to maximum performance. This is due to the interplay between receiver efficiency, which decreases with increasing operating temperature, and heat engine efficiency, which increases with increasing operating temperature. The optimal operating temperature increases with incident solar radiation, as higher concentration ratios
Figure 2.4 Contour plot of the system efficiency $\eta$ achieved with an absorber with a step function emittance profile and using Carnot heat engine efficiency for varying operating temperature $T$ and solar radiation incident on the receiver $q_{rec}$.

lead to high receiver efficiencies, so operating at a low temperature to maintain high receiver efficiency becomes less important to overall performance.

The optimal operating temperature varies from around 900 K to 1200 K in the range of incident solar radiation achieved in commercial CSP plants. For a system with an ideal step function spectrally selective absorber and a heat engine operating at Carnot efficiency, the overall efficiency is quite high: values of 60 – 70% are achieved for incident solar fluxes corresponding to concentration ratios from 30 - 1000x. Thus, spectrally selectivity has the potential to lead to high efficiency, and using it in tandem with concentration allows for higher efficiencies. If the concentration ratio is increased to its maximum value as discussed in section 2.2.1, then the optimal spectral selectivity approach would revert to the max concentration strategy of using a black absorber, and the maximum system of efficiency of 85% would be recovered (as calculated in section 2.2.2).

It should be noted that the analysis so far in this section has approximated the solar spectrum as that of a blackbody at 5800K, which is not identical to the true solar spectrum which reaches Earth’s surface. If the real spectrum were used instead the optimal emittance profile would become more complicated, with multiple steps up and down due to atmosphere absorption bands which lead to dips in the solar spectrum (and therefore windows where the ideal absorber has low emittance). If a single step absorber was still
pursued, then the ideal transition wavelength would tend to lock into certain wavelengths which correspond to edges of atmospheric absorption bands [73,74], rather than varying continuously with operating temperature as is the case in Figure 2.2. Overall however, the trends outlined in the figures above which explore spectral selectivity would still hold if the actual solar spectrum was used in place of the blackbody approximation.

2.3.2 Spectral selectivity considering the Kramers-Kronig relations

While the approach described in the previous section provides the thermodynamically limited performance of spectral selectivity, it relies on perfect step function jumps in an absorber’s spectral emittance profile, which is difficult to achieve in practice. In addition to determining the thermodynamically limited performance of spectral selectivity, it is of interest to determine the level of performance that can be achieved with more realistic absorbers. One approach to addressing achievable performance in real systems is to consider the Kramers-Kronig relations as they relate to the properties of proposed spectrally selective absorber materials.

While the Kramers-Kronig relations are commonly used in optics applications, they are fundamentally a mathematical relationship. The Kramers-Kronig relations connect the real and imaginary parts of a complex function that is analytic in the upper half plane [75]. Thus, for some complex function \( X \) given by:

\[
X = X' + iX''
\]  
(2.23)

the Kramers-Kronig relations bidirectionally relate the real part \( X' \) and the imaginary part \( X'' \) of the function [76]:

\[
X'(\omega) = \frac{2}{\pi} \int_0^{\infty} \frac{X''(\omega')\omega'}{\omega' - \omega} d\omega'
\]  
(2.24)

\[
X''(\omega) = -\frac{2}{\pi} \int_0^{\infty} \frac{X'(\omega')\omega}{\omega' - \omega} d\omega'
\]  
(2.25)

so that one is able to calculate the real part of the function from the imaginary part (given they have the entire imaginary part) or vice versa. The Kramers-Kronig relations are relevant to our study of spectral selectivity because for response functions to physical systems, causality implies that the response function is analytic in the upper half plane [77].

Causality means that a system cannot respond to inputs until after they happen. A system that behaved otherwise would be non-physical, so we can require that all of our systems act causally and therefore
follow the Kramers-Kronig relations. To understand how this manifests physically, it is helpful to consider an example, which is illustrated in Figure 2.5. Suppose we have a surface that has a reflectance of unity for all wavelengths except for one frequency \( \omega_0 \), for which it has some finite absorption (Figure 2.5a). If we shine a pulse of light on this surface which is a Gaussian in the time domain, and therefore also a Gaussian in the frequency domain (Figure 2.5b), then we might expect that the reflected pulse in the frequency domain is simply a Gaussian with part of the frequency \( \omega_0 \) reduced (Figure 2.5c). However if we explore this expectation further, there is a problem. The corresponding signal in the time domain would now be a Gaussian with a sine wave of frequency \( \omega_0 \) superimposed, and this sine wave would extend indefinitely from time \(-\infty\) to \(\infty\). This is a problem because of the portion of the sine wave extending backwards in time - the response of the system (the reflected light pulse) occurs before the input (the incident light pulse). For a real surface with this reflectance profile, there would need to be an additional imaginary part of the function to maintain causality (Figure 2.5d). This imaginary part is the phase shift, which modifies the phase of the reflected light in such a way as to contain the reflected light pulse in time (Figure 2.5e). For causality to be maintained, the reflectance and phase shift of a surface must follow the Kramers-Kronig relations.

This requirement that reflectance and phase shift follow the Kramers-Kronig relations does not inherently limit the potential for spectral selectivity. Any reflectance profile can be assumed for a surface, whether it be a delta function as in the example above, or a step function as is desired for spectrally selective absorbers in CSP receivers, and there is a matching phase shift profile that would allow the surface to have a causal response. The limitations arise when pursuing a particular strategy to achieve the desired reflectance profile, as material systems used to produce a particular reflectance profile impose additional constraints. Here we will consider the case of passive, intrinsic absorbers, and how their potential for spectral selectivity is limited by the Kramers-Kronig relations and causality. The limitations imposed from such an absorber, where passive means that there is no energy input aside from incident solar radiation and intrinsic means the absorber is composed of a homogenous material, will become clear as we explore what is required of an absorber material to achieve certain reflectance profiles.

There are a number of complex functions relevant to making a spectrally selective absorber that result in “Kramers-Kronig pairs,” or real and imaginary parts of a function that is analytic in the upper half plane. One is the index of refraction of a material, which is a property that varies with frequency (or equivalently wavelength) in materials and is leveraged to design spectrally selective absorbers [77]. The function which is most directly related to spectral selectivity, and therefore the most convenient for this investigation, is the reflection coefficient of an interface (this is the function given in the example above).
Figure 2.5 Physical example to show how the Kramers-Kronig relations lead to causality for reflection from a surface. Suppose we have a surface which is perfectly reflecting except for some finite absorption at a wavelength $\omega_0$, with the absorptance profile of this surface given by (a). If a pulse of light which is Gaussian in frequency and therefore also in time (b) is sent towards the surface, we expect that the reflected light pulse in the frequency domain is a Gaussian with part of the frequency $\omega_0$ removed (c). If this was the only change, then there is a problem, as the Fourier transform would lead to the same Gaussian except that a sine wave with a frequency of $\omega_0$ has been superimposed. This would violate causality, as this sine wave extends backwards in time, suggesting that a response happening before an input. In reality, the surface must also have an imaginary portion to its reflectance profile: a phase shift profile given by (d). This phase shift profile, which is related to the reflectance profile by the Kramers-Kronig relations, modifies the phases of the reflected light such that the reflected pulse is contained in time (e).
The reflection coefficient $r$ gives the portion of an incident electric field which is reflected at an interface, and can be separated into an amplitude $\rho$ and phase $\theta$, which are all functions of frequency [78]:

$$r(\omega) = \rho(\omega)e^{i\theta(\omega)} \quad (2.26)$$

Engineers are typically more concerned with reflectance $R$, which gives the portion of reflected incident power from an interface, which can be related to reflection coefficient by:

$$R(\omega) = |r(\omega)|^2 = \rho(\omega)^2 \quad (2.27)$$

These equations give us a complex function where reflectance is the real portion and phase shift is the imaginary portion if we take the natural log of Eq. (2.26), which yields:

$$\ln r(\omega) = \frac{1}{2} \ln R(\omega) + i\theta(\omega) \quad (2.28)$$

Thus, if we impose a reflectance profile of $R(\omega)$, we can calculate the associated phase shift using the Kramers-Kronig relations [77]:

$$\theta(\omega) = \frac{\omega}{\pi} \int_0^\infty \frac{\ln[R(\omega')/R(\omega)]}{\omega^2 - \omega'^2} d\omega' \quad (2.29)$$

As previously stated, reflectance and phase shift alone do not constrain spectral selectivity by themselves. However, if we are to use an intrinsic absorber, it would require that our absorber material have an index of refraction which would lead to this reflectance profile when light is incident on the material from air. Once the reflectance and phase shift for a surface are calculated, the real part of the index of refraction $n$ and the imaginary part $k$ which would lead to a reflectance $R$ and phase shift $\theta$ for normal incidence are given by [77]:

$$n(\omega) = \frac{1 - R(\omega)}{1 + R(\omega) - 2\sqrt{R(\omega)}\cos(\theta(\omega))} \quad (2.30)$$

$$k(\omega) = \frac{2\sqrt{R(\omega)}\sin(\theta(\omega))}{1 + R(\omega) - 2\sqrt{R(\omega)}\cos(\theta(\omega))} \quad (2.31)$$

Now once again, there is nothing inherently limiting about the resulting $n$ and $k$ profiles that we calculate here, as long as the reflectance profile stays within the bounds of zero to unity (inclusive) for all frequencies. The strategy which finally leads to a limitation is using an intrinsic absorber, which would
need to have the imaginary part of its index of refraction as given by Eq. (2.31), which is also passive. The reason for this is that certain phase shift values will lead to \( k \) being negative. Specifically, when the sine of \( \theta \) is negative, this will lead to \( k \) being negative, since \( \sin(\theta(\omega)) \) is in the numerator of Eq. (2.31). The imaginary part of the index of refraction is the absorption coefficient of that material, which corresponds to how quickly light at a given frequency (or equivalently wavelength) is absorbed as it passes through that material. If the imaginary part of the index of refraction is negative, that corresponds to optical gain, where light at that frequency will increase in intensity as it passes through the material. From conservation of energy, this is non-physical for a passive material. Thus, for a passive, intrinsic absorber, some reflectance profiles are prohibited, as they would require a material with optical gain at some frequencies.

We can easily see an example of a prohibited reflectance profile by following the principles for an ideal spectrally selective absorber. Previously we have approached spectral selectivity from a wavelength perspective, but when working with the Kramers-Kronig relations it is more convenient to think of the reflectance profile being a function of frequency. A profile with high absorptance at short wavelengths and high reflectance at long wavelengths is equivalent to a profile with high reflectance for low frequencies and high absorptance for high frequencies (we assume that incident light which is not reflected will be absorbed in the material). One example of such a profile is one which starts at a reflectance value of unity for low frequencies, and then at some frequency \( \omega^* \) it linearly drops to low reflectance value \( R_{\text{low}} \) over a frequency window \( \Delta \omega \). The equation for such a profile is given by:

\[
R(\omega) = \begin{cases} 
1 & \text{if } \omega < \omega^* \\
1 - (1 - R_{\text{low}}) \frac{(\omega - \omega^*)}{\Delta \omega} & \text{if } \omega^* < \omega < \omega^* + \Delta \omega \\
R_{\text{low}} & \text{if } \omega > \omega^* + \Delta \omega
\end{cases}
\]

(2.32)

It is worth noting that the frequencies here depend only on relative and not absolute scale, i.e. the corresponding phase shift (and \( n \) and \( k \)) can also be described in terms of \( \omega^* \), in which case \( \Delta \omega/\omega^* \) will affect the profiles but the absolute value of \( \omega^* \) will not. For the particular case of \( \Delta \omega/\omega^* = 0.2 \) and \( R_{\text{low}} = 0.01 \), the corresponding profile is shown in Figure 2.6a, and it is apparent that this reflectance profile follows the desired characteristics of a CSP absorber surface with high reflectance at low frequencies but high absorptance at high frequencies.
Figure 2.6 (a) reflectance profile given by Eq. (2.32) for the case of $\Delta \omega / \omega^* = 0.2$ and $R_{\text{low}} = 0.01$ and (b) imaginary portion of the index of refraction $k$ which would required of an intrinsic absorber material to achieve this reflectance profile. In this particular case, $\omega^* = 20$ is used, but changing this value would not change the relative shape of the reflectance or $k$ profiles.

We can find the corresponding phase shift that goes with this reflectance profile by using Eq. (2.29). It is difficult to calculate the integral for a piecewise function analytically, so in the results here the integral is performed numerically. The negative part of the index of refraction $k$ which would be required of an intrinsic absorber to achieve the reflectance profile can then be calculated from Eq. (2.31). The calculated $k$ profile is shown in Figure 2.6b, which includes a line marking the value $k = 0$. This value is marked because $k < 0$ is the condition we want to avoid in order for a passive, intrinsic absorber to be realizable. For this particular case, there are frequencies that would correspond to a negative $k$, so this reflectance profile would not be possible for a passive, intrinsic absorber.

The corresponding $k$ profile can be kept positive if less aggressive reflectance profiles are used. Two ways of achieving this are to increase the low reflectance value $R_{\text{low}}$ for the high frequency part of the profile or to increase the frequency window $\Delta \omega / \omega^*$ over which the transition from high to low reflectance occurs. Both approaches are shown in Figure 2.7, with one profile taking $R_{\text{low}} = 0.03$ and the other taking $\Delta \omega / \omega^* = 1$ instead of the values used above. The corresponding $k$ profiles are shown in Figure 2.7b, and for the less aggressive reflectance profiles, $k$ remains greater than or equal to 0 for all frequencies, and thus these reflectance profiles are possible for a passive, intrinsic absorber.

While the reflectance profile given by Eq. (2.32) with a reflectance of unity at low frequencies, a reflectance of $R_{\text{low}}$ at high frequencies, and a linear drop connecting these two values is simple and useful for exploring trends, it is not the most effective profile for a spectrally selective absorber. Our ideal
spectrally selective absorber would be able to absorb all incident solar radiation (that is, high frequency radiation), which requires reflectance to eventually drop to zero. Thus, a better profile would have reflectance decay to zero for high frequencies, rather than only reaching $R_{\text{low}}$.

A simple class of reflectance profiles take the form:

$$R(\omega) = \begin{cases} 1 & \text{if } \omega < \omega^* \\ \left(\frac{\omega^*}{\omega}\right)^n & \text{if } \omega > \omega^* \end{cases}$$

(2.33)

which meet the criteria of having high reflectance for low frequencies, and low reflectance (approaching zero) for high frequencies. Here a higher $n$ corresponds to a faster decay to zero reflectance after the transition frequency $\omega^*$, and thus a profile closer to that of an ideal spectrally selective absorber. If we ignore the piecewise nature of Eq. (2.33) and consider the case where $R(\omega) = (\omega^*/\omega)^n$, we can plug this profile into Eq. (2.29) to find the fastest decay allowed. A phase shift of $\theta = \pi$ corresponds to $k = 0$ from Eq. (2.31), and as such $\theta \leq \pi$ is the required condition such that $k \geq 0$ so that a reflectance profile is realizable for a passive, intrinsic absorber. Taking the case of $n = 4$ yields that $\theta = \pi$ for all frequencies, and thus $k$ will not be negative. For cases where $n > 4$, $\theta > \pi$, and $k$ will be negative. Thus, a reflectance profile which decays as $1/\omega^4$ is the fastest decay behavior allowed for frequencies

![Figure 2.7](image)

Figure 2.7 (a) reflectance profile given by Eq. (2.32) for various parameters. The blue curve shows the case of $\Delta\omega/\omega^* = 0.2$ and $R_{\text{low}} = 0.01$, as in Figure 2.6. The yellow curve instead uses $R_{\text{low}} = 0.03$ and the red curve instead uses $\Delta\omega/\omega^* = 1$. (b) imaginary portion of the index of refraction $k$ which would required of an intrinsic absorber material to achieve these reflectance profiles. In these particular cases, $\omega^* = 20$ is used, but changing this value would not change the relative shape of the reflectance or $k$ profiles.
Figure 2.8 (a) reflectance profile given by Eq. (2.33) for the case of \( n = 4 \), and (b) corresponding phase shift profile as calculated by Eq. (2.29). Here a dashed horizontal line marks \( \theta = \pi \) since \( \theta \leq \pi \) is the condition which must be met in order for a profile to be realizable by a passive, intrinsic absorber. In this particular case, \( \omega^* = 20 \) is used, but changing this value would not change the relative shape of the reflectance or \( \theta \) profiles.

approaching infinity for a passive, intrinsic absorber.

Taking the case of \( R(\omega) = (\omega^*/\omega)^4 \) would lead to \( \theta = \pi \) for all frequencies, however this would be a non-physical reflectance profile, as we would have \( R > 1 \) for \( \omega < \omega^* \). An acceptable profile would be to use the piecewise function given by Eq. (2.33) with \( n = 4 \), shown in Figure 2.8a, which leads to the phase shift profile shown in Figure 2.8b. This profile is acceptable, as \( \theta \leq \pi \) for all frequencies, however the fact that \( \theta < \pi \) for a large range of frequencies greater than the transition frequency \( \omega^* \) suggests that there is room for improvement. Essentially, since reflectance does not decay at all for frequencies less than \( \omega^* \), there is some capacity to have reflectance decay faster than \( 1/\omega^4 \) immediately after \( \omega^* \) before transitioning to the \( 1/\omega^4 \) profile and still maintaining \( \theta \leq \pi \).

A reflectance profile which has these characteristics of high reflectance for \( \omega < \omega^* \), \( R \propto 1/\omega^4 \) as \( \omega \to \infty \), and reflectance decaying faster than \( 1/\omega^4 \) immediately after \( \omega^* \) is given by:

\[
R(\omega) = \begin{cases} 
1 & \text{if } \omega < \omega^* \\
\left(\frac{\omega^*}{\omega}\right)^4 + \alpha \left(\frac{\omega^*}{\omega}\right)^3 & \text{if } \omega > \omega^*
\end{cases}
\]  

(2.34)

While this equation does not represent the analytically optimal reflectance profile for a spectrally selective, passive, intrinsic absorber, it achieves good performance with a tractable number of degrees of
freedom. The first degree of freedom, given by the parameter $a$, is a measure of how sharp the decay of the reflectance profile is immediately after the transition frequency $\omega^*$. The second degree of freedom, given by the parameter $b$, is a measure of how quickly the reflectance profile transitions to going as $1/\omega^4$. A sample reflectance profile with $a = 25$ and $b = 3$ is shown in Figure 2.9a, along with the corresponding $k$ profile in Figure 2.9b. As can be seen from these figures, reflectance profiles with the form given by Eq. (2.34) can achieve a sharp transition from high to low reflectance while still maintaining positive $k$ and therefore being realizable by a passive, intrinsic absorber.

Since $b$ in Eq. (2.34) denotes how quickly the profile transitions from decaying at a rate of $1/\omega^{4+a}$ to $1/\omega^4$, we desire a low value for $b$, however if $b$ is too low then it will lead to negative $k$ in the corresponding intrinsic absorber. For a given value of $a$ we can find the lowest acceptable value of $b$ by performing a bisection search: two bounding values of $b$ are chosen, and their mean is used as a trial parameter. If the trial parameter leads to an acceptable profile (i.e., $k \geq 0$ for all $\omega$), it becomes the new upper bound. If the trial parameter leads to a forbidden profile (i.e., $k < 0$ for some $\omega$), it becomes the new lower bound. With enough iterations, the bounds will converge to the lowest acceptable value of $b$, $b_{\text{min}}$. A curve of $b_{\text{min}}$ versus $a$ is shown in Figure 2.10. As we would expect, since larger values of $a$ correspond to more aggressive reflectance profiles, they lead to higher values of $b_{\text{min}}$.

Ultimately, the reflectance profile matters because it will influence the efficiency of a CSP receiver which uses an absorber with that reflectance profile. Receiver efficiency can be calculated from a reflectance profile using Eq. (2.14), reprinted here for convenience:
Figure 2.10 Minimum value of $b$ for a given $a$ for reflectance profiles given by Eq. (2.34) which lead to $k \geq 0$ for all frequencies and therefore correspond to a reflectance profile which is realizable by a passive, intrinsic absorber.

$$
\eta_{rec} = \frac{1}{CGDNI_{opt}} \int_0^\infty \epsilon_a(\lambda) [\pi CGDNI_A(\lambda) \eta_{opt} - E_{b<\lambda}(T, \lambda)] d\lambda
$$

where we make the assumption that all incident radiation which is not reflected is absorbed, and therefore:

$$
\epsilon_a(\lambda) = 1 - R_A(\lambda)
$$

and the frequency dependent reflectance profile can be converted to the wavelength dependent version through the wave relation since the speed of light $c$ is known:

$$
R_A(\lambda) = R\left(\omega = \frac{c}{2\pi\lambda}\right)
$$

It is worth noting that the constant term $c/2\pi$ is not important here as we have worked exclusively with a frequency scaled by $\omega^*$ which is effectively non-dimensionalized. It should be noted that this analysis ignores angular dependence of the absorber's reflectance, using only the normal reflectance values. The results here thus overestimate the performance achievable by passive, intrinsic absorbers, as the index of refraction which is calculated would lead to worse reflectance profiles at larger incidence angles, and some incident solar radiation would have larger incidence angles if solar concentration is employed. There are plans to extend the first order analysis presented here by including the effects of angular dependence in the near future.
As before, we can simplify our analysis using Eq. (2.35) by assuming that the solar spectrum is given by a blackbody at 5800 K, and that transmittance of any optics in the receiver \( \tau \) and the efficiency of the concentration optics \( \eta_{opt} \) are both an ideal value of unity. This leaves us with a simplified version of the receiver efficiency equation:

\[
\eta_{rec} = \frac{1}{q_{rec}} \int_0^\infty \varepsilon_\lambda(\lambda) \left( \frac{q_{rec}}{\sigma T_{sun}} E_{b\lambda}(T_{sun}, \lambda) - E_{b\lambda}(T, \lambda) \right) d\lambda
\]  

(2.38)

where \( q_{rec} \) is the concentrated solar flux incident on the receiver. In order to calculate the receiver efficiency for a particular profile, a particular transition frequency \( \omega^* \) (which corresponds to a transition wavelength \( \lambda^* \)) must be selected for a reflectance profile given by Eq. (2.34), even if the degrees of freedom \( a \) and \( b \) have been set. In the results to follow, this is handled by scanning across different values of \( \lambda^* \) and using the one which leads to the best performance. The integrand of Eq. (2.38) has two extrema: for zero wavelength it starts at zero, then it increases to positive values for short wavelengths (where the incident solar radiation outweighs the radiation that would be emitted by the absorber at its operating temperature) before decreasing to negative values for longer wavelengths (where blackbody emission from the absorber dominates), and finally returning to zero. Ideal performance is achieved when the positive portion of this integrand corresponds to high absorptance and the negative portion corresponds to high reflectance. Thus, the ideal transition wavelength \( \lambda^* \) must occur between the two extrema - the maximum of the integrand at short wavelengths and the minimum at long wavelengths. Many values of \( \lambda^* \) are evaluated between the two extrema, and the value which leads to the highest performance is used in the final reported result.

The receiver efficiency achieved from the reflectance profile given by Eq. (2.34) for a particular operating condition of \( q_{rec} = 30 \text{ kW/m}^2 \) and \( T = 700 \text{ K} \) is shown in Figure 2.11 for varying values of \( a \) and their corresponding value of \( b_{min} \) as shown in Figure 2.10. These operating conditions are typical of line focus CSP systems. In this case, a peak receiver efficiency of 96.1% is achieved for a profile following Eq. (2.34) using \( a = 12 \) and a corresponding \( b_{min} = 1.5 \). In the case of a perfect step function spectrally selective absorber, i.e. the case considered in section 2.3.1, a receiver efficiency of 96.3% would be achieved. Thus, for these operating conditions, there is not a significant different between the performance possible with a perfect step function absorber and what would be achievable by a passive, intrinsic absorber.
Figure 2.12 (a) Peak receiver efficiency achievable by a passive, intrinsic absorber with a reflectance profile given by Eq. (2.34) as a function of operating temperature $T$ and concentration ratio $C$. (b) The difference in achievable receiver efficiency between a passive, intrinsic absorber and an absorber with an ideal step function reflectance profile.

We can also explore other operating conditions with different concentration ratios (i.e., incident solar fluxes) and operating temperatures. Figure 2.12a shows the peak achievable receiver efficiency for a reflectance profile following Eq. (2.34) using values of $a$ and $b_{\text{min}}$ as given by Figure 2.10 for varying concentration ratios (assuming $G_{\text{DNI}} = 1000 \text{ W/m}^2$ and all optical efficiencies are unity) and operating temperatures. The general trends are what we would expect, with higher receiver efficiencies being achieved for higher concentration ratios and lower operating temperatures. A point which is probably of more interest for this study is the difference in receiver efficiency between a passive, intrinsic absorber with a reflectance profile given by Eq. (2.34) and a step function absorber. This difference in achievable receiver efficiency is shown in Figure 2.12b for varying concentration ratios and operating temperatures. In general the two efficiencies are close, however for low concentration ratios and high operating temperatures, the difference reaches in excess of 1%, which is non-negligible for precise calculations. Thus, if one is planning to pursue spectral selectivity using an intrinsic absorber in low concentration, high temperature applications, it is important to consider the limitations imposed by causality and the Kramers-Kronig relations.
While the approach we have followed in this section considering the Kramers-Kronig relations limits the performance of passive, intrinsic spectrally selective absorbers, this limit does not apply to all absorbers in general. By stacking multiple layers of different materials or nanostructuring a material's surface, different limits apply and better performance could be achieved. That being said, the Kramers-Kronig approach can still be applied to these other systems, since for example each material in a multi-layer stack must have an index of refraction that follows the Kramers-Kronig relations. Additionally, more realistic limits to spectral selectivity might consider less abstract models for material properties, such as the Drude-Lorentz model, as opposed to the treatment used here where any refractive index was considered acceptable as long as $k$ remained positive. The limit explored here is related to passive, intrinsic absorbers, but the same treatment could be used to explore many other limits to spectral selectivity.

2.4 Limits to directional selectivity

Another strategy for decreasing the emittance of an absorber while still maintaining high solar absorptance is directional selectivity (also called angular selectivity). While commercial systems have not adopted directional selectivity techniques, there have been a number of mechanisms proposing directional selectivity in the scientific literature [63,65,79–82].

Directional selectivity can be used to improve receiver performance since the sun subtends a very small solid angle of the Earth's sky [83–85]. As long as a surface is absorbing across that solid angle, it will not influence the solar absorptance, but if it reflects at angles outside of that solar angle, the total hemispherical emittance can be reduced. An absorber which is fully absorbing for angles smaller than an acceptance angle $\theta_{acc}$, and fully reflecting for larger angles has an effective emittance $\epsilon$ given by:

\[
\epsilon = 2 \int_0^{\theta_{acc}} \sin \theta \cos \theta \, d\theta = \sin^2 \theta_{acc}
\]

if we assume that the absorber properties do not vary with wavelength. As an example, if an acceptance angle of 0.1 radians (about 5.7°) is used, the effective hemispherical emittance is 0.01, representing a 99% reduction in losses compared to a blackbody absorber. As long as the solar input is within the 0.1 radian acceptance cone, absorptance is not reduced. Recently experimental demonstrations have shown promising approaches to achieve directional selectivity [65,81]. This section will seek to establish the directionally selective performance needed to compete with existing concentration systems.

2.4.1 Theoretical equivalence of directional selectivity and concentration

Directional selectivity increases receiver performance for a similar reason as concentration. With concentration, the solid angle over which the receiver has solar input is increased. With directional
selectivity, the solid angle over which the receiver has radiative losses is decreased. In both cases, the ratio of the solid angle of incident sunlight is increased relative to the solid angle of radiative losses compared to the non-concentrated blackbody absorber case.

The highest performance is reached when the ratio of incident sunlight solid angle to radiative loss solid angle becomes unity. For concentration, this corresponds to the maximum terrestrial concentration ratio, which is limited due to conservation of etendue [69], as discussed in section 2.2.1. An optical element which accepts light over an area $A_{in}$ up to an angle $\theta_{in}$ can redirect that light to an output with area $A_{out}$ over an angle $\theta_{out}$ with the following equation: $A_{in} \sin^2 \theta_{in} = A_{out} \sin^2 \theta_{out}$. The ratio of input area to output area gives the concentration ratio $C$, and the concentration ratio is therefore related to the input and output angles by:

$$ C = \frac{A_{in}}{A_{out}} = \frac{\sin^2 \theta_{out}}{\sin^2 \theta_{in}} \quad (2.40) $$

In the maximum concentration case, $\sin^2 \theta_{out} = 1$, and the input angle is taken to be the divergence half angle of the sun on Earth $\theta_{sun}$ (about 4.6 mrad or 0.26°), which gives $C = 1/\sin^2 \theta_{sun} \approx 47000$. For directional selectivity, the limiting case is when the acceptance angle of the absorber is matched to $\theta_{sun}$, yielding a hemispherical emittance of $\epsilon = \sin^2 \theta_{sun} \approx 1/47000$. Thus, if either of these techniques is used in a receiver, the term $\epsilon/C$ which modifies the radiative losses in the receiver efficiency equation (Eq. (2.13)) will be $\sin^2 \theta_{sun} \approx 1/47000$.

Concentration and directional selectivity can also be used in tandem as long as the concentration ratio is less than the maximum value, such that the required acceptance angle of the directionally selective absorber is less than $\pi/2$. When both techniques are used together, if they are matched at an acceptance angle $\theta_{acc}$, then concentration ratio $C = \sin^2 \theta_{acc} / \sin^2 \theta_{sun}$ and emittance $\epsilon = \sin^2 \theta_{acc}$. The ratio modifying the radiative losses becomes:

$$ \frac{\epsilon}{C} = \frac{\sin^2 \theta_{acc}}{\sin^2 \theta_{acc} / \sin^2 \theta_{sun}} = \sin^2 \theta_{sun} \quad (2.41) $$

Thus, from a receiver efficiency standpoint, pursuing concentration or directional selectivity are equivalent, and in the best case $\epsilon/C = \sin^2 \theta_{sun} \approx 1/47000$.

### 2.4.2 Practical limits to concentration

While the theoretical solar concentration limit on Earth is about 47000, in practice concentration ratios for solar systems rarely exceed 2000 [86,87]. This is due to a number of non-idealities faced in real systems.
which limit the achievable concentration. In the maximum concentration case, the sun must be tracked perfectly (the aperture of the concentrating optics must point directly at the center of the sun) and the reflecting or refracting surfaces which form the concentrating optics must follow an exact prescribed shape. If the tracking system can only track the sun to within some error angle $\theta_e$, then the acceptance angle of the concentrating optics must be made larger to accept more than just the solid angle of the sun. If the acceptance angle is not increased, incident sunlight will be rejected from the concentrating optics due to the tracking error. With the larger acceptance angle, the concentration becomes $C = 1/\sin(\theta_{\text{sun}} + \theta_e)$, and as the error angle increases, concentration decreases. This error angle can also be increased due to imperfections in the surfaces of the concentrating optics. A plot showing concentration when error is taken into account is shown in Figure 2.13.

Small angular error values can greatly reduce the achievable concentration ratio. If the total error angle has a value of 10 mrad, the concentration drops by about an order of magnitude from approximately 47000 to 4600. While it might seem that the obvious solution is to keep these angular errors low, in practice reducing these errors can be very expensive.

In addition to the concentration ratio itself being limited, there are other sources of loss from concentrating optics in a real system. For example, real mirrors are not perfectly reflecting, and a small amount of sunlight will be absorbed by a reflector used to concentrate sunlight. In the most common setup for high concentration power plants, a large central receiver sits on top of a tower, which is
surrounded by individual heliostats that each move independently to reflect sunlight to the receiver [88]. The heliostats must be spaced far apart in order to avoid heliostats from shading each other, which leads to lower concentration ratios. Additionally, significant cosine losses can result when the sun is at a low point in the sky. The concentrating optics can thus be characterized by an optical efficiency $\eta_{\text{opt}}$ which is defined as the ratio of the solar power which reaches the receiver divided by the solar power reaching the concentrating optics. This value can be lower than 65% in practice [89]. Low values of optical efficiency lead to higher relative radiation losses in concentration systems, as can be seen from Eq. (2.13), included below for convenience, since less solar power is actually reaching the receiver.

$$\eta_{\text{rec}} = \tau a - \frac{\varepsilon \sigma(T_{\text{H,abs}}^4 - T_{\text{amb}}^4)}{C_{\text{DNI}}\eta_{\text{opt}}}$$  \hspace{1cm} (2.42)

Directional selectivity could potentially reach higher performance than concentration by circumventing some of the limitations on concentration. Tracking is a shared source of error, since both concentrating optics and directionally selective surfaces need to track the sun. However, directionally selective surfaces do not have to deal with the other drawbacks of concentrating optics, such as optical efficiency or optical error from imperfect reflecting/refracting surfaces. Thus, it is worth investigating how well a directionally selective surface would need to perform to achieve greater efficiency than concentrating optics systems which are used today.

### 2.4.3 Directional selectivity versus concentration

Directionally selective surfaces (DSS) have their own non-ideal properties, which would lead to real performance lower than the theoretical limits. For an ideal directionally selective surface, the emittance as a function of incidence angle is a step function: emittance is one up until the solar angle (plus tracking error angle, this sum will be assumed at 10 mrad for the remainder of this paper) after which it immediately drops to zero for all other angles (see Figure 2.14). In real surfaces, there are two primary departures we can expect from this ideal behavior. The first is that the drop will not be immediate, but will take place over some angular transition (assumed in this section to be shaped as the error function). The second is that the emittance may drop to some lower bound greater than zero. A sample angular emittance curve of a surface which has a lower bound emittance of 0.1 over an angular transition of 0.4 radians is shown in Figure 2.14. It should be noted that the emittance profiles used in this section, including the non-ideal ones, are assumed - they do not correspond to specific demonstrated angularly selective surfaces.
The total hemispherical emittance differs drastically between the two surfaces considered in Figure 2.14. For the ideal surface, the total hemispherical emittance is $10^{-5}$, while for the non-ideal surface the total hemispherical emittance is almost 0.15. It is thus clear that determining what properties are achievable in practice will have a great impact on how much directional selectivity can improve system performance. Total hemispherical emittance for non-ideal directionally selective surfaces as a function of angular spread and the lower bound of emittance are shown in Figure 2.15.

From the plot in Figure 2.15, it is clear that the emittance lower bound is a strong driver of total hemispherical emittance. The overall emittance cannot be lower than the lower bound, and thus even a modest emittance of 0.01 as the lower bound will already increase total emittance from the ideal case by a factor of 1000. The transition over which emittance drops from one to the low value is less critical: even large angular transitions can achieve low total emittance as long as the emittance lower bound is close to zero.

A natural question that arises is how to compare the performance of this non-ideal directionally selective surface to the non-ideal concentrating optics used in practice. One method would be to compare the term $e/C\eta_{opt}$ which modifies the radiative losses in the receiver efficiency equation (lower values of this term indicating higher performance). In this approach, even a modest geometrical concentration ratio of 1000 and optical efficiency of 0.5 would lead to $e/C\eta_{opt} = 0.002$, which is significantly lower than the values
Figure 2.15 Total hemispherical emittance of a directionally selective surface as a function of emittance lower bound and angular transition from high to low emittance shown in Figure 2.15. To compete with this value, the emittance of a non-ideal directionally selective surface is shown again in Figure 2.16, this time with lower emittance and shorter angular transitions.

From Figure 2.16 we can see that in order to compete with concentration, the directionally selective surfaces should have emittance lower bounds on the order of $10^{-3}$ and angular transitions from high to lower absorptance over less than 50 mrad. From this perspective it seems unlikely that we would see directionally selective surfaces which could compete with the performance of concentration in the near future.

This is not an accurate way to characterize overall system performance, since both proposed systems involve a receiver efficiency, the concentrating system has an additional optical efficiency which is not being fully considered. A more accurate treatment would be to compare the product of the receiver and optical efficiency, yielding the ratio of collected heat to sunlight incident on the entire collector:

$$\eta_{rec\eta_{opt}} = \eta_{opt} - \frac{c \sigma T_H^4}{CG}$$  \hspace{1cm} (2.43)
In this case of the directionally selective surface, optical efficiency would be unity, since the receiver and collector areas are identical (any sunlight reaching the collector is reaching the receiver by definition). We will examine receiver efficiencies for temperatures ranging from 650K to 1000K, which represent the approximate upper temperature limits for Therminol VP-1 (a common heat transfer fluid) and operating a Rankine steam cycle, respectively [90,91]. A typical concentrating system with $C = 1000$ and $\eta_{opt} = 0.65$ is compared to three different directionally selective surfaces (properties outlined in Table 2.1) in the plot in Figure 2.17.

Table 2.1 Properties of directionally selective surfaces used for Fig. 6

<table>
<thead>
<tr>
<th>Directionally selective surface</th>
<th>Emittance lower bound</th>
<th>Angular transition [rad]</th>
<th>Total hemispherical emittance</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>0.02</td>
<td>0.1</td>
<td>0.025</td>
</tr>
<tr>
<td>#2</td>
<td>0.01</td>
<td>0.05</td>
<td>0.012</td>
</tr>
<tr>
<td>#3</td>
<td>0.005</td>
<td>0.02</td>
<td>0.006</td>
</tr>
</tbody>
</table>

Figure 2.16 Total hemispherical emittance of a directionally selective surface as a function of emittance lower bound and angular transition from high to low emittance
For temperatures below 700K, the optical efficiency is the limiting factor for the concentrating system, and modest directionally selective surfaces can outperform the concentrating system. At temperatures around 800K, the directionally selective surfaces must have better properties to compete with the concentrating system, as radiative losses become more significant. For temperatures above 900K, the directionally selective surface must be very reflecting at large angles with a sharp transition in order to compete with the concentrating system. Thus operating temperature becomes very important for determining what properties are required for a directionally selective surface to outperform concentration, with more stringent requirements the higher the operating temperature.

To summarize the results from this section, a sharp transition from high to low absorptance is desired for a directionally selective surface, but having emittance approach very close to zero at large angles is more important to achieving low total hemispherical emittance. In order to compete with concentration in terms of relative radiative loss reduction, extremely low emittance at large angles (10^{-3}) and sharp angular transitions (50 mrad) would be required. To compete with concentration in terms of overall collector efficiency, less stringent requirements are needed for operating temperatures below 700K (lower emittance bound of 0.02 and angular transition of 0.1 radians) however for higher temperatures there are still strict requirements on the directionally selective surface properties.
Limits to directionally selective surface performance are largely based on the achievable profiles, however unlike the case of spectral selectivity, there is a less clear approach to determining physical limits. For geometrical optics approaches to achieve directional selectivity (such as those which will be discussed in chapter 5 of this thesis), the transition with respect to incidence angle is diffraction limited, which effectively sets no limit for macroscale optics since the relevant part of the solar spectrum has a wavelength of at most a few microns. Instead the barriers to performance are primarily set by how well radiation can be suppressed at large angles, which is more of a practical issue than a fundamental physics problem.
Chapter 3

Modeling aerogel based solar receivers

In the first two chapters of this thesis, spectral selectivity has been discussed in the context of reflection versus absorption, which is characteristic of spectrally selective absorbers. Of course, optical elements are not limited to absorbing or reflecting incident radiation - they can also transmit incident radiation. Thus, there is another type of spectrally selective optical element which transmits radiation at certain wavelengths but reflects or absorbs at others. A relevant example is the greenhouse effect which occurs on Earth, and why carbon dioxide emissions lead to global warming: carbon dioxide transmits the majority of the solar spectrum, but absorbs some longer infrared wavelengths [51]. Carbon dioxide emissions increase the terrestrial temperature because Earth can still absorb the same amount of solar radiation, but emitted radiation is absorbed in the atmosphere and has more resistance from escaping into space.

Another simple spectrally selective transmitter which we are familiar with from everyday life is glass. Glass is generally transparent in the solar spectrum, but absorbs at longer wavelengths [92]. This is part of why a glass greenhouse can reach a much higher temperature than the ambient environment and why the interior of a car can get so hot on a sunny day (however in these scenarios reducing convection losses plays a more significant role than the radiative effects) [67]. Thus, one might try to improve the performance of a black absorber by applying a glass coating on top. Unfortunately, this would not be effective, as the thermal conductivity of glass is high enough that the exposed glass surface would reach the same temperature as the black absorber. Since glass absorbs at long wavelengths, it also emits, and thus the glass surface exposed to the environment would still have radiation losses as a blackbody at the receiver operating temperature. While glass would not be an effective spectrally selective transmitter for CSP applications, there is a promising material with spectrally selective transmission that has very low thermal conductivity: silica aerogel. Silica aerogel is a material which has recently received interest for its potential to improve solar receivers [11]. Silica aerogel is an extremely low density nanoporous network of silica particles which can be fabricated through a simple sol-gel process [93,94]. For CSP applications, aerogel should be transparent in the solar spectrum and opaque at longer wavelengths to block thermal radiation losses. The aerogel should also insulate against conductive and convective thermal losses.

This chapter will explore the potential of aerogel based solar receivers through modeling. First, the properties of silica aerogel will be reported, which are what allow for novel solar receiver configurations. Next, two novel aerogel receiver concepts will be introduced, one for solar-thermal applications and one which includes both solar-thermal and PV aspects. A strategy for modeling the performance of aerogel in
solar receivers will be described and then used to predict the potential performance of the proposed aerogel receiver concepts.

3.1 Properties of silica aerogel

In terms of radiative properties, significant work has been done to increase the solar and visible transmittance of silica aerogels. Structurally, the key to achieving high visible transmittance is small, uniform pores. Scattering is the dominant extinction mechanism in aerogels at visible wavelengths, and the observed behavior is characteristic of Rayleigh scattering, which increases drastically with increased scatterer size (in this case, the aerogel pore) [95]. Transmittance has been controlled by changing the pH of the solution in the sol-gel process, using a two-step sol-gel process, heat treatment, and alternative drying techniques [96–100]. Absorption is the dominant extinction mechanism for longer solar wavelengths, however those wavelengths do not contribute as significantly to losses in solar-weighted transmission due to absorption peaks being aligned with dips in the AM1.5 solar spectrum (see Figure 3.1a). As such, reducing absorption is not critical to achieving high aerogel transmittance.

Aerogel samples with a solar-weighted transmittance of 96% through 9.5 mm designed for solar thermal applications have recently been reported in the literature [101,102]. The spectral transmittance for a high performing sample is plotted in Figure 3.1a, along with the solar spectrum and the blackbody spectrum for a surface at 400 °C. While the aerogel has high transmittance in the solar spectrum, it blocks radiation at the longer wavelengths characteristic of radiative heat transfer for CSP receivers operating near 400 °C. By measuring both the transmittance and reflectance of the sample, one can also infer the intrinsic radiative properties (scattering and absorption coefficients) of the aerogel [95], which are plotted in Figure 3.1c. Scattering coefficient values are fit to a Rayleigh scattering model based on measured values, while absorption coefficient values are reported based on directly measured values.

Thermal conductivity in the aerogel has three components: conduction through the silica network, conduction through the air, and radiation [103]. Radiation has the most significant impact at high temperatures, and as previously mentioned, high absorptance at long photon wavelengths can reduce the radiative component of thermal conductivity [104]. Achieving low thermal conductivity is therefore also closely tied to the radiative properties of the aerogel. Increasing infrared absorption in the aerogel can be accomplished by fabricating denser aerogels or including adsorbed species in the aerogel (e.g., water) [105]. The conduction component of thermal conductivity is low due to the low volume fraction of silica, and the convection component is low due to the small pore size of the aerogel. The pore sizes are small enough to suppress convection, and can be smaller than the mean free pair of molecules in air, so the effective thermal conductivity of air in aerogel can be lower than that of air in standard conditions.
Figure 3.1 Performance of fabricated transparent aerogel samples from Bhatia, et al. [101] a) Spectral transmittance for a 9.5 mm thick aerogel sample, along with solar spectral irradiance and blackbody irradiance spectrum at 400 °C. Aerogel is highly transparent in the solar spectrum, but is absorbing in the blackbody spectrum at 400 °C. Solar weighted transmittance of this sample is 96%. b) Absorption (red) and scattering (blue) coefficients inferred from measurements for fabricated aerogel sample. Scattering dominates for short solar wavelengths, while absorption dominates for longer wavelengths. c) Measured (blue open markers) and modeled (dashed black curve) thermal conductivity of a transparent aerogel sample in vacuum. Error bars for measured results come primarily from uncertainty in aerogel sample thickness.

Thermal conductivities of the reported aerogel samples were measured using a heater bridge setup, where a temperature difference across the sample is maintained through power input to a heater [101]. The temperature difference is modulated and the corresponding change in required heater input power is measured. Measured thermal conductivity \( k \) is given by the following equation, which assumes one-dimensional thermal transport through the sample [106]:

\[
\frac{d}{dx} \left[ \frac{k(x) \frac{dT}{dx}} {\rho(x) C_p(x)} \right] = 0
\]
where \( t \) is sample thickness, \( A \) is the sample cross sectional area, \( dQ \) is change in heater input power, and \( d\Delta T \) is change in temperature difference across the sample. The measured thermal conductivity value can also be compared to a modeled value which uses the infrared absorption coefficients as input (the modeling method is described in detail in the following section) to verify the results. Thermal conductivity is strongly temperature dependent: measured effective thermal conductivities range from 0.02 to 0.07 W/m/K in vacuum for operating temperatures of 200 °C to 400 °C, with strong agreement between measured and modeled values (see Figure 3.1c).

### 3.2 Aerogel receiver concepts

The properties exhibited by silica aerogel allow for the possibility of a number of new solar receivers. Its spectral selectivity is useful in CSP systems, and will be explored in this thesis through the Solar Thermal Aerogel Receiver (STAR) concept. The spectral selectivity also leads to a novel mechanism for efficiently converting part of the solar spectrum to thermal energy and part directly to electricity by a PV cell, which is explored in this thesis through the Hybrid Electric And Thermal Solar (HEATS) receiver. Both the STAR and HEATS concepts will be investigated in this chapter.

#### 3.2.1 Solar Thermal Aerogel Receiver (STAR)

The concept of using silica aerogel in a CSP receiver to form a Solar Thermal Aerogel Receiver (STAR) is simple. It essentially takes the vacuum tube receiver traditionally used in line-focus CSP systems and replaces the vacuum and spectrally selective absorber with aerogel and a black absorber, respectively. Since the aerogel is transparent in the solar spectrum, the majority of incident solar radiation reaches the black absorber and can be converted to thermal energy. Since the aerogel is absorbing for infrared wavelengths and has low thermal conductivity due to its porous structure, thermal losses from the black absorber are significantly reduced, even as the receiver operates at high temperature. Thus, covering a black absorber with an aerogel layer allows incident solar radiation to be efficiently converted to high temperature thermal energy.

For vacuum receivers, the choice of geometry is limited as flat panes of glass typically cannot withstand the pressure differential between the ambient pressure in the environment and the vacuum pressure in the receiver. Thus, essentially all vacuum receivers take a cylindrical geometry. STAR, on the other hand, can operate efficiently even in ambient air, which opens the possibility of using different receiver geometries. We imagine the STAR approximating a flat geometry by using a bank of absorber pipes rather than a single pipe as is common for vacuum tube receivers. A cross-section of the proposed STAR is shown in
Figure 3.2 Cross section diagram of proposed Solar Thermal Aerogel Receiver (STAR). An aerogel layer covering a black absorber allows incident solar radiation to be absorbed while reducing thermal losses from the high temperature absorber. The receiver would extend into the page (this depth dimension would be much longer than its width) and would be paired with line-focus systems.

Figure 3.2. Aerogel is quite fragile, which makes it necessary to include a protective glass layer covering the aerogel. Overall, however, the STAR design is still quite simple, consisting of only pipes with a black absorber coating to convert solar radiation to thermal energy, an insulating aerogel layer, and a protective glass layer. A real implementation would also have insulation of the sides and back of the absorber pipes.

Enabling high efficiency in a flat receiver geometry is important because flat receivers pair better with linear Fresnel reflector (LFR) concentrating optics than tube receivers. LFR collector fields are cheaper than the more commonly used PTC systems, however LFR has not seen high adoption rates due to lower overall system efficiencies. STAR has the potential to unlock the potential of low cost LFR systems without sacrificing efficiency.

In addition to allowing the use of non-cylindrical receiver geometries, STAR has a number of other potential practical benefits over traditional vacuum tube receivers. The lack of vacuum in STAR means that less precision manufacturing is required, since a seal does not need to be maintained at high temperature through years of diurnal thermal expansion cycles. This could reduce the cost of the receiver and improve its reliability, as leakage into the vacuum annulus is a common failure mechanism for
vacuum tube receivers [32,107]. The fundamentally different mechanism for suppressing thermal losses in STAR also provides an opportunity to improve receiver efficiency. The efficiency achievable by STAR will be explored via modeling in the later sections of this chapter.

3.2.2 Hybrid Electric And Thermal Solar (HEATS) receiver

In chapter 1 of this thesis, two types of solar energy conversion systems were introduced: PV systems and CSP systems. A third type of system takes advantage of the best of both PV and CSP: a “hybrid” system. A hybrid system contains both a PV cell and a thermal absorber. In such a system, photons converted most efficiently by the PV cell (photons in the “PV band”) are directed to the PV cell. Low energy (long-wavelength) photons which cannot be converted by the PV cell and high energy (short-wavelength) photons which would be converted inefficiently are directed to the thermal absorber instead. This approach improves overall system efficiency and leads to the collection of some thermal energy, which is cheaper to store than electricity [45,108]. For these hybrid systems, "dispatchability" refers to the portion of electricity generated from the heat engine divided by the total electricity generated (from both the heat engine and PV), since heat is cheaper to store than electricity. Two main schemes have been proposed in the past for hybridized systems: dichroic mirror systems and hot PV cell systems. In a receiver using a dichroic mirror arrangement, the thermal collector is physically separate from the PV cell, and a dichroic mirror is used to split the solar spectrum between the PV cell and the thermal collector [109–111]. In a hot PV cell arrangement, the thermal collector is in contact with the PV cell, so the PV cell must operate at the temperature of the collected thermal energy [112–114]. Unfortunately, both dichroic mirror and hot PV systems face challenges. Dichroic mirror receivers are optically complicated, due to the multiple paths the incident solar light must traverse [115]. While this difficulty can be addressed with relative ease in spectrally splitting PV systems [116–119], hybrid systems have the added challenge of collecting thermal energy efficiently at high temperatures [120–123]. Hot PV cell systems face challenges in cell stability, as few materials can maintain efficient operation at the high temperatures required for CSP electricity generation [124,125]. Some hot PV cell systems circumvent the stability challenge by operating at relatively low temperatures (~100 °C) which allow for co-generation of thermal energy, but are not sufficient to generate electricity from the thermal energy at high efficiency [126–129]. Hybrid PV/CSP systems are therefore advantageous in theory, but existing hybrid schemes face practical challenges.

The ideal hybrid receiver would have a single optical path but would also allow the PV cell to operate at low temperature. Here we report a novel receiver structure called the Hybrid Electric And Thermal Solar (HEATS) receiver that meets both of the desired characteristics. This synergistic combination is achieved by using a spectrally selective light pipe (SSLP) structure to absorb non PV-band photons (as thermal energy) while directing PV-band photons to a cold PV cell on the other side, as shown in Figure 3.3. The
light pipe does not need to be thermally in contact with the PV cell, so the PV can operate at low temperature.

Using this "light pipe" configuration offers new opportunities and challenges in achieving efficient operation. The light pipe absorber offers more flexibility in receiver geometry than the traditional systems, which essentially always use tubes as absorbers. The challenge in achieving efficient operation in a light pipe configuration arises from minimizing thermal losses, as the light pipe must be maintained at the elevated heat delivery temperature. The traditional solution for reducing thermal losses in CSP receivers is to evacuate the receiver to eliminate convection losses and use a spectrally selective coating which has low emittance at wavelengths longer than the solar spectrum (mid to far infrared) in order to reduce radiation losses [54]. Unfortunately, the traditional strategy would not effectively reduce radiation losses for this arrangement because the light pipe’s walls have much greater surface area than its aperture. This configuration makes the light pipe look like a cavity for emitted radiation, and leads to high radiative losses even if the light pipe walls have low emittance in the mid to far infrared wavelengths [130].

An alternative approach for the HEATS receiver is to cover the light pipe apertures with a transparent thermal insulator. If the chosen material is transparent in the solar spectrum, it will not affect the path of solar photons, and its low thermal conductivity can lead to a significantly reduced surface temperature. As thermal losses originate from the exposed receiver surface, lowering the surface temperature will significantly reduce convection and radiation losses.

Thus there are two key sub-components of the HEATS receiver not already used in solar energy conversion systems: the spectrally selective light pipe (SSLP), and the transparent thermal insulator. The SSLP can be fabricated by applying a thin-film multi-layer coating on a thermally conductive (e.g., copper) substrate. Silica aerogel can be used as the transparent thermal insulator.
Figure 3.3 Hybrid Electric And Thermal Solar (HEATS) receiver concept. a) Rendering of receiver concept with cutaway section to see internal receiver structure. Note that in a real implementation the sides of the receiver would be covered (e.g., by conventional insulation) but the sides are excluded here for viewing the internal structure. The stacked structure consists of (in the order that the incident solar radiation reaches each layer) a glass cover, a thermally insulating aerogel layer, the spectrally selective light pipe (SSLP), another insulating aerogel layer, and finally the PV cell. The SSLP structure is formed from parallel fins covered by a spectrally selective coating. The fins are attached to pipes carrying heat transfer fluid which collect the thermal energy absorbed by the SSLP. b) The SSLP absorbs high and low energy photons as thermal energy, while directing mid-energy photons to the PV cell on the other side. Transparent aerogel on each side of the SSLP allow the SSLP to operate at high temperature while the PV cell and glass cover remain at low temperature.
In practice the HEATS receiver could take the stacked structure shown in Figure 3.3a. Concentrated solar radiation incident on a glass cover transmits through glass and aerogel to the SSLP. The SSLP absorbs low and high energy photons as thermal energy, conducting it to pipes carrying a heat transfer fluid. The heat transfer fluid collects the high temperature thermal energy to deliver it to a heat engine for conversion to electricity or to be stored for later use. The mid-energy photons converted most efficiently by the PV cell are transmitted through the SSLP and through another layer of aerogel to the PV cell. The aerogel layers serve to thermally insulate the SSLP from the PV cell (in order to keep the PV cell cool) and from the environment (to minimize thermal losses). It should be noted that in a real implementation, the sides of the receiver would be covered by conventional insulation to reduce thermal losses and to protect the internal receiver components from environmental factors. As silica aerogel is mechanically fragile, the other internal components would be supported by rigid connections to the receiver external frame, while the aerogel slabs would sit on the layer below them. Due to aerogel's low density, the stresses from being supported by the thin SSLP fin edges would be low enough as to not damage the aerogel. Thermal stresses due to the temperature gradient across the aerogel layers can be accommodated by the highly porous structure, and temperature gradients applied to aerogels in the process of characterizing thermal properties (discussed in detail in a later section) have not led to damage.

In addition to the prospect of higher efficiency than traditional vacuum tube receivers, the HEATS receiver also offers potential cost and reliability benefits. Since the HEATS receiver does not require vacuum operation, there is no need for high-precision bellows which maintain a vacuum seal throughout daily thermal expansion cycles. Additionally, vacuum tube receivers' performance degrade over time as gas permeates into the vacuum annulus, but this degradation mechanism would not impact the HEATS receiver.

3.3 Modeling energy transport through aerogel

The most complicated part of modeling the performance of STAR and the HEATS receiver is modeling energy transport through the aerogel layers in these systems. This modeling is complex because the properties of aerogel are highly spectrally dependent (as shown in Figure 3.1), and since there is a temperature gradient through the aerogel it would be inaccurate to simply take a weighted average as is done for the absorptance and emittance (e.g. in section 1.3.1) of spectrally selective absorbers.

In this thesis, the temperature and radiation distribution in aerogel layers are modeled by using the equation of radiative transfer (ERT) coupled to the heat equation. The ERT describes the change in radiation intensity for a particular wavelength through a participating medium (in this case aerogel) [51]:
\[
\frac{dI_{\Omega'}}{dx_{\Omega'}} = -\beta I_{\Omega'} + \kappa I_b^s + \frac{s}{4\pi} \int_{4\pi} \Phi_{\Omega'\Omega} I_{\Omega} d\Omega
\]  

(3.2)

where \( I_{\Omega'} \) is radiation intensity in the direction \( \Omega' \), \( \beta \) is the extinction coefficient, \( \kappa \) is the absorption coefficient, \( I_b^s \) is blackbody radiation intensity for the local aerogel temperature, \( s \) is the scattering coefficient, and \( \Phi \) is the scattering phase function (with all of these values corresponding to the wavelength that the ERT is being solved for). More intuitively, the left hand side of the ERT is the change in radiative intensity through the aerogel in the direction \( \Omega' \), the first term on the right hand side is a decrease in radiative intensity due to absorption and scattering into different directions, the second term is an increase in intensity due to emission from the aerogel, and the third term is an increase in intensity due to scattering from other directions into the current direction. In practice, some simplifications must be made to the ERT in order to solve for the radiation distribution in the aerogel layers. It is intractable to solve the ERT at every wavelength; instead the relevant spectrum (from about 300 nm as the shortest solar wavelength to about 50 \( \mu \)m as the longest relevant infrared wavelength) is broken into bands, over which the material properties are averaged and treated as constant [104,131]. Additionally, the scattering phase function is assumed to be isotropic [132].

The heat equation describes the temperature distribution in a solid, and for the steady-state case (which we assume for STAR and the HEATS receiver) the heat equation is:

\[
0 = \nabla^2 T + \frac{\dot{q}}{k}
\]  

(3.3)

where \( T \) is temperature, \( \dot{q} \) is volumetric heat generation/absorption in the solid, and \( k \) is (non-radiative) thermal conductivity of the solid. It should be noted that since the aerogel samples were measured in vacuum conditions, a constant air contribution of 0.01 W/m/K is included in this \( k \) when modeling the receiver, which operates at ambient pressure [103]. In the aerogel, the ERT and heat equation are coupled through two terms: the blackbody radiation intensity \( I_b \) and volumetric heat generation/absorption \( \dot{q} \). These terms lead to coupling because \( I_b \) depends on the local aerogel temperature \( T(x) \) and volumetric heat generation/absorption \( \dot{q}(x) \) comes from the net radiative flux at a point in the aerogel being non-zero (e.g., if more radiation is being absorbed than emitted at a certain point in the aerogel, this will correspond to heat generation at that point).

To use Eqs. (3.2) and (3.3) to solve for radiation and temperature distributions in the aerogel, the boundary conditions must first be determined. Boundary conditions come from the other layers of the receiver, with their modeling treatment described in their respective sections below (section 3.4 for STAR...
and section 3.5 for HEATS). With boundary conditions set, a naive temperature distribution is assumed (e.g., a linear one) which feeds into equation (3.2). Once (3.2) is solved, this provides \( \dot{q} \) for equation (3.3), and if (3.3) is not satisfied by the provided \( \dot{q} \) then the temperature distribution is modified to reduce the resulting error [131]. This iteration process continues until the temperature and radiation distributions are self-consistent solutions to both (3.2) and (3.3).

Solving the ERT and the heat equation provides the temperature distribution in the aerogel layers as well as the radiation distribution through the aerogel. These can be used to determine thermal losses from the receiver as well as how much of the incident solar radiation is absorbed, which is necessary to determine receiver efficiency.

### 3.4 Modeling STAR performance

The Solar Thermal Aerogel Receiver (STAR) is a simple implementation of a solar receiver using silica aerogel, as it essentially consists of only three layers: a black absorber, an insulating aerogel layer, and a protective glass layer. Thus, the modeling of energy transport through aerogel described in section 3.3 makes up the majority of the modeling effort for STAR. The few additional pieces required (e.g., to determine boundary conditions) are described below. Since STAR can be used as part of a traditional CSP system, it makes most sense to characterize its performance by receiver efficiency, given by Eq. (1.8) and reproduced here for convenience:

\[
\eta_{rec} = \frac{Q_{rec,\text{out}}}{q_{rec}A_{rec}} \tag{3.4}
\]

The heat delivered by STAR \( Q_{rec,\text{out}} \) can be calculated after Eqs. (3.2) and (3.3) have been solved as the net absorbed radiation at the absorber surface end of the aerogel minus the conduction loss through the aerogel layer and the insulation on the back and sides of the pipes carrying the high temperature heat transfer fluid. Overall system efficiency can be calculated from receiver efficiency by multiplying by other sub-efficiencies such as optical efficiency and heat engine efficiency, as described in section 1.2.

Energy transport through the aerogel is combined with a few other models to form the overall system model for STAR. The boundary conditions of the aerogel captures the performance of the receiver tubes at high temperature assumed to be coated with Pyromark 2500 as a black absorber [59], and the glass cover which protects the aerogel from the environment. Performance of the concentrating optics, which are assumed to be LFR as they are better suited for use with a flat receiver, can be calculated using the diverging polygon method or ray tracing [133,134]. Modeling results from the concentrating optics gives us the incident solar distribution on the receiver (both spatial and angular) which acts as the radiation...
boundary conditions in the aerogel model. Thermal losses through the backside (non-aerogel covered portion) of the receiver are treated with simple conduction models, since it is insulated with conventional materials that do not have the complex dependence on temperature and radiation that aerogels do. Heat transfer into the heat transfer fluid, as well as pumping losses from moving the fluid through the long field of pipes, are captured with well-established convection correlations and the properties of the heat transfer fluid (Therminol VP1).

3.4.1 Results and discussion

Figure 3.4 shows a contour plot of the receiver efficiency achieved by STAR with varying levels of aerogel solar weighted transmittance and effective thermal conductivity. These results are given for a 12 mm thick aerogel, which modeling has shown is the optimal thickness when considering annual average performance. The operating temperature used for these results is 400 °C, as that is the temperature limit for Therminol VP1. The open marker on the plot corresponds to the best properties measured in fabricated aerogels to date (reported in section 3.1), and such an aerogel would lead to a receiver efficiency of approximately 79.5%.
A receiver efficiency of 80% at an operating temperature of 400 °C is respectable but not record breaking. With an annual average optical efficiency of 60% (typical of LFR) [134] and a heat engine efficiency of 35% (typical of a heat engine operating at 400 °C) [50], this would lead to an overall system efficiency of about 17%, which is comparable to existing line focus systems [11]. Thus, in order to lead to higher system efficiencies higher quality aerogel is required or further receiver design improvements are needed.

The fact that STAR in its current form does not represent a huge performance increase over existing line-focus CSP systems is not too discouraging however, as there are other potential benefits. Ultimately cost is the primary driver of technology adoption, and there is potential for STAR to produce electricity at a lower LCOE than existing CSP technologies. For this reason, we have continued to investigate STAR, including building a platform to experimentally measure the performance of a STAR prototype. The details of that experimental investigation are covered in chapter 4 of this thesis.

3.5 Modeling HEATS receiver performance

Since the HEATS receiver is a hybrid system with more complexity than STAR, more than temperature and radiation distribution through the aerogel is needed to determine performance. It is also important to determine the performance of the Spectrally Selective Light Pipe (SSLP) which absorbs part of the solar spectrum but directs the rest to a PV cell, and to determine the efficiency of the PV cell itself in converting incident solar radiation to electricity. That being said, the overall system model still centers around the aerogel layers, since the majority of the computation is needed for solving energy transport through the aerogel. Before looking at the overall system model however, measured properties of demonstrated SSTC coatings will first be introduced and the relevant figure of merit for the HEATS receiver will be discussed.

3.5.1 Figures of merit for the HEATS receiver

The primary figure of merit for the HEATS receiver is its efficiency: how much solar radiation incident on the receiver is converted to useful energy. Defining efficiency for hybrid systems is not as simple as in purely PV or thermal systems, since the hybrid receiver delivers both electricity and heat. One metric which has been proposed for hybrid systems is exergetic efficiency $\eta_x$, which is the exergy collected by the receiver divided by the incident solar radiation [45]:

$$\eta_x = \frac{P + Q_h \left(1 - \frac{T_c}{T_h}\right)}{Q_{solar}} \tag{3.5}$$

where $P$ is electrical power from the PV cell, $Q_h$ is heat delivered by the receiver, $T_h$ and $T_c$ are the temperature of heat delivered to the heat engine (it is assumed that there is no temperature drop between
the receiver and heat engine) and the cold-side reservoir that the heat engine can reject heat to, respectively, and $Q_{\text{solar}}$ is incident solar radiation. This definition of efficiency puts a premium on thermal energy, which can never be converted at the efficiency of a Carnot engine in practice (the $1 - T_c/T_h$ term implies conversion at Carnot), as an intentional and quantitative way to assign value to the higher dispatchability of electricity generated from thermal energy. Exergetic efficiency therefore intrinsically increases the value of dispatchable energy by the ratio of the Carnot efficiency to the real efficiency of the heat engine. The results reported in this thesis will use electrical efficiency $\eta_{\text{elec}}$, which is the electricity delivered by the receiver divided by incident solar radiation, assuming that the heat from the receiver can be converted to electricity at the endoreversible limit [50]:

$$\eta_{\text{elec}} = \frac{P + Q_h \left(1 - \frac{T_c}{T_h}\right)}{Q_{\text{solar}}}$$

(3.6)

Here the endoreversible limit is used in place of the Carnot limit since it is much closer to the efficiency of heat engines achieved in practice [135]. Electric efficiency does not include any information about the fraction of dispatchable electricity (that is, the portion which comes from heat rather than PV), so this fraction will be explicitly reported alongside mentions of efficiency. In this case, the dispatchability ratio $\gamma$ is given by:

$$\gamma = \frac{Q_h \left(1 - \frac{T_c}{T_h}\right)}{P + Q_h \left(1 - \frac{T_c}{T_h}\right)}$$

(3.7)

which corresponds to the portion of electricity from the receiver that comes from thermal energy divided by the total electricity generated. While splitting exergetic efficiency into electrical efficiency and dispatchability requires more numbers to describe receiver performance, electrical efficiency is more easily compared to other systems, and in this approach the added value of dispatchability is not prescribed.

From equations (3.6) and (3.7), in order to determine the electrical efficiency and dispatchability of the HEATS receiver, we need to know how much of the solar radiation incident on the receiver is converted to electricity by the PV cell as well as how much thermal energy can be collected from the SSLP for a given $T_h$ (where thermal energy collected is solar radiation absorbed minus thermal losses). Efficiency
also depends on $T_c$, which is assumed to be 37 °C for this paper, a representative value for power plant cooling systems [45].

### 3.5.2 Properties of Spectrally Selective Light Pipe (SSLP) coating

The SSLP coatings should reflect photons converted most efficiently by PV while absorbing the rest of the solar spectrum. The physical design of the SSLP is such that reflected photons will be directed to the PV cell. To more precisely understand the ideal spectral properties of the SSLP coating, it is helpful to first look at traditional CSP coatings. A traditional spectrally selective absorber has high absorptance in the solar spectrum, but high reflectance (and therefore low emittance) at longer wavelengths. An absorber with these properties can effectively absorb solar radiation, but has minimal radiative losses. The ideal SSLP coating is similar, but has a high reflectance band in the middle of the solar spectrum in order to direct photons which are converted most efficiently by PV to the PV cell (the wavelength band used to maximize system efficiency with real silicon PV cells was 725 – 1100 nm) [136]. This leads to four distinct bands in the spectral reflectance profile: high reflectance in the PV band and for mid to far infrared wavelengths, with high absorptance in solar wavelengths outside the PV band, as shown in Figure 3.1a. For the HEATS receiver, having high reflectance at long wavelengths may not be critical, as the thermal insulator should block thermal losses, however having high reflectance in this wavelength range will still reduce thermal losses, even if only by a small amount.

In practice, these spectral properties can be achieved by depositing a thin-film multi-layer stack (thereby forming an interference filter) [109] on top of a traditional cermet absorber [137]. The reflection band can be tuned by changing the thicknesses of alternating layers of high and low index of refraction materials. Details of the quad-band coatings have been reported in the literature [137]. Using a SiO$_2$/TiO$_x$ filter deposited on a W-Ni-SiO$_2$ cermet spectrally selective absorber achieved the properties shown in Figure 3.5. The AM1.5D solar-weighted reflectance within the PV band is about 89%, although it is slightly lower at larger incidence angles, while the solar-weighted reflectance outside the PV band is about 25%.
Figure 3.5 Performance of a fabricated SSLP coating from Cao, et al. [137] a) Spectral reflectance of fabricated SSLP coating for various angles of incidence. The coating is designed to reflect photons converted efficiently by silicon PV (725 – 1100 nm, the “PV band”), absorb the rest of the solar spectrum, and have low emittance at longer wavelengths b) AM1.5D solar-weighted reflectance within the PV band (blue markers) and in the rest of the solar spectrum (red markers) as a function of incidence angle

3.5.3 System HEATS model

As previously mentioned, the overall HEATS system model centers around the aerogel layers, since the majority of the computation is needed for solving energy transport through the aerogel. Modeling of the aerogel layers is coupled to the rest of the receiver via boundary conditions to Eqs. (3.2) and (3.3). The radiative boundary conditions to the receiver as a whole are that the front side has incident concentrated solar irradiance, while the back side is simply exposed to the environment at ambient temperature. Radiation transport through the glass is determined using the Fresnel equations. Radiation transport through the SSLP is determined using ray tracing simulations to determine the spectral and directional transmittance, absorptance, and reflectance of the structure [138]. Radiation which reaches the PV cell is absorbed proportionally to its absorption coefficient, and absorbed radiation is converted to both electricity and thermal energy, with the proportion depending on the PV cell efficiency (the method used to calculate PV efficiency is described below). Natural convection to the surrounding environment is assumed for the receiver temperature boundary condition. The SSLP temperature is taken as the average temperature over a receiver section heating the heat transfer fluid from its entry temperature to $T_H$. The SSLP itself is hotter than the heat transfer fluid, due to convective thermal resistance between the fluid and pipe walls as well as thermal resistance in the metal SSLP fins. These temperature rises are calculated using convection correlations and a 1-D fin heat transfer model, respectively [139]. Efficiency can be determined from the thermal energy collected from the SSLP and electricity collected from the PV cell.
Thermal energy collected from the SSLP is calculated as the net radiation absorbed by the SSLP minus conduction losses into the aerogel.

Some boundary conditions and system properties must be prescribed in order to fully model the receiver. The thickness of the aerogel layers is optimized based on the aerogel properties used. For the results reported in the following section aerogel thickness is close to 1 cm thick for the layer between the glass and SSLP, and 4 cm thick between the SSLP and PV cell. The layer in front of the PV cell can be much thicker because the aerogel is most transparent in the PV band of the solar spectrum, and a thicker layer helps keep the PV cell cool. The SSLP fins are assumed to be made of copper, and are modeled as being 1 mm thick, spaced 10 mm apart, 14 mm tall, and the optically active width of the receiver is 75 mm. These values were chosen to optimize the receiver performance, as a tradeoff between fin edge shadowing, temperature rise in the fins, and receiver side losses. The fins are angled at 44° from being perpendicular to the receiver axis, which was chosen based on results from ray tracing simulations, shown in Figure 3.6. This SSLP fin configuration being optimal makes intuitive sense: a near 45° inclination means most of the incident solar radiation reflects near a 45° incidence angle, which is the angle for which the SSLP coatings perform best. Additionally, this configuration leads to almost all incident rays requiring exactly two reflections off the fins to be transmitted through the SSLP structure. Shallower tilt angles lead to more solar energy in the thermal bands leaking through the SSLP, as some rays require only one reflection. Steeper tilt angles lead to worse performance in both the PV and thermal bands, as some rays are reflected from the SSLP back to the ambient environment, unable to be collected as either thermal energy or electricity. The effective transmittance of the SSLP within the PV band is 76.1%, and the effective absorptance in the thermal bands is 93.3%. Note that these values are worse than simply taking the weighted reflectances squared (this would yield a PV band transmittance of 79% and a thermal band absorptance of 93.8%) because incidence angles on the SSLP fins skew larger than 45° due to the concentrating optics rim angle, where the coatings perform slightly worse. Side losses lead to a lower transmittance in both bands, which further hurts the PV band performance.
3.6 Results and discussion

Using the best measured performance to date of subcomponents in the HEATS receiver with a silicon PV cell leads to a total electrical efficiency of 22.8% and a dispatchability of 81%. This is notable as the predicted efficiency is higher than if the HEATS receiver was replaced with a PV only or thermal only
receiver, corresponding to efficiencies of about 20% and 21.4% respectively. It should be noted that the PV efficiency reported here is lower than values given in the reference due to the high cell operating temperature in the PV only configuration. With passive cooling, a PV only configuration leads to cell temperatures greater than 70 °C, while the PV cell remains below 50 °C when integrated into the HEATS receiver. The hybrid receiver achieves this improved efficiency while still preserving high dispatchability, as the majority of the generated electricity comes from thermal energy. Performance can be improved by using a GaAs PV cell rather than silicon, as the higher band gap allows relevant photons to be converted to electricity more efficiently. In the GaAs configuration, we assume that demonstrated SSLP properties could be maintained while shifting the PV window to a more appropriate range (550 – 850 nm). With GaAs, the HEATS receiver achieves a total electrical efficiency of 24.2% with a dispatchability of 76% (a GaAs PV cell in place of the hybrid receiver would achieve 23.6% efficiency).

The potential performance of the HEATS receiver can further be explored as a function of subcomponent properties. Figure 3.7 shows total electrical efficiency and dispatchability contour plots of the HEATS receiver as a function of the SSLP fin coatings, with the solar weighted reflectance of the PV band varying between 85% and 97%, and the solar weighted reflectance of the thermal band varying between 10% and 28%. Figure 3.7a shows that a modest increase in efficiency can be achieved, on the order of tenths of a percent in absolute efficiency, if the SSLP coatings can be improved to reflect more of the PV band and less of the thermal band when a Si PV cell is used. Efficiency is more sensitive to the thermal band reflectance than the PV band reflectance, suggesting that improving the thermal band should be a higher priority. This is reinforced by the effect of SSLP performance on dispatchability, shown in Figure 3.7b. Improving the PV reflectance band improves efficiency, but it decreases dispatchability as it leads to less incident solar radiation being absorbed as thermal energy. Figure 3.7c and Figure 3.7d show the efficiency and dispatchability, respectively, of a HEATS receiver that uses a GaAs PV cell, and show similar trends to the Si HEATS receiver. The most notable difference is that efficiency in the GaAs case is about equally sensitive to the thermal and PV band reflectances. The GaAs HEATS receiver is more sensitive to the PV band reflectance because GaAs has a higher spectral efficiency in the range of photons being directed to it, so there is a larger benefit from converting those photons to electricity at the PV cell rather than thermal energy at the SSLP.
Figure 3.7 Contour plots showing HEATS receiver performance with varying SSLP coating properties. Blue open circles mark values obtained from the best measured SSLP properties to date. a) Electrical efficiency (%) for HEATS receiver with Si PV cell; b) dispatchability (%) for HEATS receiver with Si PV cell; c) electric efficiency (%) for HEATS receiver with GaAs PV cell; d) dispatchability (%) for HEATS receiver with GaAs PV cell.

Modifying aerogel transmittance and thermal conductivity will also impact HEATS receiver performance. Figure 3.8 shows the effect of varying aerogel solar weighted transmittance and thermal conductivity on the HEATS receiver total electrical efficiency for both the Si and GaAs PV cell configurations. For results shown here, the solar weighted transmittance is varied by scaling the extinction coefficient for wavelengths shorter than 2.5 μm, while thermal conductivity is varied by scaling the extinction coefficient for wavelengths longer than 2.5 μm. The values for both solar weighted transmittance and effective thermal conductivity correspond to a 10 mm thick sample. As shown in Figure 3.8, there is room for improvement to efficiency of about 1% absolute if aerogel properties can be further improved. Efficiency is sensitive to both transmittance and thermal conductivity, so improving either would lead to
Figure 3.8 Contour plots of HEATS receiver electric efficiency [%] as a function of aerogel solar weighted transmittance through 10 mm and effective thermal conductivity through 10 mm for a) Si HEATS receiver and a b) GaAs HEATS receiver. The open circles mark the best measured aerogel properties to date.

valuable increases in efficiency. Dispatchability is not a strong function of aerogel properties, varying less than 5% over the range of interest plotted in Figure 3.8, and as such has not been included here.

In most solar thermal systems, higher concentration ratios lead to higher efficiency, and the results reported here are for the case of a geometric concentration ratio of 35x. Lower concentrations also lead to worse performance in this case, however a concentration of 20x leads to only a moderate drop in total electrical efficiency of about 1% (absolute). Efficiency is more sensitive to lowering concentration for values less than 20x. Increasing the concentration ratio above 35x leads to only minor gains, as without active cooling of the PV cell the elevated cell temperatures begin to degrade PV performance. Thus the chosen value of 35x strikes an effective balance: it is high enough to allow efficient thermal operation without overheating the PV cell.

While the efficiency predicted in the HEATS system using the best measured values to date is not groundbreaking in its own right, the receiver is still shown to be a capable platform, as it achieves higher efficiency than a PV only or thermal only receiver used in its place. Modest gains in efficiency could be achieved by improving the subcomponents of the HEATS receiver, but there is more room for improvement in the HEATS receiver as progress is made in PV and solar thermal technologies. Efficiency could be pushed higher if there were heat transfer fluids compatible with line focus solar thermal systems that were stable above 400 °C. [108] Additionally, the HEATS receiver could achieve higher efficiency if there were production ready PV cells better suited for spectral splitting. Production silicon cells typically
have a peak spectral conversion efficiency around 40% - not substantially higher than the efficiency at which heat at 400 °C can be converted to electricity. [122] Gallium arsenide cells could provide a better option if the SSLP coatings can be demonstrated with reflectance bands appropriate to GaAs.

The proposed HEATS receiver efficiently converts solar radiation to both thermal energy and electricity through use of a spectrally selective light pipe and transparent thermally insulating aerogel layers. When considering measured sub-component properties, modeling indicates that the HEATS receiver can achieve an total electrical efficiency of 22.8% when a Si PV cell is used and 24.2% when a GaAs PV cell is used, with over 75% dispatchability in both cases. Notably, these efficiencies are higher than if the HEATS receiver was replaced with just a PV cell or a purely thermal receiver. Moderate improvement in properties could be achieved if the aerogel and SSLP properties can be improved further, and more significant improvements could be achieved as progress in solar thermal technologies allow operation at higher temperature and production PV cells become available that are more suited for spectral splitting in this application. The HEATS receiver offers a new direction for solar energy that can achieve both high electrical efficiency and high dispatchability.
Chapter 4

Characterizing a STAR prototype

Modeling the performance of the Solar Thermal Aerogel Receiver (STAR) as was done in chapter 3 is an important first step in establishing its potential, and modeling is an important tool for guiding device and system design, but ultimately the performance must be measured experimentally in order to convince industry and the relevant stakeholders that the technology is worth pursuing further. This chapter details efforts to experimentally characterize a STAR prototype, and the results collected so far.

To briefly review, the concept behind STAR is to use a transparent, thermally insulating aerogel layer in a CSP receiver to allow sunlight to transmit through to an absorber, but insulate that absorber (which operates at high temperature) from the ambient environment. A cross sectional diagram of a sample STAR was shown in Figure 3.2, and is also reproduced below in Figure 4.1 for convenience.

Figure 4.1 Cross section diagram of proposed Solar Thermal Aerogel Receiver (STAR). An aerogel layer covering a black absorber allows incident solar radiation to be absorbed while reducing thermal losses from the high temperature absorber. The receiver would extend into the page (this depth dimension would be much longer than its width) and would be paired with line-focus systems.
4.1 Measuring receiver efficiency

Since the STAR is being proposed as an alternative to vacuum tube receivers and other traditional receivers used in CSP systems, and STAR could replace these receivers with relatively few changes to the rest of the system, the most relevant performance metric is receiver efficiency. Receiver efficiency $\eta_{\text{rec}}$, which measures the high temperature thermal energy delivered by the receiver divided by the solar radiation incident on the receiver, is given by Eq. (1.8) and reproduced here for convenience:

$$\eta_{\text{rec}} = \frac{Q_{\text{rec, out}}}{q_{\text{rec}}A_{\text{rec}}}$$

Thus, in principle it is very simple to measure the receiver efficiency of a prototype system: we only need to know the thermal energy delivered by the receiver $Q_{\text{rec, out}}$ and the incident solar radiation, given by the product of the incident flux $q_{\text{rec}}$ and the receiver aperture area $A_{\text{rec}}$. Note that receiver efficiency only considers radiation which reaches the receiver – radiation incident on the concentrating optics which does not reach the receiver is captured by the system’s optical efficiency.

A simplified diagram showing the principle by which we measure the receiver efficiency of a STAR prototype is shown in Figure 4.2. The STAR prototype consists of an absorber pipe with a black coating

![Image of receiver efficiency measurement concept](image)

Figure 4.2 Diagram of receiver efficiency measurement concept. The receiver consists of a pipe carrying heat transfer fluid which is coated with a black paint and insulated by an aerogel layer protected by glass. Sunlight is concentrated on the receiver with concentrating optics. The temperature rise of the heat transfer fluid as it passes through the receiver is measured by thermocouples, and the incident solar flux is measured by a flux gauge. A pump circulates heat transfer fluid through the piping loop, and a heater pre-heats the fluid to the temperature of interest for a given receiver operating temperature. A flow meter measures the fluid flow rate, which can be used with the temperature rise through the receiver to calculate heat delivered by the receiver.
which carries a heat transfer fluid to collect the absorbed radiation as thermal energy. The heat transfer fluid is pumped through the receiver in a loop and can be preheated to characterize the receiver at different temperatures of interest by an electric heater. The absorber pipe is insulated by an aerogel layer on one side, and this aerogel layer is protected by a pane of glass. The other sides of the pipe are insulated with traditional insulation. Solar radiation is concentrated onto the absorber pipe through the glass and aerogel layers. The flux incident on the receiver is measured with a flux gauge that sits just outside the aperture of the receiver.

The denominator of Eq. (4.1) is simple to measure in this idealized setup. The area of the receiver aperture $A_{rec}$ is known from the design and fabrication of the receiver, and the flux incident on the receiver $q_{rec}$ is measured by the flux gauge. The thermal energy delivered by the receiver (the numerator of Eq. (4.1)) is slightly more difficult to measure in this setup. This thermal energy is collected by the heat transfer fluid that flows through the receiver, and this thermal energy goes into raising the temperature of the heat transfer fluid. The change in temperature $\Delta T$ for a mass of material $m$ which absorbs an amount of thermal energy $U$ is given by:

$$\Delta T = \frac{U}{mc_p} \quad (4.2)$$

where $c_p$ is the heat capacity of the material. Thus, if the mass flow rate $\dot{m}$ of the heat transfer fluid flowing through the receiver is known, and the temperature rise of the heat transfer fluid across the receiver is known, the heat delivered by the receiver can be given by:

$$Q_{rec,out} = \dot{m}c_p\Delta T \quad (4.3)$$

The mass flow rate can be monitored in the prototype system by adding a flowmeter in series with the rest of the piping components, and the temperature rise can be measured by placing thermocouples in the heat transfer flow before and after the receiver. The receiver efficiency of the prototype receiver can thus be calculated from:

$$\eta_{rec}(T) = \frac{\dot{m}c_p\Delta T}{q_{rec}A_{rec}} \quad (4.4)$$

where mass flow rate $\dot{m}$, temperature rise $\Delta T$, and incident flux $q_{rec}$ are measured by the flow meter, thermocouples and flux gauge, respectively, and where the heat transfer fluid heat capacity $c_p$ is known from the manufacturer and the receiver aperture area $A_{rec}$ is known from the receiver prototype design.
Here receiver efficiency is a function of the output temperature $T$ of the heat transfer fluid from the receiver, since that is the temperature at which the receiver is delivering heat. Thus, the relatively simple setup illustrated in Figure 4.2 allows for the characterization of a CSP receiver under various fluxes and at various operating temperatures. The principle behind Eq. (4.4) is the one which was followed in building the full prototype system described in the following section.

### 4.2 Prototype STAR system

In order to characterize a physical STAR prototype, a STAR prototype and test platform were built. The test platform was built at the MIT Bates laboratory in Middleton, MA, due to more space and more appropriate auxiliary services being available at MIT Bates than on MIT’s main campus. While the novel portion of the system is the STAR prototype, and the performance of the STAR prototype as calculated from Eq. (4.4) is the primary metric of interest, a significant amount of support structure also needed to be fabricated in order to characterize the STAR prototype.

The fabricated STAR prototype test platform is shown in Figure 4.3, with subfigure a showing the outdoor equipment and subfigure b showing the indoor equipment. The following sections will describe the fabricated test platform in detail and is broadly separated into three categories: the receiver platform (section 4.2.1), the concentrating optics (section 4.2.2), and the auxiliary equipment (section 4.2.3). The receiver platform can be seen in the green outlined portion of Figure 4.3a and labeled with a 1. The concentrating optics and associated components are shown in Figure 4.3a in the blue dashed boxes. 2 marks the reflecting mirror segments which redirect incident solar radiation to the receiver, and they are controlled by the motor and linkage marked by 3. The prototype system includes a pyroheliometer, marked by 4, to measure the solar direct normal irradiance which allows the concentrating optics performance to be characterized. The auxiliary equipment is primarily indoors, shown in Figure 4.3b, with the exception of the flow calorimeter shown in Figure 4.3a outlined by a dashed red box and marked 5. In Figure 4.3b, 6 marks a packaged skid which includes a pump for the heat transfer fluid and a heater to control the temperature of the fluid delivered to the receiver. 7 marks the flowmeter to measure heat transfer fluid flow rate through the receiver, and 8 marks the expansion tank which is necessary for the fluid piping loop to safely accommodate thermal expansion in the fluid. Information on components ordered from manufacturers is included in Appendix A, as this could be useful for future improvements to the system or for designing similar systems.

Building this system was a concerted effort and would not have been possible without contributions from many different individuals. Aerogel fabrication was led by Dr. Sungwoo Yang, with help from Lin Zhao and Elise Strobach. The receiver structure was designed by Dr. Bikram Bhatia and Lin Zhao, while the receiver piping was designed by Dr. Thomas Cooper. Receiver instrumentation was fabricated by Dr.
Figure 4.3 Photographs of fabricated STAR prototype test platform, with a) being the outdoor components and b) being the indoor components. The receiver platform (green dashed outline) and the concentrating optics and associated equipment (blue dashed outlines) are located outdoors, while the majority of the auxiliary equipment is located indoors, with the exception being the flow calorimeter (red dashed outline). Some points of interest have been labeled with numbers and are described in the text.

Cooper and this thesis' author. The concentrating optics were designed by Dr. Cooper. The system piping outside the receiver was designed by this thesis' author. Equipment for the system was sourced by Dr. Cooper and this thesis' author. System assembly and fabrication was led by Dr. Cooper and this thesis' author, and they were assisted by all other team members (Drs. Bhatia and Yang, Mr. Zhao, and Ms. Strobach).

4.2.1 Receiver platform

In order to characterize the performance of a novel CSP receiver, it is natural that the receiver platform would be a critical part of the system. As described in section 4.1, the essential parts of the receiver in order to measure performance are an absorbing tube which is instrumented to be able to measure temperature rise in the heat transfer fluid that flows through it and a flux gauge for measuring the incident solar flux on the receiver aperture. In addition to these two pieces which are important to measuring performance, the receiver platform must also include the elements of the novel STAR to be tested: the insulating aerogel, a protective glass layer, and additional insulation for the back and sides of the receiver.

For the STAR prototype system, the receiver platform is raised approximately 2 meters in the air, with the aperture facing downwards. A photograph of the constructed receiver platform is shown in Figure 4.4. The receiver is raised with a downward facing aperture to allow the concentrating optics, which consist of reflecting surfaces close to the ground, to redirect incident sunlight to the receiver aperture.
The absorber piping loop is central to the receiver platform. While in principle only a single absorber pipe is necessary for the receiver (as in the diagram in Figure 4.2), this significantly limits the width of the receiver aperture. For the STAR prototype, six receiver pipes were arranged side by side, to accommodate a 10 cm wide receiver aperture. It was opted to connect the receiver pipes in series (rather than in parallel) to allow for the piping inlet and outlet to both be located on the North side of the receiver (closer to the building with the auxiliary equipment) and to allow for a higher fluid flow rate through the pipes while still achieving a measurable temperature rise. A high fluid flow rate is important to achieving high convection heat transfer between the heat transfer fluid and the absorber pipes. If the pipes were arranged in parallel, then either a very high overall flow rate would be required (leading to a small temperature rise,
Figure 4.5 Absorber piping loop for STAR prototype a) Solidworks render of piping loop design, with the dark section denoting the absorbing portion of the piping loop and b) Photograph of fabricating piping loop as it is being installed in the receiver box. The piping segment is rotated 90° counter clockwise in the photograph as compared to the render. The absorbing portion of the piping loop is not visible in the photograph, as the absorbing portion faces downwards.

as from Eq. (4.3)) or the flow rate through each individual pipe would be small, leading to laminar flow and poor heat transfer from the pipe walls to the fluid.

The piping loop is shown in Figure 4.5, with a SolidWorks render of the loop design in Figure 4.5a and a photograph of the fabricated absorber piping loop as it is being installed in the receiver box in Figure 4.5b. The relatively large pipe loops at the ends of the absorbing section (the darker color section in
Figure 4.5a) are to accommodate thermal expansion in the piping loop, as an overly stiff design could lead to high thermal stresses throughout operation. The piping loop was fabricated by a local welding shop. While it is not visible in Figure 4.5b, which shows the top of the receiver box, the bottom of the six parallel absorbing pipes are painted with Pyromark 2500 to act as a near black absorber coating.

Figure 4.5b also shows some of the traditional insulation which goes around and on top of the piping loop, which is important for minimizing thermal losses from the receiver. This improves receiver performance because any thermal losses from the receiver come at the expense of thermal energy delivered to the heat transfer fluid. While not shown in Figure 4.5b, additional insulation was placed around and on top of the receiver piping loop before the receiver box was closed by securing the stainless steel sheet to the top of the receiver box.

In order to characterize the performance of the receiver, one of the key parameters to measure is the heat collected by the receiver, which can be accomplished by measuring the temperature rise in the fluid that flows through the receiver. In principle, this can be accomplished by simply measuring the inlet and outlet temperatures of the heat transfer fluid, as in Eq. (4.3). For the piping loop in our receiver, however, this method would underestimate performance, as there are significant thermal losses originating from the looped end sections which would not be present in a real system. Thus, for our system we measure the temperature rise across each pipe individually, and take the total temperature rise through the receiver as the sum of these individual temperature rises. The temperature rise in each pipe is measured by a thermopile which consists of 5 thermocouples welded together in series in order to increase the measurement sensitivity (since it is expected that the temperature rise across the pipes is small, typically on the order of 1 °C). In addition to this thermopile, each end of each pipe is instrumented with a thermocouple, which allows the absolute temperature of the pipe to be measured, and also serves to enable a backup measurement of the temperature rise across the pipe. The thermocouples are not placed in the flow, but are instead clamped to the outside of the pipes. While the temperature of interest is the heat transfer fluid and not actually the pipe, if there is turbulent flow in the pipes, the temperature drop between the fluid and pipe walls should be small. Additionally, the metric of interest is temperature rise, not absolute temperature, so if the small temperature difference between the pipe walls and the heat transfer fluid is similar for each pipe inlet and outlet, it should not affect the temperature difference measurement. Good contact between the thermocouple beads and the pipe walls are ensured by clamping the thermocouples to the pipe. Figure 4.6 shows a photograph of the thermopiles and thermocouples attached to the absorber pipes in the receiver platform.
Figure 4.6 Thermopiles (left) and thermocouples (right) attached to one end of the absorbing section of the receiver pipes. The thermopiles and thermocouples are clamped to the pipes using the pictured high temperature hose clamps to ensure good thermal contact between the thermocouples and pipe walls.

In installing the thermopiles, care should be taken to keep the individual thermocouple beads electrically insulated from the piping loop, pipe clamps, and each other. If beads are electrically shorted within a single thermopile, it reduces the effective number of thermocouples, which reduces the sensitivity of the thermopile. If beads are electrically shorted across different thermopiles, it can make the readings completely useless. The section of piping where the thermopiles are clamped is painted black (visible in Figure 4.6) in order to electrically insulate the thermopiles from the piping loop. The thermopile heads are also covered with a kapton film to further insulate them. The thermocouple beads do not need to be electrically insulated as long as those readings are made using a differential measurement (e.g., rather than using a common ground for all the negative legs of the thermocouples).

Another challenge in precisely measuring temperature rise through the pipes is in ensuring that readings are not being influenced by thermal shunting between neighboring pipes. While the piping loop is designed such that there is a small (~1 mm) gap between each pipe, this spacing was not perfectly uniform in the manufactured loop. Additionally, the loop must be supported towards the end by clamps.
Figure 4.7 Photographs of the flux gauges which are used to measure the flux incident on the receiver aperture: a) the receiver aperture as seen from below. The absorbing pipes are visible in the middle of the photograph with the flux gauges mounted in Lambertian reflector targets to the North and South of the aperture b) the North Lambertian target, with a photodiode flux gauge c) the South Lambertian target, with three Gardon flux gauges d) sample photograph used to character incident flux over the width of the receiver aperture area, with the Lambertian targets (the areas of interest) marked with dashed red boxes.

In addition to measuring temperature rise in the heat transfer fluid as it flows through the receiver, measuring incident flux is also critical to calculating receiver efficiency. Measuring incident flux on the aperture of the receiver platform is accomplished using flux gauges mounted in Lambertian reflector plates that are placed to the North and South of the receiver aperture on the underside of the receiver platform. The flux gauges as installed in the receiver platform are shown in Figure 4.7, with subfigure a showing the whole receiver aperture from below, and subfigures b and c consisting of zoomed in images of the North and South flux gauges, respectively.

The flux gauges are mounted in Lambertian reflector targets: metal plates painted with a diffuse white coating. This is to allow the flux distribution over the width of the receiver aperture to be characterized, rather than just measuring the incident flux at the specific points of the flux gauges. Flux distribution is
measured by taking a photograph of the Lambertian target (as in Figure 4.7d). The flux measured at each flux gauge is used to calibrate the image, with the measured flux corresponding to the image brightness in the area immediately surrounding the flux gauge. The image brightness over the region of interest on the Lambertian target, the 10 cm width of active aperture area, can then be averaged to calculate the average flux incident on the receiver aperture. The aperture of the camera being used to capture this image should be set such that no pixels in the region of interest are overexposed. If any pixels in the region of interest reach the maximum brightness value, the image should be discarded, as these overexposed regions would be receiving a higher incident flux than can be measured by the camera. Care should be taken when choosing the location of the camera to minimize specular reflections of direct solar radiation reaching the camera, as this can damage the camera sensor and lead to overexposed pixels near the region of interest. For our installation which is in the northern hemisphere, placing the camera to the south of the receiver would have avoided specular reflections of direct sunlight, as can be seen in Figure 4.7d.

Two types of flux gauges are used in the receiver platform: a photodiode on the North target and three Gardon gauges on the South target. A photodiode is essentially a PV cell, and the voltage output is proportional to the incident solar radiation by connecting the output to a shunt resistor [147]. A Gardon gauge is essentially a thermocouple, with incident radiation heating up a thin film where the temperature of the center of the film corresponds to the incident radiative power [148]. This temperature rise corresponds to a thermoelectric output voltage, which corresponds linearly to incident solar radiation as long as the dominant mechanism for heat transfer from the film is conduction to the edges. The photodiode and the three Gardon gauges were calibrated using a solar simulator and a power meter to confirm that they have linear responses under the fluxes of interest and to determine their sensitivities. Even though the Lambertian targets are painted white, they can reach fairly high temperatures (~150 °C) during normal operation. The flux gauges should be designed such that they can operate under high flux while the target is at least 150 °C. One of our Gardon gauges was damaged due to reaching excessive operating temperatures, but fortunately since we have three Gardon gauges we are still able to collect enough data to make accurate measurements with the other two.

The thermocouples and flux gauges allow for temperature rise $\Delta T$ in the heat transfer fluid through the receiver and incident solar flux $q_{\text{rec}}$ at the receiver aperture to be measured for use in Eq. (4.4), but the receiver platform must also include the novel part of STAR – an insulating transparent aerogel layer. The receiver platform was designed with a portion which stays installed permanently which includes the receiver piping loop and the majority of the instrumentation, and a removable section which holds the aerogel sample. This removable section is shown in Figure 4.8. It includes an aluminum frame which can be fastened to the permanently installed receiver platform, a protective glass layer and traditional
Figure 4.8 Removable section of the receiver platform which forms the receiver aperture and holds the aerogel layer on top of a protective glass layer. The middle of this photograph shows the aerogel tiles: the 1 meter long by 10 cm wide aperture is formed by 7 aerogel tiles which are 14 cm long and 10 cm wide being placed end to end. The edges of the aerogel tiles are visible in this photograph. The aerogel layer is surrounded by conventional insulation to reduce losses from the sides of the absorbing portion of the receiver piping loop.

Insulation which goes around the sides of the absorber piping loop when it is installed. When designing and fabricating this removable section, care must be taken to ensure that it can be installed and removed without disrupting or damaging insulation in the fixed receiver, but the tolerances should be tight enough that there are no gaps which would lead to large thermal losses from the receiver once the removable section is installed. In our system, we accomplished this by making the insulation on the sides of the pipes part of the removable section, and having the insulation on top of the pipes rest on the pipes when the removable section is not installed. When the removable section is installed, the top insulation becomes supported by the side insulation, slightly raising it from the pipes, thus ensuring there is no air gap.

The transparent aerogel layers sit on top of the protective glass layer in the removable section. The receiver aperture is 10 cm wide and 1 meter long, however due to the aerogel fabrication process, which involves critical point drying [102], a single aerogel monolith cannot be made with these dimensions. The aerogel monolith size is limited by the size of the critical point dryer, and the chamber of the dryer used to
produce these samples has an 8 inch (~20 cm) diameter. Instead of making a 1 meter long aerogel monolith, 7 tiles that are 14 cm in length (and 10 cm wide) are arranged to form a layer which covers the entire aperture length. The edges of the aerogel tiles where they are laid end to end can be seen in Figure 4.8. The aerogel tiles are supported on the pane of glass, and when the removable section is installed there is a small air gap between the aerogel tiles and the absorbing pipes. Thus, the aerogel tiles are in contact with the glass but not the pipes.

The receiver platform was constructed and instrumented to measure temperature rise in the receiver, which allows the calculation of heat delivered by the receiver. The platform also includes flux gauges mounted in Lambertian targets, which allow the incident flux on the receiver aperture to be characterized. A removable section in the receiver platform carries the aerogel samples which form the core of the novel portion of the STAR prototype, and insulates the receiver pipes when installed.

### 4.2.2 LFR concentrating optics array

In order to characterize the performance of the STAR prototype which is housed in the receiver platform, solar radiation must be concentrated on the receiver aperture so that it can be absorbed as high temperature thermal energy. A linear Fresnel reflector (LFR) array was designed and built to form the concentrating optics for the prototype system. As a brief reminder, an LFR optics array consists of a number of long, narrow mirrors which are mounted close to the ground. In an LFR system, the receiver remains stationary and the mirrors rotate over the course of the day, tracking the motion of the sun to continuously redirect and concentration incident solar radiation to the raised receiver. LFR optics were used because one of the primary advantages of STAR over other CSP receiver options is its flexible geometry, as discussed in section 3.2.1. STAR can be used in a flat configuration, which is better suited for use with LFR than cylindrical receivers. Additionally, LFR has potential cost advantages over the industry standard PTC systems [24], but has faced challenges when used with other receivers, which makes STAR a potentially enabling technology to leverage the low cost of LFR. Thus, experience with LFR concentrating optics used in tandem with STAR would be more valuable than experience with other types of concentrating optics.
Figure 4.9 LFR concentrating optics array, which consists of 11 mirror lines which are each 30 cm wide and 6 m long that focus incident solar radiation on the receiver aperture. The concentrating optics array has a geometric concentration ratio of 33× when used with the 10 cm wide aperture of the receiver platform designed for the STAR prototype.

The LFR system for the STAR prototype consists of 11 mirror lines, and the constructed LFR array is shown in Figure 4.9. More mirror lines lead to better performance, since more mirror lines allow for narrower mirrors for the same collection width, and narrower mirrors have lower shading and blocking losses [133], while fewer mirror lines lead to a simpler system. In this case, 11 mirror lines was chosen as a compromise between a simpler system and better performance. The mirror lines are each 30 cm wide, so with 11 lines this corresponds to a geometric concentration ratio of 33× when used with the 10 cm receiver aperture of the STAR prototype. While the receiver aperture is only 1 meter long, the mirror lines are 6 meters long. This added length is to accommodate low solar altitudes so that testing can be performed year round and solar irradiance will still illuminate the full meter long aperture of the receiver. In utility scale systems which are at least hundreds of meters long, these end effects are insignificant and the mirror length and receiver length can remain equal without any meaningful degradation in optical performance. The mirrors are slightly curved in order to be able to focus reflected solar radiation from a 30 cm wide mirror segment to a 10 cm wide aperture. To achieve the desired radius of curvature, custom
mirror panels were fabricated by Reflective Concepts Inc. The mirror panels are 1 meter long by 30 cm wide, and as such, 6 panels were connected by a shaft through their axis of rotation to form each mirror line.

We faced a number of small challenges in fabricating the LFR optics. The mirror curvatures for our fabricated panels were not sufficiently precise to the point that each line had its ideal radius of curvature: each line essentially had the same radius of curvature, and therefore a fixed focal length. Since it is more difficult to keep the flux from the outermost mirror lines within the receiver aperture, we addressed this problem by setting the receiver height to accommodate the outermost mirror lines. In this configuration, most of the flux from the central mirror lines is still contained within the receiver aperture. The mirror panels also lacked torsional stiffness, and over time some would become twisted, leading to a reflected beam which deviated from a purely North-South axis. We could remedy this by manually twisting the panels back to a straight shape, however future efforts should more explicitly consider torsional stiffness in the mirror panel design.

During operation, the mirrors track the motion of the sun over the course of a day to continuously redirect incident solar radiation to the aperture of the receiver. All 11 mirror lines are controlled by a single stepper motor, which actuates all 11 axes of rotation through a single linkage mechanism. The motor and linkage bar are shown in Figure 4.10, with the motor directly actuating the middle mirror line and the rest of the lines being connected by the long coupler bar at the bottom of the photograph. The coupler connects to the other mirror lines through 10 rockers. It is possible to track all the mirror lines using a single motor because the principle of LFR optics leads to the angular changes being equal across all mirror lines. This can be most simply understood through the following argument: at a specific solar position, each mirror has a particular angle which leads to the central solar ray being reflected to the center of the receiver aperture. Over the course of the day, we want to maintain the condition that this

![Figure 4.10 Motor and linkage mechanism to track LFR mirrors over the course of a day. The motor directly actuates the middle mirror line, while the remaining mirror lines are moved via rockers connected to a long coupler bar.](image-url)
reflected ray strikes the center of the receiver aperture. If the solar angle (projected in the tracking
direction) changes, in order to maintain that the reflected ray still reaches the center of the receiver
aperture, the mirror angle should rotate by half the change in the solar angle. This mirror rotation rate
being half the rate of change of the solar angle is independent of mirror position, and thus the change in
angle of each mirror is equal. The change in all mirrors being equal is what allows the entire array to be
controlled by a single motor.

While concentrating sunlight on the receiver aperture is sufficient for characterizing the receiver
performance, it is also of interest to measure the performance of the concentrating optics. That is,
determining the optical efficiency $\eta_{opt}$ given by Eq. (1.5) and reproduced here for convenience:

$$\eta_{opt} = \frac{Q_{rec}}{Q_{solar}}$$

(4.5)

where $Q_{rec}$ is the solar power incident on the receiver and $Q_{solar}$ is the solar power incident on the
concentrating optics. We can calculate $Q_{rec}$ from the product of the area of the receiver aperture and the
flux measurement on the aperture given by the flux gauges and Lambertian targets as described in section
4.2.1. To calculate $Q_{solar}$, it is necessary to know the flux of direct normal irradiance reaching the
concentrating optics, since that is the flux which can be concentrated on the receiver. This is measured
using a Kipp and Zonen pyrheliometer, shown marked with a 4 in Figure 4.3a. A pyrheliometer tracks
the path of the sun over the course of the day and measures the direct normal irradiance. Since the
concentrating optics have a much longer collection area than the receiver to accomodate low solar angles
(a situation which would not be replicated in full scale systems as explained previously), in practice
optical efficiency of the LFR optics are calculated by:

$$\eta_{opt} = \frac{q_{rec}}{C G_{DNI}}$$

(4.6)

which can be found by rearranging Eq. (1.6), where $q_{rec}$ is measured from flux gauges in the receiver
platform, $C$ is the concentration ratio of 33×, and $G_{DNI}$ is the direct normal irradiance measured by the
pyrheliometer.

The constructed LFR array concentrates solar radiation onto the receiver aperture continuously over the
course of a day. Flux gauges in the receiver measure the incident flux on the receiver, and when used in
tandem with a pyrheliometer to measure direct normal irradiance, the optical efficiency of the LFR array
can also be calculated.
4.2.3 Auxiliary test platform equipment

While the receiver platform and concentrating optics form the bulk of the system and instrumentation which allows the calculation of a receiver efficiency, there is a significant amount of additional auxiliary equipment required to facilitate the experiment running. The majority of this equipment is dedicated to safely delivering the high temperature heat transfer fluid to the receiver. Some auxiliary equipment is also needed to measure the fluid flow rate, which is a critical part of calculating receiver efficiency, as mass flow rate $\dot{m}$ is one of the measured parameters needed for Eq. (4.4).

The biggest piece of auxiliary equipment used in the STAR prototype setup is a packaged skid which includes a pump and heater, which was purchased as a factory made system from Chromalox, a thermal technology company. The skid is shown in Figure 4.11 and its primary components are a pump and heater. The pump serves to move the heat transfer fluid through the piping loop, and the heater pre-heats the heat transfer fluid to the temperature of interest so that the receiver can be characterized at different operating temperatures.

The pump is designed to deliver flow rates around 30 gpm, which is much higher than the desired flow rate through our receiver loop. While we would like the flow rate through the receiver loop to be high enough to achieve good heat transfer between the fluid and the absorber pipe walls, if the flow rate is too high then the temperature rise through the pipes will be small, and therefore difficult to measure, as can be seen from Eq. (4.3). For the receiver pipe diameter used (schedule 80 1/2 NPS, which has an inner diameter of roughly 0.54 inches or equivalently 14 mm), turbulent flow of the Therminol VP-1 heat transfer fluid is achieved for flow rates of 0.5 gpm or higher. This means that for flow rates greater than 0.5 gpm, there will be good convective heat transfer between the fluid and pipe walls. In order to send of flow on the order of 0.5 – 2 gpm through the receiver loop when the pump nominally operates with a flow rate of 30 gpm, two piping loops were constructed. The majority of the oil output from the pump flows through a short bypass loop which connects the output of the Chromalox system back to its input. A small flow is tapped from the main bypass loop by a receiver piping loop, which travels outside to the receiver platform and returns after being heated by solar input. The flow through the receiver piping loop is controlled by two valves, visible in Figure 4.11: one on the receiver piping loop and one on the bypass loop. Opening or closing these valves allows the flow rate through the receiver loop to be controlled and set to desired values between 0 and 5 gpm.
Figure 4.11 Auxiliary equipment for the STAR prototype setup which is located indoors. The packaged heater skid from Chromalox roughly takes up the left half of the photo. The pump is visible at the bottom of the system (with the orange and gray casing), while the heater is on the left side of the system with a reflective insulation cover and is partially obscured. The flow rate from the pump through the receiver piping loop which travels outdoors to the receiver is controlled by the blue handled valves visible immediately to the right of the heater skid.

The heater delivered with the Chromalox system is a 9 kW circulation heater which is controlled by the front panel of the system. The desired temperature is input into the system and the heater raises the temperature of the fluid to the desired value by heating while the temperature is below the set point and turning off while the temperature is above the set point. While this on/off control mechanism is very simple, it is sufficient in this application as the thermal mass of the heat transfer fluid and the piping loops is sufficient to damp out sharp changes in temperature when the heater turns on and off. It should be noted that this 9 kW heater is not sufficiently powerful to reach operating temperatures above 200 °C if the pump is properly cooled, as the pump has a very large cooling load (approaching 9 kW at 200 °C). We have been able to reach slightly higher temperatures with some additional heating (pipe heat tracing, solar input, etc.), however in our efforts to take measurements up to 400 °C we plan to replace the 9 kW heater with a more powerful immersion heater for future experiments.

In order to calculate receiver efficiency, the mass flow rate of heat transfer fluid through the receiver piping loop must be measured. This is accomplished by using a flow meter manufactured by Krohne,
placed in series as part of the receiver piping loop. The flow meter measures the bulk flow velocity of the heat transfer fluid by measuring the vortex shedding frequency from an obstacle placed in the flow [149]. This shedding frequency can be related back to the flow velocity using the Strouhal relation [150]. With the flow velocity known, volumetric flow rate can be calculated by multiplying velocity by the cross sectional area of the flow region through the meter. This can be converted to a mass flow rate by multiplying by the heat transfer fluid density, which is provided by the heat transfer fluid manufacturer.

While in principle the mass flow rate as measured by the flow meter is sufficient to calculate receiver efficiency, other researchers have found that the volumetric heat capacity of Therminol VP-1 and similar fluids can significantly vary from manufacturer reported values [151]. During early testing, we also experienced issues with noise in the flow meter signal, which further reduced our confidence in the flow meter measurements. Due to this, we additionally installed a flow calorimeter in the receiver piping loop. The flow calorimeter consists of tightly wound heating wire wrapped around a segment of pipe, with the temperature of the heat transfer fluid being monitored before and after the heated section of pipe. These temperatures are monitored in a similar way to the temperature measurements performed in the receiver platform as described in section 4.2.1. The power input to the heating wire can be monitored by an electrical power meter, and if all of the heater power is transferred to the heater (a reasonable assumption since the flow calorimeter is heavily insulated), then the power input $P$ can be related to the temperature rise, fluid and flow properties by:

$$ P = \Delta T \dot{m} c_p $$  

where $\Delta T$ is the temperature rise measured across the flow calorimeter, $\dot{m}$ is the mass flow rate of heat transfer fluid through the receiver piping loop, and $c_p$ is the heat capacity of the heat transfer fluid. Thus, using the flow calorimeter, we can measure the combined flow property (e.g., for use in Eq. (4.4)) $\dot{m}c_p$ by:

$$ \dot{m} c_p = \frac{P}{\Delta T} $$  

This provides a more direct measurement of the heat capacity of the heat transfer fluid flow, and can be used in addition to flow meter reading to gain more confidence in the accuracy of measurements made to the receiver piping flow.

The heat transfer fluid used in this system, which is a eutectic mixture of biphenyl and diphenyl oxide sold commercially as Therminol VP-1 or Dowtherm A, is stable at temperatures up to 400 °C [32], but
Figure 4.12 Indoor auxiliary system equipment, including expansion tank which is located near ceiling. The expansion tank is mounted at this height because it must be the highest point in the system, and as such must be higher than the receiver platform which is raised off the ground in the outdoor portion of the test system. The expansion tank is connected to the main piping loop via two vertical piping legs.

requires a number of safety measures to be taken for this high temperature operation. First, the system must accommodate thermal expansion in the fluid, since operating temperatures can range from room temperature up to 400 °C. If the piping loops were sealed and full of heat transfer fluid at room temperature, they would experience significant stresses as the fluid expanded for higher operating temperatures. Instead, the loops are connected to an expansion tank, pictured at the top of Figure 4.12. The tank is maintained partially full, so that as the heat transfer fluid expands when its temperature increases, the fill level of the tank is increased rather than the fluid volume being contained by the pipe walls.

In addition to provisions needing to be made to accommodate expansion and contraction of the heat transfer fluid as it goes through temperature cycling, the fluid must be pressurized during high temperature operating in order to maintain the fluid in the liquid phase. The normal boiling point of Therminol VP-1 is 257 °C, and its vapor pressure at 400 °C is 1070 kPa (156 psia) [152]. Thus, in order to operate at temperatures up to 400 °C, a minimum pressure of 1070 kPa must be maintained through the
piping loop, or the heat transfer fluid could boil. This is a problem because the density (and therefore volumetric heat capacity) of the vapor phase is much lower than the liquid phase. The piping loop is pressurized via a nitrogen cylinder connected to the expansion tank. Since the expansion tank legs are connected near the inlet to the pump, the pressure at the expansion tank corresponds to the lowest pressure value in the loop. The pump further pressurizes the flow such that the pressure downstream from the pump will be higher than the pressure in the expansion tank.

All the auxiliary equipment associated with the prototype setup allows the heat transfer fluid to be safely heated and pumped through the receiver loop, so that the receiver has a mechanism for delivering thermal energy. The flow meter and calorimeter also allow the flow to be characterized in terms of its heat capacity, which allows the temperature rise through the receiver to be converted to a thermal power collection rate.

4.3 Results from STAR prototype

The setup which has been built allows us to measure receiver efficiency for the fabricated STAR prototype under a variety of different operating conditions. Dependence on clear weather for good results, as well as some challenges with the Chromalox heater skid, have limited the amount of data we have collected to date. Data will continue to be collected throughout the remainder of summer and fall, however for this thesis only the preliminary data which is available will be reported. Results from running experiments on August 1st, 2017 and August 10th, 2017, up to an operating temperature of approximately 250 °C are shown in Figure 4.13. The blue circular marks correspond to experimentally measured data points, while the red dashed curves correspond to simulated results, using methods described in chapter 3. The blue bars show the uncertainty of the measured results, with the large uncertainty in efficiency owing to the difficulty in precisely measuring incident flux on the receiver aperture. The higher simulated curve corresponds to clean glass and an incident flux of 18 kW/m² on the receiver aperture, while the lower simulated curve corresponds to dirty glass (5% reduction in transmittance) and an incident flux of 12 kW/m². These values were chosen because the nominal incident flux on the receiver aperture over the course of testing on August 1st varied from 12 - 18 kW/m².

The simulated results do not show strong temperature dependence over the temperature range of interest, as across this range the thermal losses are calculated to be small compared to the incident solar flux, even for low values on the order of 15 kW/m². The experimental results which are available also show little dependence on operating temperature, although this trend would be more convincing if higher temperature data was available. Nevertheless, the measured results that are available show good agreement with the simulated results, suggesting that the aerogel layer is successfully performing as expected.

107
Figure 4.13 Experimentally measured receiver efficiency. Blue circles mark experimentally measured points, with bars corresponding to uncertainty. Uncertainty in measured efficiency is primarily due to uncertainty in the flux incident on the receiver. Red dashed curves represent simulated performance using methods discussed in chapter 3. The higher simulated curve corresponds to clean glass and an incident flux of 18 kW/m² on the receiver aperture, while the lower simulated curve corresponds to dirty glass (5% reduction in transmittance) and an incident flux of 12 kW/m².

While further experimental results are undoubtedly needed before drawing strong conclusions, the results so far are promising. In the tests run to date, the measured receiver efficiency of the STAR prototype matches results from simulations, providing confidence in the simulated results presented in section 3.4.1. If the high temperature experimental results continue to match the simulated results, it will provide more evidence that STAR successfully operates as we expect, and that STAR could offer a vacuum-free, high-performance alternative to conventional line focus receivers.
Chapter 5

Directional selectivity with a reflective cavity

So far this thesis has primarily explored spectral selectivity: restricting the wavelengths of radiation that a receiver can absorb in order to reduce radiative losses from that receiver. A similar strategy restricts the incident directions rather than wavelengths that a receiver can absorb, which is called directional (or angular) selectivity. Directional selectivity seeks to improve the performance of solar receivers by suppressing losses in directions with no incident sunlight (i.e., at large incidence angles, if the absorber is pointed towards the sun), while still absorbing in the directions with incident solar radiation (i.e., at small incidence angles). For CSP systems, this improves performance because it allows total hemispherical emittance $\varepsilon$ to be reduced while maintaining a high solar absorptance $\alpha$. The effect on receiver efficiency can be seen from Eq. (1.9), reproduced here for convenience:

$$\eta_{rec} = \tau \alpha - \frac{\varepsilon \sigma (T^4_{H,abs} - T^4_{amb})}{CG_{DNI}\eta_{opt}}$$  \hspace{1cm} (5.1)

For PV systems, directional selectivity improves performance because it can increase the effective absorptance of the PV cell and it can reduce radiative recombination losses. This chapter will report a method to achieve directional selectivity in solar receivers which is applied to both CSP and PV systems.

A number of different methods for achieving directional selectivity have been explored in the literature [61,65,79–81]. These methods can generally be separated into two categories: wave optics approaches and geometrical optics approaches. In wave optics approaches, a surface is structured at the scale of the wavelength of the light of interest, which leads to interference and other effects that produce the desired outcome. In geometrical optics approaches, the receiver geometry is modified at the macroscale such that reflection or refraction leads to the desired outcome. This chapter concerns a geometrical optics solution: the use of a specularly reflective cavity.

5.1 Reflective cavity concept

The geometrical optics solution used here is a simple one: if an absorber is surrounded by a specularly reflective cavity which reflects radiation back to the absorber, it can decrease radiative losses (in the case

Figure 5.1 Operating principle of specularly reflective cavity to achieve directional selectivity. An aperture allows incident sunlight normal to the absorber to reach the absorber and be collected, while radiation emitted at large angles towards the walls is reflected back and has an opportunity to be absorbed.

of a CSP receiver) or radiative recombination losses (in the case of a PV receiver) [63,81]. Here specular reflection (as opposed to diffuse reflection) refers to “mirror-like” reflection where the angle of reflection from a surface is equal to the angle of incidence. The benefit of using a specularly reflective cavity is illustrated in Figure 5.1. Such a cavity can also improve the effective absorptance of the absorber, since incident photons which are not absorbed initially might be reflected back to the absorber, yielding multiple chances for absorption [153].

For this cavity to be effective, it should be shaped to reflect radiation which is emitted or reflected from the absorber back to the absorber. The simplest shape which achieves this is a circle (in two dimensions) or a hemisphere (in three dimensions), with the absorber being located at the center. Intuitively, these geometries make sense — a ray emitted from the center of a circle or hemisphere and specularly reflecting off that circle or hemisphere will return to the center. However, because a real absorber will have a finite size, not be an infinitesimal point, not all rays emitted from an absorber in a specularly reflecting circle or hemisphere will return to the absorber. The ideal geometry when considering a finite absorber is an ellipse (in two dimensions) or a hemi-ellipsoid (in three dimensions). For the two dimensional case, the reflective cavity should follow:

\[
\left(\frac{x}{a}\right)^2 + \left(\frac{y}{b}\right)^2 = 1
\]  

(5.2)

\[
w_{abs} = \sqrt{a^2 - b^2}
\]  

(5.3)

where \(r_{abs}\) is the absorber half width located at an elevation of \(x = 0\), \(a\) is the semi-major axis of the
ellipse, $b$ is the semi-minor axis of the ellipse, and $x$ and $y$ parameterize the cavity surface through Eq. (5.2). The three dimensional case is given by:

$$\frac{x^2}{a^2} + \frac{y^2}{a^2} + \frac{z^2}{b^2} = 1$$

(5.4)

$$r_{abs} = \sqrt{a^2 - b^2}$$

(5.5)

where $r_{abs}$ is the absorber radius located at an elevation of $z = 0$, $a$ is the semi-major axis, $b$ is the semi-minor axis, and $x$, $y$, and $z$ parameterize the cavity surface through Eq. (5.4). The optimality of the ellipsoidal geometries will not be discussed in detail in this thesis, but the interested reader is invited to read the author's master's thesis for a full explanation of the ideal cavity geometry [154].

In this chapter, the CSP application includes a physical experiment, and it is easier to realize the hemispherical geometry in practice, so the hemispherical is primarily used. For the PV application, only modeling is pursued, and since the hemi-ellipsoidal geometry leads to better performance, a hemi-ellipsoidal geometry is used in the PV section.

5.2 Reflective cavity for CSP applications

The purpose of using a reflective cavity in a CSP receiver is to reduce the radiative losses emitted from that receiver's absorber. Thus, the performance of the cavity is measured by the effective emittance $\varepsilon^*$ of the absorber in the cavity. Due to the finite absorber size the directional emittance properties are not identical across the entire surface. Thus the directional emittance $\varepsilon'$ must be integrated over all solid angles and averaged over the entire absorber surface (this expression is simplified to only consider directional dependence in the polar angle $\theta$):

$$\varepsilon^* = \frac{2}{A_{abs}} \int_{A_{abs}} \int_{0}^{\pi/2} \varepsilon'(\theta, x, y) \cos \theta \sin \theta \, d\theta \, dA$$

(5.6)

where $A_{abs}$ is the area of the absorber surface. If this system was used as a solar receiver, the radiative losses from the absorber would depend on its effective emittance, and thus the receiver efficiency can be calculated by:

$$\eta_{rec} = \alpha T - \frac{\varepsilon^* \sigma (T_H^4 - T_{amb}^4)}{C_{GDNI} \eta_{opt}}$$

(5.7)

with the only difference between this equation and Eq. (5.1) being the substitution of $\varepsilon^*$. Therefore to improve receiver efficiency, the goal of the cavity is to reduce the effective emittance of the absorber. It
has been shown that the ideal geometry for specularly reflecting radiation from a circular surface back to itself is a hemi-ellipsoid [155]. This paper investigates a hemispherical specularly reflective cavity, which can perform similarly to a hemi-ellipsoidal cavity [154], but is more readily available as a stock geometry.

5.2.1 Simulating receiver cavity performance

It is intractable to determine the directional emissivity analytically at every point on the absorber, due to the complications created by the curved, specularly reflecting cavity. Thus, a ray tracing simulation code was developed in Matlab and was used to predict the cavity performance. Ray tracing is a Monte-Carlo technique in which many rays, representing bundles of radiative energy, are generated and their progression through a system is tracked. Ray tracing can be used to evaluate the overall radiative properties of a system [138]. In this case, rays were generated originating at the absorber surface, and the effective emittance is determined by tallying the number of rays which returned to the absorber versus leaving through the aperture or being absorbed at the cavity walls.

The specific geometry of the cavity investigated is shown in Figure 5.2a. There are two key geometric parameters: the cavity size ratio, which is the ratio of the cavity radius to the absorber radius, and the acceptance angle of the cavity, which is important to determining aperture size and to determining the maximum solar concentration ratio usable with the cavity/absorber system. Additionally, the alignment of the absorber within the cavity can be very important to the performance, which can manifest as height misalignment \( z_{mis} \) or radial misalignment \( r_{mis} \). Various radiative properties (absorber emittance, specular and diffuse reflectances of all surfaces) can also be adjusted for different surfaces within the system. Figure 5.2b shows the different outcomes for rays emitted from the absorber. Rays which are successfully confined are reflected back to the absorber where they are reabsorbed. Rays directed towards the aperture are lost to the environment ("aperture losses") and rays which reflect off the cavity but miss the absorber are lost through the floor of the cavity to the environment ("floor losses"). Ideally the cavity walls are perfectly reflecting but in practice they have finite absorptance and some rays are absorbed by the mirrored cavity walls ("mirror losses").
5.2.2 Experimentally measuring cavity performance

Measuring total hemispherical emittance directly is very difficult as it requires isolating radiative losses from the surface being measured from all other heat transfer mechanisms, and this difficulty would only be compounded by attempting to use the cavity in conjunction with an existing measurement method [156]. Instead, the following comparative experimental procedure was developed to measure the effective emittance of the absorber within the cavity (see Figure 5.3):
Figure 5.3 Experimental procedure for measuring the effective emittance of an absorber within an optical cavity: a) first the power required to maintain the absorber surface at $T_H$ is measured, then b) the power required to maintain the absorber surface at $T_H$ with the optical cavity is measured. The difference in power inputs gives the effective emittance as in Eq. (5.11)

1. Attach the absorber surface to a heater and suspend the heater within a vacuum chamber such that there are minimal losses to the chamber. After evacuating the chamber, raise the heater to a specific elevated temperature and measure the power required to maintain that temperature.

2. Place the same heater/absorber structure in the vacuum chamber, now within the optical cavity. After evacuating the chamber, raise the heater to the same elevated temperature. Measure the power required to maintain the elevated temperature.

If there is good thermal contact between the absorber and heater, and if the whole heater/absorber structure is close to isothermal, then assuming a gray absorber with emittance $\varepsilon$, the power inputs in the two cases $P_1$ and $P_2$ can be given by

$$P_1 = Q_{loss} + A_{abs} \sigma e (T_H^4 - T_{amb}^4)$$
$$P_2 = Q_{loss} + A_{abs} \sigma e^* (T_H^4 - T_{amb}^4)$$

where $Q_{loss}$ is the backside losses from the heater/absorber structure, $A_{abs}$ is the area of the absorber, $\sigma$ is the Stefan-Boltzmann constant, $e^*$ is the effective absorber emittance with the cavity, $T_H$ is the elevated absorber temperature and $T_{amb}$ is the ambient temperature. If the experiment is designed such that the back side losses depend only on the elevated temperature and not on input power (e.g., power dissipation in the wires is negligible, etc.) then the back side losses should be the same for both cases.

Taking the difference in power inputs between the two cases thus calibrates out the back side losses and the reduction in effective emittance is given by
\[ \varepsilon - \varepsilon^* = \frac{P_1 - P_2}{A_{\text{abs}} \sigma (T_H^4 - T_{\text{amb}}^4)} \]  

(5.10)

If the emittance of the absorber is known, then the effective emittance of the absorber within the cavity is given simply by

\[ \varepsilon^* = \varepsilon - \frac{P_1 - P_2}{A_{\text{abs}} \sigma (T_H^4 - T_{\text{amb}}^4)} \]  

(5.11)

The setup shown in Figure 5.4 was built in order to perform the experiment. The optical cavity being tested was a stock 9.2 cm inner diameter glass hemisphere from Edmund Optics, coated with an optically thick film of silver to form the reflective layer. The absorber surface was HE6 reference black paint on a 1 cm diameter copper block with a heater on the back side. The absorber temperature was measured with a 5-mil K-type thermocouple (SLE) embedded in the heater assembly. The electrical heater power was supplied and measured with a precision current source meter and digital multimeter by Keithley (Model: 2425/2010). The absorber/heater assembly was suspended on a ceramic pillar to minimize conductive losses. The pillar was mounted on a two axis linear stage to allow for precise absorber alignment. A machined aluminum plate was used as the cavity floor, which was suspended on threaded rods to allow for precise height adjustment between the cavity floor and absorber surface. Experiments were conducted in a Kurt J. Lesker box vacuum chamber with internal dimensions of 0.6 m per side at an operating pressure of approximately 10⁻⁴ torr.

Using a hemisphere with no aperture (as in Figure 5.4) maximizes the experimental signal to noise ratio, and is therefore effective for investigating the effects of parameters other than aperture size. In order to test the effect of an aperture without fabricating a new cavity for each aperture size, “virtual apertures” were used. To simulate an aperture, an absorbing black plastic disk was suspended at the top of the hemisphere using magnets (see Figure 5.5a). The radiation which is absorbed by the black disk is the same as the radiation which would be lost to an aperture of the same diameter as the disk, so in this manner the disk acts as a “virtual aperture”. Switching between disks of different diameters allowed for rapid interchanging of different aperture sizes. Virtual apertures as used in the setup are shown in Figure 5.5b. The plastic disks and magnets used as virtual apertures were measured in a Thermo Scientific FTIR Nicolet 6700 and showed specular reflectance of less than 5% for IR radiation with wavelengths in the range of 2 – 25 μm.
Figure 5.4 Photos of experimental setup a) heater and absorber surface suspended on ceramic pillar mounted to two axis linear stage b) absorber surface with cavity floor c) specularly reflective hemispherical dome d) fully assembled setup

Figure 5.5 Diagram of virtual aperture concept: an absorbing black disk is suspended at the apex of the hemisphere and acts as a "virtual aperture." Radiation directed towards it will be absorbed and lost to the environment, as if there was an aperture of the same diameter as the disk. b) Photographs of the virtual apertures used for testing the effect of aperture size on cavity performance. Disks of varying diameter allow for rapid testing of different aperture sizes.
Figure 5.6 Effective emittance as a function of cavity size ratio predicted by ray tracing simulations for a blackbody absorber in a 95% specularly reflecting cavity with a 5° acceptance angle. Total effective emittance is plotted (solid blue curve), as are contributions from aperture losses (dashed green curve), mirror losses (dash dotted red curve) and floor losses (dotted black curve).

5.2.3 Simulation results and discussion

Ray tracing simulations were performed to identify important parameters for cavity performance and inform design decisions. Simulations showed that effective emittance is very sensitive to the cavity size ratio, which is the ratio of cavity radius to absorber radius. Figure 5.6 shows effective emittance as a function of cavity size ratio for a blackbody absorber in a 95% specularly reflecting cavity with a 5° acceptance angle.

As seen in Figure 5.6, use of the cavity can significantly reduce radiative losses. For a moderate cavity size ratio of 10, the effective emittance drops to below 0.15, representing a decrease in radiative losses of over 85% from the case of a black absorber with no cavity. For large cavity size ratios above 20, effective emittance drops to below 0.1. The cavity shows better performance for large cavity size ratios (corresponding to a cavity much larger than the absorber) for two reasons. First, for a given acceptance angle there is a smaller view factor to the aperture in larger cavities, resulting in fewer aperture losses. Second, in large cavities the hemispherical geometry more closely mimics the ideal hemi-ellipsoidal
geometry, resulting in less reflected radiation missing the absorber and being lost through the cavity floor. Mirror losses are insensitive to cavity size at 0.05 in this case, matching the mirror absorptance. Thus, reductions in mirror absorptance lead to approximately equal reductions in effective emittance.

Another important geometric parameter of the cavity is the acceptance angle. Larger acceptance angles allow for higher concentration ratios to be used for the solar receiver system, but also result in more radiative losses from the absorber and thus higher effective emittance. In theory, for direct solar insolation on Earth, an acceptance angle of 5° allows for concentration ratios in excess of 300x, and an acceptance angle of 20° allows for concentration ratios around 5000x [69]. Figure 5.7 shows effective emittance as a function of cavity acceptance angle for a black absorber in a 95% specularly reflecting cavity with a cavity size ratio of 10.

As expected, an increase in acceptance angle increases effective emittance due to increased aperture losses, with minimal influence on mirror and floor losses. At a cavity size ratio of 10, effective emittance...
Figure 5.8 Effective emittance as a function of normalized height misalignment predicted by ray tracing simulations for a blackbody absorber in a 95% specularly reflecting cavity with a 5° acceptance angle. Total effective emittance is plotted for \( r_{\text{cav}}/r_{\text{abs}} = 5 \) (solid blue curve), \( r_{\text{cav}}/r_{\text{abs}} = 10 \) (dashed green curve) and \( r_{\text{cav}}/r_{\text{abs}} = 25 \) (dotted black curve).

approaches 0.1 for very small acceptance angles near zero. Even for large angles, effective emittance is significantly reduced. An acceptance angle of 25° yields an effective emittance of about 0.33, corresponding to a reduction in radiative losses of two thirds from the case of a black absorber with no cavity.

The results above show significant reductions in effective emittance of an absorber within a reflective hemispherical cavity, however these results assume that the absorber is perfectly aligned at the center of the cavity. In practice, alignment of a small absorber within a large cavity is difficult, and can only be achieved to finite precision. Ray tracing simulations were also performed to predict the influence of misalignment on cavity performance. Figure 5.8 shows effective emittance as a function of absorber height misalignment normalized to absorber radius.

Figure 5.8 shows two important features of absorber height misalignment. First, it is clear that performance is very sensitive to height alignment. Changing the position of the absorber by 0.1 absorber
radii can increase effective emittance by about 0.15, more than doubling radiative losses in the large cavity cases. While not shown in the figure, the additional losses due to misalignment are floor losses, as changing the position of the absorber results in more of the reflected radiation missing the absorber. The second important feature to note is that the optimal absorber height is not at the equatorial plane of the hemisphere ($z_{mis} = 0$), but slightly above. The ideal height is slightly higher than the center of the hemisphere because when the absorber is raised, the hemisphere more closely resembles the ideal oblate hemi-ellipsoidal geometry. The height which the absorber should be raised is a function of cavity size: larger cavities are closer to the ideal geometry, so the height to raise the absorber for ideal performance is smaller. It should be noted that for the results shown in all plots aside from Fig. 7 the absorber was placed at the ideal height, not at $z_{mis} = 0$.

Radial misalignment can also be important to the performance, and was also investigated using ray tracing simulations. Figure 5.9 shows effective emittance as a function of absorber radial misalignment normalized to absorber radius.
Parameters for simulation:

- $e_{\text{abs}} = 0.95$
- $e_{\text{ca}} = 0.04 - 0.06$
- $r_{\text{mis}} = 0.15 - 0.25 \text{ mm}$
- $z_{\text{mis}} = 0.15 - 0.25 \text{ mm}$

Figure 5.10 Measured effective emittance of near black absorber with cavity using prototype system as a function of absorber temperature. Error bars include systematic error and 3 standard deviation statistical error. Ray tracing simulation results are shown (red shaded region) for the same cavity geometry for comparison.

The ideal radial alignment is always $r_{\text{mis}} = 0$, corresponding to the absorber being perfectly centered within the cavity. Performance is not quite as sensitive to radial alignment as height alignment, but radial alignment is still important. Deviations by 0.1 absorber radii increase effective emittance by about 0.1, a significant increase for ideal effective emittances in the range of 0.05 to 0.2. This increase in effective emittance comes from losses through the cavity floor when the misaligned absorber no longer intercepts radiation reflected from the cavity walls. While the effective emittance trend appears very similar for the different cavity size ratios, it is worth noting that the radial misalignment is normalized to the absorber radius, so achieving $r_{\text{mis}}/r_{\text{abs}} < 0.05$ is more difficult for the higher cavity size ratio cases.

### 5.2.4 Experiment results and discussion

In order to validate the ray tracing simulation results, proof of concept experiments as described in section 0 were also performed. The measured effective emittance of the 1 cm diameter HE6 reference black paint absorber in a 9.2 cm diameter reflective hemisphere is shown in Figure 5.10 for various elevated temperatures and compared to ray tracing simulations for the same conditions.
Figure 5.11 Measured effective emittance of near black absorber with cavity using prototype system as a function of aperture acceptance angle. Y-axis error bars include systematic error and 3 standard deviation statistical error, x-axis error bars account for smaller virtual apertures not being flush with the top of the cavity. Ray tracing simulation results are shown (red shaded region) for the same cavity geometry for comparison.

Measured effective emittance was significantly reduced with the use of the cavity, from the reference value of 0.95 \[157\] to below 0.2, an almost 80% reduction in radiative losses. These results show reasonable agreement with the effective emittance of 0.125 – 0.18 predicted by ray tracing simulations for the same cavity geometry and a range of realistic cavity reflectances and absorber alignments. The expected dependence on absorber temperature is weak because none of the relevant radiative properties (emittances and reflectances) should change radically over the range of absorber temperatures investigated. Uncertainty at low temperatures is dominated by statistical error associated with taking the difference between two relatively similar numbers (power input with and without the cavity) while uncertainty at high temperature is dominated by systematic error associated with the large differences in power input for the cavity and no cavity cases. The remainder of the reported experimental results use data for an absorber temperature of 300 °C as this temperature has the smallest overall uncertainty.
Figure 5.12 Measured effective emittance of near black absorber with cavity using prototype system as a function of absorber height misalignment. Y-axis error bars include systematic error and ±3 standard deviation statistical error, X-axis error bars denote precision which can reasonably be achieved for this system. Ray tracing simulation results are shown (red shaded region) for the same cavity geometry for comparison.

Most of the physical experiments were performed using a reflective hemispherical cavity with no aperture in order to maximize signal to noise ratio. As the role of aperture size on performance is important, the effect of aperture size was still investigated using the virtual aperture system discussed in section 0. Figure 5.11 shows measured effective emittance as a function of aperture acceptance angle for the virtual apertures. As expected, effective emittance increases with larger acceptance angles, as more radiation is lost through the larger apertures. Measured effective emittances show very good agreement with those predicted by ray tracing simulations for the range of acceptance angles investigated.

As simulations showed that absorber alignment was very important to cavity performance, the experimental setup was designed to allow for precise positioning of the absorber relative to the reflective hemisphere. Measured effective emittance as a function of absorber height position in the cavity is shown in Figure 5.12. Measured results show good agreement with predictions from ray tracing simulations, and
Parameters for simulation:

- $\varepsilon_{abs} = 0.95$
- $\varepsilon_{cav} = 0.04 - 0.06$
- $h_{mis} = 0.15 - 0.25 \text{ mm}$

**Figure 5.13** Measured effective emittance of near black absorber with cavity using prototype system as a function of absorber radial misalignment. Y-axis error bars include systematic error and 3 standard deviation statistical error, X-axis error bars denote precision which can reasonably be achieved for this system. Ray tracing simulation results are shown (red shaded region) for the same cavity geometry for comparison.

The high sensitivity to height alignment is confirmed, as measurable differences in performance are observed for changes in alignment as small as 0.2 mm in the proof of concept experiment.

Effective emittance was also measured as a function of radial alignment and the results are shown in Figure 5.13. Measured results again show reasonable agreement with predictions from ray tracing simulations. Performance is sensitive to radial alignment, however not as sensitive as height misalignment. Measurable differences in performance occur for changes in alignment as small as 0.5 mm in the proof of concept experiment. It should be noted that the mirrored hemisphere surface was lightly scratched before performing the radial alignment experiments, which could explain why the measured effective emittance values are slightly higher than the predictions from simulation.

### 5.2.5 Effect on receiver efficiency

In order to appreciate how a reduction in emittance leads to increased receiver efficiency, the receiver efficiency is plotted as a function of absorber temperature for various receiver systems in Figure 5.14.
These efficiencies were calculated using Eq. (5.7), assuming the receiver is exposed to ASTM AM1.5 Direct + Circumsolar insolation [158] with a solar flux concentration ratio of 100. An effective emittance of 0.2 was used for the blackbody absorber with an optical cavity, which was demonstrated to be achievable for cavity receivers compatible with the concentration ratio of 100 (see Figure 5.11). For the spectrally selective absorbers, the absorptance is treated as a step-function from 1 to 0 at an optimized transition wavelength [73] and a step function from 0.95 to 0.05 at a wavelength of 1.8 μm for an ideal and more realistic surface, respectively. Transmittance is assumed to be unity for all the investigated systems.

As expected, a blackbody absorber by itself is only effective at lower temperatures. The ideal spectrally selective absorber outperforms the blackbody absorber with the optical cavity at all temperatures, however the ideal characteristics used for the ideal absorber would be very difficult to achieve in practice. Comparing the cavity to the more realistic 95/5 spectrally selective absorber, one can see that the two systems have very similar performance in the temperature range of 700 °C – 1000 °C. At temperatures

![Diagram](image)

Figure 5.14 Receiver efficiency as a function of absorber temperature for a blackbody absorber (solid black curve), a blackbody absorber with an optical cavity (this work, solid blue curve), an ideal spectrally selective absorber with a step function absorptivity from 1 to 0 at an optimized wavelength (dashed green curve) and a more realistic spectrally selective absorber with a step function absorptivity from 0.95 to 0.05 at 1.8 μm wavelength (dotted red curve). These results assume AM1.5 Direct + Circumsolar illumination with a solar flux concentration ratio of 100.
below 700 °C the spectrally selective absorber performs worse due to absorptance being below unity. At temperatures greater than 1000 °C the proposed receiver design outperforms the 95/5 spectrally selective absorber due to the overlap between the solar and IR spectra increasing the emittance of the spectrally selective absorber at high temperature. It is worth noting that this is a favorable treatment of spectrally selective absorbers, as in practice they do not have ideal step function spectral absorptances and are typically not stable at temperatures above 600 °C [159]. Thus, it is readily apparent that the optical cavity provides a significant advantage over a simple blackbody absorber, and can outperform spectrally selective surfaces at low and very high temperatures.

A specularly reflecting hemispherical cavity was proposed as a means to achieve directional selectivity for a solar receiver. Ray tracing simulations showed that the use of the cavity could reduce radiative losses from a blackbody surface by over 75%, if the absorber could be precisely aligned within a large cavity. Results from proof of concept experiments demonstrated significant reductions in radiative losses that were reasonably matched with simulation results. These reductions in radiative losses indicate that the proposed optical cavity could potentially improve the efficiency of solar thermal systems without increased heat fluxes and their associated challenges. Potential future directions include the integration of this cavity concept into a solar thermal prototype system to characterize efficiency improvements and the investigation of a cylindrical cavity for use with line focus solar thermal systems.

5.3 Reflective cavity for PV applications

Photovoltaics (PV) offer a promising answer to the challenge of a renewable energy future [160]. Even with significant progress in recent years, efforts are being made to reduce cost even further so that PV can reach parity with conventional fossil fuels without government subsidies [44]. One approach to cost reduction is using thin-film crystalline silicon (c-Si) PV cells, which use significantly less high-quality silicon material than traditional cells [161]. The silicon wafer typically accounts for 30% - 40% of the total PV module cost, and this cost can be reduced if less material is used [162,163].

The drawback of thin-film cells is that incident photons have a shorter travel distance through the material than in traditional cells, yielding a lower chance of being absorbed. Tiedje and Yablonovitch, et. al. established an absorptance limit for silicon PV cells as a function of cell thickness (the “Yablonovitch limit” or “Lambertian limit”) [164]. This absorptance limit can be combined with the Shockley-Queisser limit (for example) to predict a solar to electricity conversion efficiency limit [53]. Absorptance in the Yablonovitch limit assumes incident photons are perfectly coupled (100% transmittance) into the cell and scattered isotropically at the front and back surfaces of the cell. Photons which would otherwise escape from the cell are trapped inside the cell if they have been scattered into an angle exceeding the critical
angle (total internal reflection). This results in longer photon path lengths through the cell and therefore higher chance of absorption [165]. The absorption limit $A$ is given by:

$$A(\lambda) = \frac{\alpha(\lambda)L}{\alpha(\lambda)L + \frac{1}{F}}$$

(5.12)

where $\alpha(\lambda)$ is the wavelength dependent absorption coefficient of the PV material, $L$ is the cell thickness, and $F$ is the absorption enhancement factor. The absorption enhancement factor is $4n^2$ in the Yablonovitch limit, where $n$ is the PV refractive index. Substituting this into Eq. (1) yields the familiar form of the Yablonovitch limit:

$$A(\lambda) = \frac{\alpha(\lambda)}{\alpha(\lambda) + \frac{1}{4n^2L}}$$

(5.13)

There is also a lower 2D absorption limit for surfaces which only scatter in one dimension. In this case, the absorption enhancement factor is $\pi n$ rather than $4n^2$ [166].

Most strategies for enhancing thin-film cell absorption pursued up to this point have used cell surface texturing to scatter photons into a wider range of angles into the cell with the aim of approaching the Yablonovitch limit [167–171]. However, the PV cell efficiency can also be increased by limiting the angular range through which photons (both trapped and emitted in the process of radiative recombination) can escape the cell [60–62,82]. For angle limited PV cells, the maximum absorption enhancement factor is increased from $4n^2$ to $4n^2 / \sin^2 \theta$ where $\theta$ is the half-angle of the absorption cone of the PV cell [172,173]. In this section we investigate the use of an external optical cavity to improve absorption of light in thin-film silicon PV cells both with and without surface texturing via the angular selectivity mechanism.

### 5.3.1 Hemi-ellipsoidal optical cavity for a PV receiver

The optical cavity investigated is an ellipsoidal dome with a reflective coating and a small aperture allowing sunlight to reach the cell, as shown in Figure 5.15. Similar cavities have been shown to reduce radiative recombination emission losses in PV cells [64] and thermal emission losses in thermal systems [81,155]. Here, we show how it can also increase absorption in thin film PV cells. If the cell is slightly tilted, some of the photons that are not absorbed and leave the PV cell after bouncing off its back reflector can now be trapped inside the cavity. Owing to its ellipsoidal shape, the cavity reflects these photons back to the PV cell, which allows for more opportunities for absorption and effectively increases absorptance of the cell.
photons not absorbed by the PV cell are reflected back, yielding additional opportunities for absorption.

Figure 5.15 Diagram of the PV cell cavity enhancement concept. Sunlight incident on a tilted cell that is not absorbed is reflected back to the cell, yielding more opportunities for absorption. Important geometric parameters include: aperture acceptance angle $\psi$, cell tilt angle $\gamma$, cell radius $r_{\text{cell}}$, and cavity radius $r_{\text{cav}}$.

The geometry of the cavity is an oblate ellipsoid, with the relationship between the semi-major axis $r_{\text{cav}}$ ("radius" of the ellipsoid) and semi-minor axis $h$ ("height" of the ellipsoid) given by

$$r_{\text{cav}} = \sqrt{h^2 + r_{\text{cell}}^2} \quad (5.14)$$

where $r_{\text{cell}}$ is the radius of the PV cell in the cavity. This geometry is used because it ensures that any ray originating from the PV cell which is specularly reflected from the ellipsoidal cavity will return to the PV cell [154,174]. The ellipsoid is tilted along with the cell such that its minor axis remains orthogonal to the PV cell, in order to preserve the previously mentioned geometrical reflecting property. Slight variations to this configuration (e.g., ellipsoid minor axis aligned with incident sunlight, a hemispherical cavity, etc.) were investigated and found to have marginally lower performance, so the results for those studies will not be reported here.

Cavity performance is predicted using ray tracing, which is a Monte Carlo technique that can be used to evaluate the radiative properties of systems [138]. Rays representing incident solar radiation are incident on the PV cell, with location and incidence angle determined by randomly generated numbers and the appropriate weighting functions. Based on the cell absorptance, the rays have a chance of being absorbed or reflected specularly (our optical simulations detailed below show that higher order surface diffractions are negligible for the investigated structured surfaces). The rays are propagated through the cavity until all rays have been absorbed by the cell ("absorbed"), absorbed by the cavity walls ("mirror losses"), lost
through the aperture ("aperture losses") or absorbed by the cavity floor ("floor losses"). The effective absorptance $A$ of the cell embedded into the cavity is given simply by

$$A = \frac{N_{cell}}{N_{inc}} \cos \gamma$$

(5.15)

where $N_{cell}$ is the number of rays absorbed at the cell, $N_{inc}$ is the total number of rays incident on the cell, and $\gamma$ is the tilt angle. The $\cos \gamma$ term accounts for effective area losses due to the incident sunlight not being normal to the cell.

There are three primary geometric parameters of the cavity to optimize for achieving high absorption and energy conversion efficiency: the acceptance angle of the cavity aperture, the tilt angle of the PV cell, and the size ratio of the cavity radius to the PV cell radius (all shown in Figure 5.15). Another important cavity parameter is the wall specular reflectance, which is assumed to be 95%, a value which is achievable in the relevant spectral range using conventional metal coatings [175].

The cavity aperture acceptance angle, defined as the angle between a line from the edge of the PV cell to the near edge of the aperture and a normally incident ray from the sun, determines the maximum solar concentration ratio achievable at the cell [69]. It should be noted that this cavity aperture acceptance angle (shown in Figure 5.15 as $\psi$) is different from the acceptance angle typically used in CPV applications, which refers to the tolerance of concentrating optics to misalignment. Larger cavity acceptance angles allow for higher concentration ratios but reduce the cavity effectiveness by allowing more photons to escape through the aperture. A fixed acceptance angle of 5° is used in this study, which allows for moderate concentration ratios (up to 360 suns).

Tilt angle is an important parameter to consider because if the cell is not tilted then most photons reflected from the cell leave the cavity through the aperture, but if the cell is tilted too steeply then the projected area of the cell in the direction of the incident sunlight becomes small. The maximum tilt angle to consider is the smallest angle such that no photons coming through the aperture are reflected directly back toward the aperture. This maximum tilt angle $\gamma_{max}$ can be given by:

$$\gamma_{max} = \psi + \sin^{-1}\left(\frac{r_{cell}}{r_{cav}}\right)$$

(5.16)

where $r_{cell}$ and $r_{cav}$ are the radii of the cell and cavity respectively, and $\psi$ is the aperture acceptance angle. In order to derive Eq. (5.16) it is useful to define geometric parameters with respect to the PV cell, as shown in Figure 5.16. In this figure, the lines normal to the incident sunlight (dotted green) intersect
Figure 5.16 Diagram of cavity with the PV cell taken as horizontal. Lines and angles important to the derivation of Eq. (5.16) are marked.

the lines normal to the PV cell (solid red) at the tilt angle $\gamma$. If the cell is tilted clockwise, the last ray to be captured in the cavity is at the acceptance angle $\psi$ relative to the normal incidence sunlight. This last ray is labeled “A” in Figure 5.16. When it reflects from the PV cell, it forms an angle $\gamma - \psi$ relative to the line normal to the PV cell, this reflected ray is labeled “B” and should hit the edge of the aperture. The edge of the aperture is defined by the opposite side of the PV cell, and the line between the edge of the aperture and PV cell (labeled “C”) should be at the acceptance angle $\psi$ relative to the normal incidence sunlight.

Thus, lines from both edges of the PV cell to the edge of the aperture form the same angle with the lines normal to the PV cell: $\gamma - \psi$. This symmetry indicates that this edge of the aperture is at the apex of the hemi-ellipsoidal cavity, at a height of $h$. The distance between the edges of the PV cell and the apex of the dome is given by the Pythagorean theorem as $\sqrt{r_{cell}^2 + h^2}$. By applying Eq. (5.14), we can see that the distance is simply the semi-major axis of the ellipsoidal cavity $r_{cav}$. This sets up a simple trigonometric equation

$$\sin(\gamma - \psi) = \frac{r_{cell}}{r_{cav}}$$

which when rearranged for the tilt angle $\gamma$ yields the form shown in Eq. (5.16).

The max angle calculated from Eq. (5.16) is not necessarily optimal, as shallower angles resulting in lower cosine losses may outweigh the additional aperture losses. To find an optimum value for the tilt angle, in Figure 5.17 we plot the effective absorptance of a cell with an absorptance of 0.5 and varied tilt angle. As expected, effective absorptance increases with tilt angle as aperture losses are reduced until the optimal angle, after which performance degrades due to cosine losses. The maximum tilt angle of 16.5°
Figure 5.17 Effective absorptance of a cell within a cavity as a function of the cell tilt angle. The dotted black line at 0.5 shows the absorptance of the cell in the absence of the cavity. The vertical dashed red line denotes the maximum tilt angle of 16.5° given by Eq. (5.16), while the optimal angle is about 14.5°. Predicted by Eq. (5.16) is marked by the dashed vertical line, and in this case the optimal angle is slightly smaller, about 14.5°. It is worth noting that other absorptance values besides 0.5 can be used to optimize the geometric parameters, and the difference in results is negligible for a wide range of absorptances.

Cavity size ratio (the ratio of cavity radius to cell radius) is also important to consider for maximizing cell absorption. Figure 5.18 shows the fractions of the rays initially reflected from a cell with absorptance of 0.5, which – after bouncing within the cavity – are (i) absorbed by the cell, (ii) absorbed by the cavity and (iii) lost through the aperture. There is an optimal size ratio, as very small cavities require large apertures to maintain a decent concentration ratio (leading to large aperture losses), while large elliptical cavities

Figure 5.18 Fraction of rays which absorbed by the cell ("absorbed"), absorbed by the cavity ("mirror losses") and lost through the aperture ("aperture losses") as a function of cavity size ratio. The cell absorptance is taken as 0.5, and the tilt angle used is given by Eq. (5.16).
focus the rays back out of the aperture in only one reflection off the cell. It can be noted that larger size ratios call for shallower tilt angles and therefore lower cosine losses, an advantage not reflected in Figure 5.18. It should also be noted that these results use the tilt angle given by Eq. (5.16), so slightly improved performance could be obtained by finding the optimal angle at each cavity size ratio.

5.3.2 Absorption enhancement for thin-film PV

To calculate how much the cavity enhances the effective absorptance of the embedded PV cell, we fixed the cavity geometry and ran ray tracing simulations for cell absorptances varying from 0 to 1 (Figure 5.19b). The cavity parameters used for the results in Figure 5.19b (and hereafter) were as follows: an acceptance angle of 5°, a cavity specular reflectance of 95%, a cavity size ratio of 5, and a cell tilt angle of 14.5°. As can be seen in Figure 5.19b, the largest enhancements occur for moderate absorptances in the range of ~0.2 – 0.7. The enhancement is small for low cell absorptances because even with additional opportunities for absorbing incident photons, the photons are still more likely to be reflected away from the cell and either escape or get absorbed elsewhere in the cavity. The enhancement is small for high absorptances because almost all the photons are absorbed on the initial incidence on the cell, so there are few additional photons left to absorb with the aid of the cavity. It is also worth noting that for absorptances very close to 1 the cavity actually lowers the cell performance, as the cosine losses from the tilted cell outweigh the advantage of increased absorptance of incident photons.

In order to calculate the absorptance of a PV cell without a cavity, the wave optics module in COMSOL Multiphysics was used to simulate the PV cell optical response including cell reflectance and absorptance for both transverse electric (TE) and transverse magnetic (TM) polarizations. Three types of c-Si PV cell were studied, including unpatterned (planar) thin-film cells and cells with either a three dimensional (3D) pattern of inverted nano-pyramids (INPs) or a two dimensional (2D) pattern of parallel periodic grooves. Silicon nitride antireflection layers with thicknesses of 70 nm and 100 nm were placed on top of the planar and textured silicon layers, respectively. The periodicities for both the 2D grooves and 3D INPs are 700 nm. For textured solar cells, an unavoidable planar area between each repeating unit cell forms a ridge region, which can be seen in Figure 5.19a, and this ridge separation is set to be 50 nm [167]. Floquet periodic boundary conditions are implemented on the sides of the computation window, and a perfect electric conductor (PEC) boundary condition is used to mimic the effect of a back mirror for the PV cell. The 2D grooved solar cells have 200nm-thick oxide and 600nm-thick silver on the back of the silicon. For the 3D inverted pyramids, we assumed a PEC boundary condition directly underneath the silicon layer to improve numerical accuracy and reduce computation time. Absorptance for varying incidence angles from normal to 20° were calculated (capturing the majority of ray incidence angles), however no significant angular dependence was observed in this range.
Figure 5.19 (a) The schematic of simulated planar, 2D grooved, and 3D INPs solar cells: the layers shown in purple, gray, blue and black represent antireflective silicon nitride, silicon, silicon dioxide and silver, respectively. (b) Effective absorptance of cell within a cavity as a function of cell absorptance (solid blue curve) with cell performance in absence of cavity for comparison (dotted black curve). (c) Spectral absorptance of a 5 μm thick planar silicon cell with (solid blue curve) and without the cavity (dotted black curve). (d) Spectral absorptance for 5 μm silicon cells within a cavity (solid curves) and without a cavity (dashed curves). Surface patterns shown are grooved surface (green curves) and inverted nano-pyramids (INPs, blue curves). The Yablonovitch limit (dashed black curve) and 2D absorption limit (dotted black curve) are shown for comparison.

Since photons absorbed in parts of the cell other than the silicon (e.g., the nitride layer) are not useful, effective absorptance of the cell $A_{\text{eff}}$ with the cavity (for a particular wavelength) is given by

$$A_{\text{eff}} = \frac{A_{\text{Si}}}{A_{\text{tot}}} F(A_{\text{tot}})$$

(5.18)

where $A_{\text{Si}}$ is the absorptance of the silicon portion of the cell, $A_{\text{tot}}$ is the total absorptance of the cell and $F$ is the function which gives the cavity enhancement (i.e., the solid blue curve in Figure 5.19b). Applying Eq. (5.18) to the spectral absorptance curve of a solar cell yields the enhancement with the cavity, as shown in Figure 5.19c for a 5 μm thick planar c-Si cell. There is significant absorption enhancement in wavelength range of 700 – 1000 nm, as the cell by itself has moderate absorption values in this range. For the range of 450 – 700 nm, the enhancement is small, as the bare cell already absorbs effectively in this range.
The absorptance enhancement spectrum for 5 μm c-Si cells with surface patterning (grooves and inverted nano-pyramids) is shown in Figure 5.19d, along with the Yablonovitch absorption limit for comparison. For the cell with the grooved surface, the introduction of the cavity brings performance close to the Yablonovitch limit, while the cell with the inverted nano-pyramids and cavity exceeds the Yablonovitch limit for wavelengths greater than 800 nm. It should be emphasized that photons with the energies in this spectral range close to the bandgap of silicon can be converted most efficiently by Si PV cells. The angle-limited absorption limit is not plotted here (which the proposed cavity would never be able to exceed) as for our cavity’s acceptance angle the absorptance would effectively be unity across the entire spectral range.

To quantify how cavity-enhanced absorptance affects PV cell performance, we calculate the photo-generated current density, $J_{ph}$, and the cell efficiency. Both of these quantities are calculated assuming a solar concentration of 25, chosen because such an optical concentration captures all the sunlight that would be incident on the cavity ($r_{cav}/r_{cell} = 5$). The photo-generated current density can be modeled by assuming that every absorbed photon in the silicon with energy above the bandgap excites one electron-hole pair. The AM1.5D solar spectrum [52] is used, as the cavity-embedded cell is expected to be operated under concentrated sunlight illumination. Efficiency can be calculated using a simple 1D model, with the current density $J$ calculated as:

$$J = J_o [\exp(qV/kT) - 1] - J_{ph} \quad (5.19)$$

where $J_o$ is dark current density, $q$ is elementary charge, $V$ is voltage, $k$ is the Boltzmann constant, and $T$ is cell temperature, with proper silicon properties [176,177]. Efficiencies are calculated assuming p-type cell doping level of $10^{16}$cm$^{-3}$, 500nm-thick n-type junction on the top surface with doping level of $10^{19}$cm$^{-3}$, and surface recombination velocities of 30cm/s at both top and bottom surfaces. Figure 5.20a shows photo-generated current density and efficiency of planar, grooved, and inverted nano-pyramid (INP) patterned cells with and without the cavity as a function of the cell thickness. The photo-generated current density obtained using the Yablonovitch limit of absorption is shown for comparison.
Figure 5.20 (a) Photo-generated current density and (b) efficiency as a function of cell thickness for planar (red), 2D grooved (green) and 3D INP (blue) surfaces both with (solid curves with pentagrams) and without the cavity (dashed curves with open circles). The photo-generated currents and efficiencies assuming the Yablonovitch limit (dashed black curve) and 2D limit (dotted black curve) for the cell absorptance are shown for comparison.

The photo-generated current density enhancement is most pronounced for planar cells, with improvements of about 7 mA/cm²/sun for very thin cells, and of about 5 mA/cm²/sun for conventional cells with thicknesses of 100μm and above. Planar cells have moderate absorption for a wide range of wavelengths, and thus benefit most from the cavity effect. The enhancement is less dramatic for patterned cells, as they already have fairly good absorptance, however there is still a significant improvement of around 5 mA/cm² for thin cells and 2 - 3 mA/cm² for thicker cells. The enhancement is significant enough that for INP patterned cells of < 2 μm in thickness, the cavity effect pushes the PV photo-generated current above the Yablonovitch limit. The performance of INP patterned cells is only plotted for cells with up to 13 μm thickness due to computational limitations for 3D COMSOL simulations. INP performance is expected to approach grooved cell performance at large thicknesses, as the increased scattering gives diminishing returns for thicker cells, and this trend is already noticeable for the thicknesses shown in Figure 5.20. It is also worth noting that the planar cell with the cavity outperforms the grooved cell without the cavity, indicating that use of the cavity as a light trapping strategy achieves PV cell performance improvement comparable to that achieved via surface texturing. The trends for the efficiency results, which are shown in Figure 5.20b, closely mirror what was discussed for photo-generated current.

While prior research efforts have focused primarily on surface patterning of solar cells to enhance light trapping, the results reported here show that the proposed optical cavity can also lead to significant absorptance enhancements. This offers an alternative path to improve thin-film PV cell absorptance, which can be pursued either in parallel with surface patterning or separately. Modeling shows that the
optical cavity used in conjunction with patterned PV cells can even exceed the Yablonovitch limit for absorption, especially for ultrathin (<2μm) solar cells. The effect of the cavity can be even stronger for thin film PV cells with higher radiative recombination emission rates (such as GaAs), as the cavity-imposed emission angular selectivity also enables re-cycling of emitted photons [64,82].
Chapter 6
Summary and future directions

6.1 Summary
All renewable energy sources have the potential to play an important part in our efforts to reduce carbon emissions and minimize the deleterious effects of global warming. Solar energy in particular is of critical importance due to its abundance. Within solar energy technologies, CSP has the advantage of being easily paired with inexpensive thermal energy storage, and for this reason it looks to be increasingly significant as intermittent renewable energy technologies gain wider deployment. Thus, the continued investigation of CSP systems and methods to improve their performance are imperative.

Two methods which can be used to improve CSP receiver performance are spectral and directional selectivity, which were both explored in this thesis. With spectral selectivity, a CSP receiver is designed to only absorb solar wavelengths. If a receiver only absorbs solar wavelengths, it will not emit at longer wavelengths, which can significantly reduce the radiative losses from the receiver when it operates at elevated temperatures. In directional selectivity, a solar receiver is designed to only absorb incident radiation near normal to the absorber surface. If the receiver is pointed towards the sun, all incident sunlight can still be absorbed, but losses which would be emitted towards non-normal directions are suppressed, which reduces the overall radiative losses from the receiver.

This thesis investigated the limit of performance enhancement capable when using spectral and directional selectivity, with the corresponding results reported in chapter 2. The Kramers-Kronig approach used to investigate spectral selectivity offers a valuable way to probe the potential for improvement in different systems. In this thesis, the system considered was a passive, intrinsic absorber with no further constraints applied. Analysis showed that the achievable performance for CSP systems with such an absorber is very close to the performance achieved by a step function spectrally selective absorber, with the exception of operating at high temperatures under low solar concentrations. A geometric approach for determining the maximum performance of directional selectivity, as well as its theoretical equivalence to concentration, was also reported in chapter 2.

Spectral selectivity is already commonly used in commercial CSP plants through the use of spectrally selective absorber surfaces, but there is still room for further improvement of CSP systems using spectral selectivity. While spectrally selective absorbers are commonly seen in CSP systems, spectrally selective transmitters are a less explored concept. Silica aerogel is one such spectrally selective transmitter, and due to its low thermal conductivity owing to its nanoporous structure, it has a number of potential applications...
in solar thermal systems. Two such systems were investigated using simulations in this thesis, covered in chapter 3: the Solar Thermal Aerogel Receiver (STAR), an alternative to vacuum tube receivers for CSP systems, and the Hybrid Electric And Thermal Solar (HEATS) receiver, which converts incident solar radiation to both heat and electricity. Simulation results show that both aerogel based receivers could achieve high efficiencies, and warrant further investigation. The thesis additionally included the characterization of a STAR prototype, covered in chapter 4. Initial results from the STAR receiver prototype are promising, however significant characterization and design work remains before it could be convincingly claimed that STAR could outperform existing CSP receiver technologies in the field.

Directional selectivity is another strategy for improving solar receiver performance, which industry has much less expertise in than directional selectivity. From the theoretical study of directional selectivity, it is clear that there is a good opportunity to improve overall system performance by using directional selectivity to rely less heavily on concentration, since directionally selective absorbers do not suffer from the optical losses associated with concentrating optics. Strategies for directional selectivity which do not require concentration thus have the potential to significantly improve CSP receivers. Of course, many strategies for directional selectivity (including the reflective cavity explored in chapter 5) would still need to use concentration. In these cases, opportunities for improvement with directional selectivity exist for systems with concentration that do not use an input angle close to 90°, since there will be a wide range of emission angles for which radiation losses can be suppressed.

6.2 Future directions

While this thesis sought to explore the potential for improvement of solar receivers through spectral and directional selectivity, it by no means closed the book on either technique. If anything, the work presented opens up more questions and possibilities for spectral and directional selectivity. On the spectral selectivity front, future work could apply the Kramers-Kronig approach to systems beyond passive, intrinsic absorbers with more constraints considered. Very few researchers are pursuing intrinsic absorbers for spectral selectivity, and for those who are, unprecedented material control would be required to begin to approximate the reflectance profiles given in chapter 2. If the Kramers-Kronig approach was integrated with other models for materials’ response to electric fields (such as Drude-Lorentz), it could serve as a much more practical tool for guiding the design of real absorbers. Considering multi-layer absorbers adds another degree of freedom, so with only the passive constraint, it should be possible to improve the near perfect profiles of an intrinsic absorber to an essentially perfect profile. Further work would be needed to determine whether multi-layer structures with additional constraints (e.g., using Drude-Lorentz rather than arbitrary indices of refraction) would lead to better or worse performance than the passive, intrinsic absorbers explored in this thesis. Even within the material
system considered for the Kramers-Kronig approach in this thesis, analysis should be extended to consider the angular dependence of the proposed absorbers, as they were optimized for normal incidence, but concentrated solar radiation will not be entirely normally incident.

Additionally, there is still significant work that can be done on silica aerogel as a spectrally selective transmitter for solar applications. In addition to the continued testing we plan to perform on the STAR prototype setup, there is room for further material development, pushing the aerogel to be even more transparent by making the aerogel pores smaller and more uniform and more thermally insulating by increasing absorption at infrared wavelengths. There is also the hurdle of improving the mechanical properties of silica aerogel, which were not addressed in this thesis, but are critically important for many potential applications. Beyond material science and chemistry related to the intrinsic properties of silica aerogel, design work could lead to novel devices and better performance.

One potential aerogel application which is close to the STAR explored in this thesis is using aerogel in a tubular geometry, essentially replacing the vacuum in a traditional vacuum tube receiver with aerogel. Such a receiver would be optically more appropriate for the industry standard parabolic trough collector concentrating optics, but would have potential advantages in reliability and cost since it would not require vacuum. In pursuing such a design, there are many questions which would need to be explored: would aerogel need to surround the entire tube, or would it be beneficial to cover the top of the tube (which sees little incident radiation) with conventional, opaque insulation? How precisely shaped would the curved aerogel panes need to be, i.e., how close would the aerogel need to be to the absorber pipe and glass tube? What would the most cost effective method for manufacturing curved aerogel panes be, would they need to be cast as curved monoliths or could aerogel be slumped? Using aerogel in a tubular receiver is only one example of what could be possible with transparent aerogel. The combined properties of high optical transparency, low thermal conductivity, and low density should enable more technologies than just STAR and HEATS which have been described in this thesis.

Directional selectivity is worth focusing further effort on in the future, as there have been limited studies into integrating directional selectivity into CSP systems. The most straightforward extension of work presented in this thesis would be exploring ways to integrate the reflective cavity considered in chapter 5 into point-focus CSP systems. Power tower systems typically have acceptance angles reasonably far below 90°, as large incidence angles correspond to heliostats at a further distance operating at a lower optical efficiency. Thus, there is an opportunity to reduce radiation losses of power tower systems by reflecting back losses that are not directed towards heliostats.
Solar energy conversion systems are key to a renewable energy future, and there is still significant room for improvement to existing systems in terms of both efficiency and cost. Further effort into improving solar energy systems has the potential to yield valuable dividends, and spectral and directional selectivity are both valid approaches to achieving improved performance.
Appendix A: Strengths and weaknesses of STAR components

While many parts of the experimental setup for measuring STAR performance were custom fabrications, many components were ordered directly from a manufacturer. The following table lists these components, their source, and the strengths and weaknesses of the piece of equipment. This info is provided as it should be useful when assessing the possibility of future improvements to the system or if another research team is designing a similar system.

Table 2 Info on manufacturer ordered components of STAR experimental test setup

<table>
<thead>
<tr>
<th>Component</th>
<th>Manufacturer &amp; Model</th>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Packaged pump and heater system</td>
<td>Chromalox CLS-750A-9XX</td>
<td>Rated to max intended operating temperature and pressure (400 °C and 200 psi). System was relatively “plug and play”</td>
<td>Heater (9 kW) was not sufficient to bring heat transfer fluid to 400 °C, even with no thermal load. This is primarily due to cooling load of pump, which is significantly oversized for our application.</td>
</tr>
<tr>
<td>Flow meter</td>
<td>Krohne Optimass 6400</td>
<td>Rated to max intended operating temperature and pressure (400 °C and 200 psi).</td>
<td>Large noise in signal made measurements for low flow rates (&lt;2 gpm) unreliable.</td>
</tr>
<tr>
<td>VOC detector</td>
<td>Aeroqual AQ S-500</td>
<td>High sensitivity to volatile organic compounds, inexpensive</td>
<td>No significant weaknesses</td>
</tr>
<tr>
<td>Motor (for LFR)</td>
<td>Oriental Motor AZ66AAD-HS100-3</td>
<td>Relatively “plug and play,” high resolution, inexpensive</td>
<td>No significant weaknesses</td>
</tr>
<tr>
<td>Reflector panels</td>
<td>Reflective Concepts, Inc.</td>
<td>Maintain reasonable specular reflectivity with outdoor use, inexpensive</td>
<td>Fabrication tolerances were not sufficient to achieve precise focal lengths. Torsional stiffness of panels (as designed) was not sufficient to prevent torsional bending.</td>
</tr>
<tr>
<td>Two axis tracker (for pyrheliometer)</td>
<td>iOptron AZ Mount Pro GoTo Alt-Az</td>
<td>Inexpensive, “plug and play”</td>
<td>No significant weaknesses</td>
</tr>
<tr>
<td>Pyrheliometer</td>
<td>Kipp &amp; Zonen CHP 1</td>
<td>High resolution</td>
<td>No significant weaknesses</td>
</tr>
</tbody>
</table>
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