SPECTRAL INVESTIGATION OF SOLAR ENERGY ABSORPTION AND LIGHT TRANSMITTANCE IN A WATER/NANOFUID-FILLED PRISMATIC GLASS LOUVER

By

Yaomin Cai

A dissertation submitted to the School of Graduate Studies Rutgers, The State University of New Jersey

In partial fulfillment of the requirements For the degree of Doctor of Philosophy

Graduate Program in Mechanical and Aerospace Engineering

Written under the direction of Zhixiong Guo

And approved by

_____________________________________  
_____________________________________  
_____________________________________  
_____________________________________  

New Brunswick, New Jersey

October 2021
ABSTRACT OF THE DISSERTATION

SPECTRAL INVESTIGATION OF SOLAR ENERGY ABSORPTION AND LIGHT TRANSMITTANCE IN A WATER/NANOFLUID-FILLED PRISMATIC GLASS LOUVER

by Yaomin Cai

Dissertation Director:
Zhixiong Guo

The energy demand is vastly increasing recently due to population and economic growth, particularly in some fast-developing countries. Also, the enormous consumption of fossil fuels, such as coal, petroleum, and natural gas, produces much more greenhouse gas emissions, especially for carbon dioxide, than decades ago, which contributes a lot to global warming. In order to better solve these issues, the dissertation studies the radiation heat transfer in a new energy-saving device: a water-filled or nanofluid-filled prismatic louver, which can transmit sufficient visible solar light for natural illumination and harvest the most solar energy.

The Ni-water nanofluid-filled prismatic glass louver was proposed to save energy consumptions in buildings since such innovative louvers can absorb the most solar energy,
as well as improve daylighting quality rather than “block” visible sunlight, compared with traditional louvers or windows. To achieve this innovative technology, the effectiveness of ultraviolet (UV) and infrared (IR) energy harvest and visible (VIS) light transmittance was investigated. The Monte Carlo ray tracing model was developed to simulate the collimated (direct) and diffuse solar radiation through the prismatic glass louver for solar energy harvesting and improved daylighting. Computational efficiency and accuracy were examined through intensive comparisons of different band partition approaches, various photon numbers, and element divisions. The influence of irradiation direction on solar energy harvest efficiency was scrutinized. Absorption and transmittance in UV, VIS, and IR band regimes as well as in filling liquid and glass were differentiated and compared, respectively. The 7-band spectral model for glass and water/Ni-water nanofluid was evaluated and adopted for several cases of solar spectra of air mass (AM) 1.0, AM1.5, AM2.0, and AM3.0 with both direct and diffuse irradiation. It also investigated the absorption and scattering efficiencies of nanoparticles (NPs) commonly used in solar energy research, including Ni, SiO$_2$, Fe$_2$O$_3$, Al$_2$O$_3$, TiO$_2$ and ZnO; and we found that Ni NPs are the most desirable due to an excellent balance between UV and IR absorption and VIS transmission. Then the influences of Ni NPs with different diameters and volume concentrations were analyzed. A dilute 0.00004 vol% Ni-water nanofluid with 80 nm diameter particles was found to absorb more solar energy and provide sufficient VIS for daylighting. A glass louver filled with such a Ni-nanofluid can transmit 46.5% solar VIS for daylighting and harvest 65.7% of the total solar energy under the AM1.5 model, which increases 25.9% as compared to pure water.
Acknowledgements

On the journey to my Ph.D. degree, there are many I would like to acknowledge, who helped me and contributed to this research in one form or another. First and foremost, I would like to thank my Ph.D. advisor, Dr. Zhixiong Guo, with my deepest sincere gratitude, whose ideas and characteristics that lead me to the world of being a scientist. Words cannot express how grateful I feel to have him as my mentor, guidance, and friend, offering me countless help and enlightening discussions not just on this research but also on my personal growth in professional development. His passion for extremely excellence in science and engineering research always inspires me. In fact, I have never met someone like him, who can answer all questions of my research and spark novel ideas.

Secondly, I would like to thank other committee members, Dr. Prosenjit Bagchi, Dr. Yuebin Guo, and Dr. Nicholas Madamopoulos, for their professional comments and suggestions. Much gratitude also goes to all professors and staff members in the MAE department. Moreover, I also would like to extend my thanks to group members: Haoxiang Cao, Xu Huang, Yi Nan, Yihua Hao, Jue Min, Hang Zhang, Nai-Jei Tang, Fengyi Ren, Dr. Zhangmao Hu, Dr. Yasong Sun, Dr. Richardo Diaz, and Dr. Matthew Frenkel. In addition, I would like to express my thanks to the project collaborator Dr. Nicholas Madamopoulos and his graduate student Mr. Michael Alva at CCNY for their help during my research work, especially for providing me Fig. 1.5. In the meantime, I appreciate Dr. Sergey Kuznetsov and Dr. Brian Labombard during my internship at Commonwealth Fusion System (CFS) and MIT for mentorship and sharing expertise in
thermal stress multiphysics modeling. I appreciate the help from Dr. Ruoqian Wang during my last semester at Rutgers. I would also thank all of my true friends at Rutgers: Chaoke Guo, Zheyuan Ji, Xiaoran Chen, Haidong Gu, Jian Zhou, Gaurav Misra, etc. I will remember all your comforting words and encouragements eternally.

Finally, I would like to appreciate the warmest encouragement and continual love from my family: thanks go to all family members, especially for Dr. Niannian Cai, who is a diligent and intelligent big brother and always encourages me to chase my dreams; importantly, without the support and encouragement from my dad and mom, I can barely reach here. Also, the most profound love goes to my wife, Xuanye. We have been together for more than eight years, from China to the USA. No matter how hard the life is, she always backs me up.

This material is based upon work supported by the National Science Foundation under Grant No. ECCS-1505706.
# Table of Contents

ABSTRACT OF THE DISSERTATION ................................................................. ii  
Acknowledgements ...................................................................................... iv  
Table of Contents .......................................................................................... vi  
List of Tables ................................................................................................. viii  
List of Figures ............................................................................................... ix  
List of Illustrations ....................................................................................... xi  

CHAPTER 1 INTRODUCTION .............................................................................. 1  
1.1 Background and literature review ............................................................. 1  
1.2 Objectives .................................................................................................. 17  
1.3 Survey of the Dissertation ....................................................................... 18  

CHAPTER 2 SIMULATION MODELS ................................................................. 20  
2.1 Radiative transfer equation (RTE) ............................................................. 20  
2.2 Mie scattering theory .............................................................................. 22  
2.3 Mathematical model ................................................................................ 25  
2.4 Simulation method of collimated light ..................................................... 28  
2.5 Simulation method for diffuse light ......................................................... 34  
2.6 Validation ................................................................................................. 37  

CHAPTER 3 SPECTRAL MONTE CARLO SIMULATION OF COLLIMATED SOLAR IRRADIATION TRANSFER IN A WATER-FILLED PRISMATIC LOUVER ........... 41  
3.1 Introduction ............................................................................................. 41  
3.2 Simulation Method .................................................................................. 44  
3.3 Results and discussion ........................................................................... 48  
3.4 Conclusions ............................................................................................ 60  

CHAPTER 4 SPECTRAL INVESTIGATION OF SOLAR ENERGY ABSORPTION AND LIGHT TRANSMITTANCE IN A WATER-FILLED PRISMATIC GLASS LOUVER .......... 62  
4.1 Introduction ............................................................................................. 63  
4.2 Simulation model .................................................................................... 65  
4.2.1 Absorption efficiency ....................................................................... 65  
4.2.2 Band-averaging method .................................................................... 66  
4.3 Results and discussion ........................................................................... 67  
4.3.1 Validity of the 7-band model ............................................................ 67  
4.3.2 Absorption/transmittance efficiency ............................................... 72  
4.3.3 Effect of air mass spectrum .............................................................. 79  
4.3.4 Proof-of-concept study ..................................................................... 84
List of Tables

Table 3-1 Spectral optical properties of different band models .......................................................... 46
Table 3-2 The CPU times .................................................................................................................... 49
Table 4-1 CPU times .......................................................................................................................... 68
Table 4-2 Spectral properties of material in the 7-band model for AM1.0 to AM3.0 spectra. (D/C = Diffuse/Collimated) ......................................................................................................................... 80
Table 4-3 Spectral properties of material for the three selected locations. a ...................................... 85
Table 5-1 Spectral properties of material in the 7-band model for different particle sizes at 0.00004 vol% concentration. (Df/C = Diffuse/Collimated) ................................................................. 104
Table 5-2 Spectral properties of material in the 7-band model for different particle volume concentration at diameter of 80 nm nickel particle. (Df/C = Diffuse/Collimated) .... 106
Table 5-3 Required VIS transmittance in different AM models with desired lumen .................... 108
Table 5-4 Comparisons between water-filled and Ni-water (D=80 nm) nanofluid-filled louvers ......................................................................................................................................................... 116
List of Figures

Figure 1.1 U.S. primary energy consumption by energy source, 2019 (https://www.eia.gov/energyexplained/renewable-sources/). ........................................ 2

Figure 1.2 Schematic diagrams of concentrating solar power with different types of collectors: a) parabolic trough; b) disk/engine; c) linear Fresnel; and d) heliostats and central receiver [2].................................................. 4

Figure 1.3 Schematic diagram of PV generating the DC [7].......................................................... 5

Figure 1.4 Total site energy consumption [11].......................................................... 6

Figure 1.5 Schematic diagram of the novel prismatic louvers: a) single louver; and b) cascade louvers. (Acknowledgement: Dr. Nicholas Madamopoulos and Mr. Michael Alva provided the photos) ........................................................................................................ 7

Figure 1.6 Solar spectral irradiance within different #AM at different wavelengths (https://en.wikipedia.org/wiki/Simple_Model_of_the_Atmospheric_Radiative_Transf er_of_Sunshine#/media/File:Simulated_direct_irradiance_spectra_for_air_mass=0_to _10_with_SMARTS_2.9.5.png) .................................................................................. 11

Figure 1.7 Schematic diagram of direct and diffuse solar radiation [30]................................. 14

Figure 1.8 Schematic diagram of solar tilt angle and azimuth angle (https://www.13kuga.com.au/solar-panel-orientation-vs-production/). ........................................ 15

Figure 1.9 Applications of nanofluids [36].................................................................................. 16

Figure 2.1 Schematics of coordinate system [47].......................................................... 22

Figure 2.2 Comparison of Monte Carlo and conventional solution techniques [48]............... 26

Figure 2.3 A) sketch of the louver cross section with collimated solar irradiation from the top; and b) a representative nodes division........................................................................ 29

Figure 2.4 Flowchart for photon tracing .................................................................................. 32

Figure 2.5 Sketch of louver cross-section with direct and diffuse irradiation. ....................... 35

Figure 2.6 Comparison between Beer’s law results and MC results for absorption/transmittance efficiencies at seven points along X direction......................................................... 39

Figure 3.1 Normalized energy harvest along the centerline: a) for different photon numbers; b) for different element numbers; c) for different band numbers ........................................ 51

Figure 3.2 Solar energy absorption efficiency vs. elements division........................................ 52

Figure 3.3 Contours of the normalized energy harvest (m⁻¹) for different divisions............... 53

Figure 3.4 Solar energy absorption efficiency vs. band division.............................................. 54

Figure 3.5 Contours of normalized energy harvest (m⁻¹) with different bands ...................... 55

Figure 3.6 Normalized energy harvest (m⁻¹) for different incident angles ............................. 56

Figure 3.7 Effect of incident angle on solar energy absorption efficiency ................................ 57
Figure 3.8 Solar energy absorption efficiencies in three distinct spectra with incident polar angle of 0°, 15°, 30°, 45°, 60° and 75°, respectively.................................59
Figure 4.1 Normalized diffuse solar energy harvest along the louver centreline (x=y=0) for different band models..........................................................70
Figure 4.2 Diffuse solar energy absorption and transmittance efficiencies vs. band division......71
Figure 4.3 Contours of normalized diffuse solar energy harvest (m⁻¹) for different spectral models. .............................................................................................72
Figure 4.4 Solar energy absorption/transmittance efficiencies in three distinct spectra for both diffuse and direct irradiation....................................................74
Figure 4.5 Solar energy absorption/transmittance efficiencies vs. diffuse ratio. ..................76
Figure 4.6 Effects of incident angle of the collimated irradiation on solar energy absorption and VIS transmittance: a) polar angle; and b) circumferential angle. ............78
Figure 4.7 Effects of air mass spectrum on solar energy absorption and transmittance in UV, VIS, and IR regions, respectively. .................................................................82
Figure 4.8 Solar energy absorption efficiency and VIS transmittance vs. air mass coefficient..83
Figure 4.9 Spectral solar irradiances at Flagstaff, Golden and Phoenix during summer time.....85
Figure 4.10 Absorption/transmittance efficiencies in three places with practical solar data. .....87
Figure 5.1 Sketch of nanofluid-filled louver cross-section with direct and diffuse irradiation....95
Figure 5.2 AM1.5 spectral solar irradiances [15] and water spectral absorption coefficient. ...98
Figure 5.3 Spectral efficiency factors for different NPs: a) absorption; and b) isotropic-scaled scattering..........................................................100
Figure 5.4 Spectral absorption/scaled isotropic scattering efficiency factor for different Ni NP diameters.........................................................................................101
Figure 5.5 Spectral asymmetry factor for different Ni NP diameters..................................102
Figure 5.6 Comparison of spectral absorption/scattering coefficients of Ni-water nanofluids for different particle sizes.................................................................104
Figure 5.7 Comparison of spectral absorption/scattering coefficients of Ni-water nanofluids for different NP concentrations.........................................................106
Figure 5.8 Effect of particle size on solar energy absorption and transmittance efficiencies.....110
Figure 5.9 Contours of normalized solar energy harvest (m⁻¹) with different Ni NP diameters: a) 20nm; b) 40 nm; and c) 80nm...............................................................111
Figure 5.10 Effect of Ni NP diameters on solar energy absorption and transmittance efficiencies in different spectra.................................................................112
Figure 5.11 Solar energy absorption efficiency and VIS transmittance vs. Ni NP concentrations. ........................................................................................................113
Figure 5.12 Absorption and transmittance efficiencies in three distinct spectra for three different Ni NP volume concentrations.......................................................114
Figure 5.13 Solar energy absorption and transmittance efficiencies in three distinct spectra for direct and diffuse irradiation, respectively. ........................................115
List of Illustrations

\( a_n, b_n \) \hspace{1cm} \text{Mie scattering coefficients}

\( D \) \hspace{1cm} \text{Diameter, m}

\( E \) \hspace{1cm} \text{Solar heat flux, W/m}^2

\( g \) \hspace{1cm} \text{Asymmetry factor}

\( H \) \hspace{1cm} \text{Height, m}

\( I \) \hspace{1cm} \text{Intensity, W/m}^2

\( L \) \hspace{1cm} \text{Photon flight distance, m}

\( N \) \hspace{1cm} \text{Number of photons absorbed in an element}

\( k \) \hspace{1cm} \text{Absorptive index}

\( m \) \hspace{1cm} \text{Complex refractive index}

\( N_p \) \hspace{1cm} \text{Particle number per unit volume, m}^{-3}

\( n \) \hspace{1cm} \text{Refractive index}

\( \bar{n} \) \hspace{1cm} \text{Normal direction outward a surface}

\( N_{RAY} \) \hspace{1cm} \text{Number of total emission photons}

\( P_n \) \hspace{1cm} \text{Legendre polynomials}

\( Ph \) \hspace{1cm} \text{Possible hitting parameter}

\( P \) \hspace{1cm} \text{Optical property in a discrete band}

\( Q \) \hspace{1cm} \text{Efficiency factor}

\( Q' \) \hspace{1cm} \text{Normalized energy harvest, m}^{-1}

\( R \) \hspace{1cm} \text{Random number}

\( rd \) \hspace{1cm} \text{Diffuse component ratio}
\( \vec{r} \)  Ray vector

\( S \)  Cross-sectional area of an element, \( m^2 \)

\( q_{\text{tum}} \)  Luminous flux, lm

\( q_{d\nu} \)  VIS power, W/m\(^2\)

\( V_p \)  Particle volume concentration

\( W \)  Width, m

\( w \)  Weight factor

\( X, Y, Z \)  Coordinates

\( x \)  Size parameter

**Greek symbols**

\( \alpha \)  Absorption coefficient, \( m^{-1} \)

\( \beta \)  Extinction coefficient, \( m^{-1} \)

\( \epsilon \)  Solar energy absorption efficiency

\( \eta_m \)  Required VIS transmittance

\( \theta \)  Angle, degree

\( \lambda \)  Wavelength, nm

\( \varphi \)  Circumferential angle, degree

\( \rho \)  Reflectivity

\( \sigma_s \)  Scattering coefficient, \( m^{-1} \)

\( \omega \)  Scattering albedo

\( \tau \)  Thickness, m

\( \phi \)  Scattering phase function

\( \psi_n, \xi_n \)  Riccati-Bessel functions
\( \Omega \)  
Solid angle, sr

\textit{Subscripts}

0  
Initial condition

A  
Refraction

abs  
Absorption

c  
Collimated

cr  
Critical

d  
Diffuse

i  
Surface index

in  
Incoming direction

k  
Element index

l  
Reflection

f  
Base fluid

nf  
Nanofluid

p  
Particle

r  
Refraction

sca  
Scattering

\( \lambda \)  
Spectral
CHAPTER 1

INTRODUCTION

1.1 Background and literature review

Wood was nearly the only source of a country’s energy needs for heating, cooking, and lighting until 1800’s. After that, fossil fuels, for example, coal, petroleum, and natural gas, have been the majority consumption sources of energy both industrially and commercially. However, renewable energy such as biofuels, geothermal energy, solar energy, and wind energy increased tremendously in the recent 20 years. Particularly, the combined percentage share of these renewable energy sources was greater than the combined share of wood and hydro energy in 2019. The consumption of renewable energy sources, including biofuels, geothermal, solar, and wind energy in 2019 was almost three times greater than in 2000 in the United States, which made up more than 18 percent of net U.S. electricity generation for the first 10 months of 2019, while they were only accounted for 10% back to 2010 [1].
Figure 1.1 U.S. primary energy consumption by energy source, 2019 (https://www.eia.gov/energyexplained/renewable-sources/).

As Fig. 1 shows, in 2019, renewable energy provided about 11.5 quadrillion British thermal units (Btu), which equals to 11.4% of total U.S. energy consumption. This is a milestone as it is the first time that renewable energy consumption is greater than coal consumption. Around 17% of total U.S. electricity was generated from renewable energy sources [1].

Recently, climate change leads to a large number of natural disasters such as droughts, floods, fires, hurricanes, etc., putting all living creatures, including human beings in danger. Renewable energy plays an important role in solving the climate change and global warming problem, typically for reducing greenhouse gas emissions. Using renewable energy can decrease fossil fuels utilization, which is the largest source of U.S. carbon dioxide emissions. The U.S. Energy Information Administration (EIA) projected that U.S. renewable energy consumption would keep increasing through 2050.
Simultaneously, solar power generation (including distributed solar power) is projected to climb from 11% of total U.S. renewable generation in 2017 to 48% by 2050, making it the fastest growing electricity source (https://www.c2es.org/content/renewable-energy/).

Concentrated Solar Power (CSP) and Photovoltaic (PV) systems are two prevalent solar energy technologies. CSP technologies basically concentrate solar radiation to heat a substance first and then apply it to drive a heat engine or electric generator. One vital advantage of CSP systems is that they are capable of storing solar energy through Thermal Energy Storage technologies (TES). The TES can utilize the stored energy under low or no solar light scenarios. Thus, CSP systems are extremely attractive and becoming much more popular, especially for large-scale power generation, since TES are far more efficient than traditional electricity storage technologies. Besides, CSP technologies incorporated with TES can enhance financial performance and dispatch the ability to generate solar power and flexibility in the regular power network. Fig. 1.2 shows some populous CSP technologies [2]. Also, there are some remarkable researches [3-6] discussing the progress of CSP technologies.
Figure 1.2 Schematic diagrams of concentrating solar power with different types of collectors: a) parabolic trough; b) disk/engine; c) linear Fresnel; and d) heliostats and central receiver [2].

In addition to CSP, Photovoltaic (PV) solar panels are another promising solar technology. Their schematics are different from CSP because they utilize solar light through the “PV effect” to generate direct electric current (DC), shown in Fig.3 [7], instead of heating to generate electricity. One disadvantage of PV systems is that they produce electricity instantly; however, unlike the TES technologies, the electricity cannot be stored easily. For a small-scale power level, most electricity is commonly storing by batteries. But it is meaningless and pretty costly to use them at large power levels. On the other hand, the advantages of PV systems are that they can be built more quickly, easily,
and cheaper than CSP plants. It is reported that PV panels have a 30%-40% price drop in the past decades and will continue dropping in a long term due to the new materials, innovative designs, and advanced manufacturing processes. According to market data and research, a total capacity of approximately 3 GW has been converted from CSP to PV solar plants in the US. Some of these conversions include the 500 MW project of Solar trust & Solar Millennium, and the 709 MW, 850 MW projects of Tessera-SES (www.morguefile.com/creative/mzacha). There are plenty of pioneers working on this topic, and some researchers give comprehensive reviews on this topic [8-10].

Figure 1.3 Schematic diagram of PV generating the DC [7].
In this dissertation, we consider a third way using solar energy: improve the natural illumination and store the solar-thermal energy. There is a desperate need for green energy, and next-generation net-zero energy buildings. The U.S. Department of Energy [11] calculates that the existing building stock in the United States accounts for about 41% of national energy consumption. About 58% is used for lighting and space heating, shown in Fig. 1.4, making the building sector the largest energy consumer. Abundant solar energy can provide natural lighting as well as heating; thus, well-utilized solar energy will lead to energy savings. At present, the majority of green facilities utilize solar energy performs either for heating or power generation, making use of only several certain bands of solar irradiation. Most often seen examples are solar water heaters, solar PV systems, and CSP plants. It is needed to develop new technologies to take full advantage of the whole solar spectrum energy.

![Figure 1.4 Total site energy consumption [11].](image)
Dr. Madamopoulos at City College of New York initially proposed a prismatic louver to improve daylighting quality [12, 13]. Later on, he and my advisor Dr. Guo proposed a nanofluid-filled hollow prismatic louver for improved daylighting and enhanced solar energy harvesting [14]. The physical louvers can be shown in Fig. 1.5.

Figure 1.5 Schematic diagram of the novel prismatic louvers: a) single louver; and b) cascade louvers without any liquid. (Acknowledgement: Dr. Nicholas Madamopoulos and Mr. Michael Alva provided the photos)
The concept of the proposed glass louver (Fig. 1.5) in a glazing system is based on a prism’s ability to deviate incident light. The collimated solar irradiation will be redirected by the louver to ceiling and reflected diffusely to room space for illumination. This will eliminate the “glare effect”, improve natural lighting quality, and increase occupants’ comfort. The concern of “rainbow effect” in an individual louver, because of material dispersion to different colors of light, can be minimized by installing many louvers in a stacked configuration in practical applications. Furthermore, multiple-reflection of light inside the louver will also lessen the dispersion effect. Enhanced daylight has the potential to reduce energy consumption due to artificial lighting for both residential and commercial buildings. On the other side, the water/nanofluid flowing inside the hollow louver will absorb solar energy. The harvested solar energy may be used to replace water heaters or stored for other purposes.

Solar irradiance received from the sun by the form of electromagnetic waves as reported in the wavelength range of the measuring instrument (https://en.wikipedia.org/wiki/Solar_irradiance). With solar radiation passing through the Earth’s atmosphere, it is attenuated gradually by scattering and absorption effects; the more solar light passes through the atmosphere, the more substantial attenuation becomes. Chemical materials interact with the solar light and then absorb some wavelengths so that they alter the percentage of short-wavelength light reaching the Earth as the solar light travels through the atmosphere. Water vapor, which leads to different absorption bands at a variety of wavelengths, makes this process more appealing, while molecular nitrogen, oxygen, carbon dioxide, and some other chemicals are added to this process. The solar
spectrum is strongly confined between the IR and UV by the time sunlight reaches the Earth’s surface.

The solar spectrum spans a wide range from 100 nm to 1 mm. In terms of the significance of energy, sunlight at Earth’s surface is around 52~55% infrared (IR) (above 700 nm), 42~43% visible (VIS) (400 to 700 nm), and 3~5% ultraviolet (UV) (below 400 nm) calculated from reference air mass (AM) 1.5 spectra [15]. The air mass coefficient defines the direct optical path length through the Earth's atmosphere, expressed as a ratio relative to the path length vertically upwards, i.e., at the zenith. The air mass coefficient can be used to help characterize the solar spectrum after solar radiation travels through the atmosphere (https://en.wikipedia.org/wiki/Air_mass_(solar_energy)). Countries and areas, such as Europe, China, Japan, United States, and others, with the world’s large population, refer to AM1.5. “AM1.5” corresponds to a solar zenith angle of 48.2°. For the summertime, AM number for these areas during the middle parts of the day is less than 1.5. However, higher figures apply in the morning, evening, or at other times of the year. Therefore, AM1.5 can well represent the overall yearly average for these areas. AM1.5 has been selected for standardization purposes through an analysis of solar irradiance data in the United States [16]. Since then, the solar industry in the USA has been accepted AM1.5 for all standardized testing. The latest AM1.5 standards pertaining to photovoltaic applications are the ASTM G-173[15], derived from simulations obtained with the Simple Model of the Atmospheric Radiative Transfer of Sunshine (SMARTS) code.

SMARTS is known as a spectral model, which is programmed by Fortran to predict the direct, diffuse, and global irradiance incident on surfaces of any geometry at the
Earth’s surface [17]. It covers the entire shortwave solar spectrum (280 to 4,000 nm), including the UV, VIS, and IR bands. Besides the regular irradiance predictions needed for many possible applications, and can be used to simulate the spectral or broadband irradiance that would be measured by a radiometer. In addition, it can also predict the photosynthetically active components of radiation, the illuminance, the luminous efficacy of direct, diffuse, and global radiation, as well as various other weighted spectra [18]. In this dissertation, AM1.0, AM1.5, AM2.0, and AM3.0 spectral solar irradiance data are derived from the SMARTS code.

The solar spectrum outside the Earth is referred to as AM0.0, meaning “zero atmosphere”. Space appliances, for example, solar PVs installed for space power generations, are typically characterized as AM0.0. The solar irradiance travels directly to sea level after passing through the atmosphere is referred to AM1.0. This means “one atmosphere”. AM1.0 to AM1.1 is a valuable range for calculating the performance of solar applications in tropical areas. Moreover, AM2.0 and AM3.0 are two essential spectra for estimating the solar applications, which is installed at high latitude regions, such as in Canada, Russia, or northern Europe. Simultaneously, AM2.0 to AM3.0 can represent the solar irradiance in temperate latitudes. Nevertheless, different AM models have different spectra shown as Fig. 1.6.
Figure 1.6 Solar spectral irradiance within different AM at different wavelengths (https://en.wikipedia.org/wiki/Simple_Model_of_the_Atmospheric_Radiative_Transfer_of_Sunshine#/media/File:Simulated_direct_irradiance_spectra_for_air_mass=0_to_10_with_SMARTS_2.9.5.png).

The optical properties of the solar devices, such as absorption coefficients, scattering coefficients, refractive index, etc., are highly spectral dependent. Line-by-line spectral calculations are extremely time-demanding even with deterministic methods, not to mention for time-consuming MC methods. Therefore, it is crucial to consider band-average techniques based on the significance and difference of various bands. Many researchers spent a lot of efforts in finding appropriate solar spectra bands divisions: CLIRAD-SW is a radiative transfer model which is developed by NASA to estimate the clear sky solar irradiance [19]. CLIRAD-SW is a calculation-efficient radiation scheme for application within general circulation models. The model also requires a 1-
dimensional model and the following input variables: the solar irradiance, water vapor, liquid water, ice, aerosols, vertical profiles of temperature, carbon dioxide, and methane. CLIRAD-SW model splits the solar radiation into eight spectral bands: UV (bands 1 to 4), VIS (band 5), and IR (bands 6 to 8). Every single band interacts with different chemical components suspended in the atmosphere through absorption and scattering effects; for example, UV absorbs ozone, VIS, and IR absorb water vapor and IR absorbs carbon dioxide. Besides this, Molina et al. [20] established a solar radiation database for Chile. Yolalmaz et al. [21] managed to spectrally split solar light into two separate bands between 400 nm - 700 nm and 701 nm - 1100 nm. Meftah et al. [22] analyzed the solar irradiance from 165 nm to 400 nm in 2008 and UV variation in three spectral bands during solar cycle 24. Significantly, Cai and Guo [23] divided the full solar spectra into 1, 3, 7, 20, 40 band models and found that the 7-band model can achieve computational efficiency and accuracy. The detailed spectral research analysis of Cai and Guo can be found in chapter 3.

The sunlight consists of collimated (direct) sunlight, which refers to the fixed angle projection, and the diffuse sunlight irradiation, which refers to the random angle projection, schematically shown in Fig. 1.7. Diffuse sky radiation is solar radiation reaching the Earth's surface after having been scattered from the direct solar beam by chemical components in the atmosphere. The dominant solar radiative scattering processes in the atmosphere are Rayleigh scattering and Mie scattering; they are elastic, which means that a photon of solar light can be deviated from its own flight path instead of being absorbed or changing wavelength. Jiang et al. [24] evaluated the total, direct, and diffuse solar radiations from the ERA5 reanalysis data in China. Rusen et al. [25] did
a quality control of diffuse solar radiation component with satellite-based estimation methods. The critical point of the research is to provide accurate global and diffuse radiation data and thus to improve the efficiency of the solar energy system. Kafka et al. [26] implemented a climatology of solar irradiance and its control across the United States and provided the guidance of the solar panel orientation. They pointed out that the ratio of diffuse to direct radiation is exceptionally high across the eastern U.S. Therefore, it is vital for the solar industry to pay attention to the diffuse component harvesting in the east of the U.S. Also, with the advent of artificial intelligence and big data, some researchers realize predicting the direct and diffuse solar radiation through computer modeling, such as Fan et al. [27], Benali et al. [28], and Kurniawan et al. [29], to name a few.
Two angles in the solar industry are necessary to clarify: tilt/elevation angle and azimuth angle, in reference to solar energy systems, shown as Fig. 1.8. The tilt angle is the vertical tilt of the solar device, and the azimuth angle is the horizontal orientation of the solar device. Cai and Guo [31] discussed the tilt angle and azimuth angle effects of a solar water-filled prismatic louver. Roux et al. [32] optimized tilt and azimuth angles for fixed solar collectors in South Africa using measured data. Smith et al. [33] predicted optimal tilt and azimuth angles of the solar collector through an all-sky radiative transfer method. Hafez et al. [34] provide a decent review on tilt and azimuth angles in solar
energy applications. It involves an overview of design parameters, applications, simulations, and mathematical techniques, covering different usage applications.

![Schematic diagram of solar tilt angle and azimuth angle](https://www.13kuga.com.au/solar-panel-orientation-vs-production/)

Figure 1.8 Schematic diagram of solar tilt angle and azimuth angle (https://www.13kuga.com.au/solar-panel-orientation-vs-production/).

Nanofluid is a mixture in which nanometer-sized solid particles are dispersed in a base fluid. The NPs used in nanofluids are typically made of metals, oxides, carbides, or carbon nanotubes. Common base fluids include water, ethylene glycol, and oil [35]. Nanofluids have novel properties that make them potentially useful in many applications in heat transfer, including solar thermal applications, automobile applications, electronic cooling applications, medical applications, detergency applications, military applications, etc., shown as Fig. 1.9 [36]. They exhibit enhanced thermal conductivity and convective heat transfer coefficient compared to the base fluid [38]. Knowledge of nanofluids’ rheological behavior is found to be critical in deciding their suitability for convective heat transfer applications [39]. Guo [40] gives a comprehensive review on heat transfer
enhancement with nanofluids, mainly discussing a variety of the experimentally measured thermal properties of common nanofluids, the enhancement mechanisms discovered or hypothesized, the models used for properties and heat transfer characteristics, and the applications of nanofluids for enhancing heat transfer.

Nanofluids also have unique optical properties showing the potential in solar harvesting or enhanced natural illumination. Said [41] explored the optical properties of single-wall carbon nanohorns (SWCNHs) nanofluids. Karami et al. [42] analyzed the
thermo-optical properties of CuO-water nanofluid for direct solar radiation absorption. Ni-water nanofluid is evaluated to enable simultaneous daylighting and energy harvesting by Cai et al. [43]. Also, they compared spectral radiative properties of some commonly used nanoparticles: Ni, SiO$_2$, Fe$_2$O$_3$, Al$_2$O$_3$, TiO$_2$ and ZnO. Ahmad et al. [44] provided a review on the optical properties of various nanofluids used in the solar collector. It addressed optical properties (absorption, transmittance, scattering, and extinction coefficient) based on metal, metal oxide, carbon nanotubes, graphite, and graphene, which have been reviewed thoroughly in variation with particle size and shape, path length, and volume fraction.

1.2 Objectives

This dissertation is aimed at developing an innovative nanofluid-filled louver that could be treated as a novel multi-purposes solar device: VIS light redirectors and solar energy absorbers. Through their radiative transparency to VIS light and radiative properties, the louver redirect the incoming collimated and diffuse sunlight so that they can highly improve natural illumination and allow deeper VIS light penetration. In addition, it reduced “glare effect” and offered VIS lighting needs, which significantly improved residents’ comfort inside the buildings. The main objective of this dissertation is to study the fundamental solar radiation mechanisms for enhanced daylighting and solar energy harvesting via the use of the proposed Ni-water nanofluid-filled prismatic louvers. In particular, the dissertation also investigated the effects of the prismatic louver’s geometry, orientations, AM numbers, diffuse and direct solar light, and different commonly used nanofluids for achieving: (a) VIS light redirection and diffusion, and (b) enhanced selective solar energy absorption through UV, VIS and IR absorption via Ni-
water nanofluid for thermal energy gain manipulation of the incoming solar radiation. The specific aims of the dissertation include but are not limited to: (i) comparing spectral radiative properties of some commonly used NPs such as Ni, SiO₂, Fe₂O₃, Al₂O₃, TiO₂ and ZnO; (ii) analysis of enhanced VIS light daylighting; (iii) spectral analysis of selected water/Ni-water nanofluid for enhanced solar radiation harvesting; and (iv) proposing a natural illumination criterion. At the same time, Ni-water nanofluids tailored for selectively increasing solar energy absorption/harvesting but not affecting natural illumination have been developed and explored.

The dissertation potentially has an important impact on the adaptation of commercial, residential or industrial buildings to contemporary utilization by virtue of this innovative solar device. The results also show the solar device can lower the energy consumptions and the carbon footprint of buildings.

1.3 Survey of the Dissertation

The subsequent chapters provide how multiple objectives and novel ideas are investigated, developed, and implemented. Chapter 2 introduces the mathematical models, including the radiative transfer equation (RTE), the boundary conditions, the Monte Carlo ray tracing method, as well as the Mie scattering theory. Chapter 3 discusses the spectral collimated solar radiation harvesting through a water-filled glass hollow louver. The diffuse and collimated solar radiation incorporated with different AM models and several locations is analyzed with the water-filled glass prismatic louver in Chapter 4. Chapter 5 mainly proposes a Ni-water nanofluid that can enhance the solar energy absorption efficiency in the novel prismatic louver. It also investigates the absorption and scattering efficiencies of commonly used nanoparticles (NPs) in solar energy research,
including Ni, SiO₂, Fe₂O₃, Al₂O₃, TiO₂ and ZnO; and demonstrated that Ni NPs are the most desirable for the present dual-purpose because they have an excellent balance between UV, VIS, and IR absorption, as well as VIS transmission. Finally, summaries and contributions of this dissertation are drafted in Chapter 6.
Chapter 2 provides simulation models for the calculations applied in this dissertation. The radiative transfer equation (RTE) is introduced in the beginning. Then, several ways to solve the RTE are briefly discussed. The Monte Carlo method is adopted and incorporated with the spectral analysis of multiple AM models. Here, the dissertation also emphasizes the Mie scattering theory with different NPs, which helps to predict the spectral scattering and absorption coefficients in the simulation. Afterward, the mathematical modeling equations are covered.

2.1 Radiative transfer equation (RTE)

Radiative transfer is a fundamental physical phenomenon of energy transfer through electromagnetic radiation. The propagation of radiative transfer through a body is affected by several effects, for example, absorption/emission/scattering processes. It is also strongly dependent on the nature of wavelength/absorption/emission/reflection/refraction properties. These properties themselves require a consideration of the dependence of temperature, wavelength, and even angular direction. RTE describes these complicated interactions mathematically. RTE has significant applications in a wide variety of scenarios, including but not limited to astrophysics, remote sensing, optics, and atmospheric sciences. Analytic solutions to the RTE only exist for simple cases, but for more media in reality, numerical methods are required with complex multiple scattering effects [45].
Thermal radiation is one of the fundamental modes of energy transfer between two regions with different temperatures. It can be expressed that the energy being conveyed by electromagnetic waves. All materials with a temperature greater than absolute zero Kelvin (0 K) emit thermal radiation. This mechanism represents the conversion of thermal energy into electromagnetic energy. Thermal energy is composed of the kinetic energy of random movements of atoms and molecules in the corresponding matter. Moreover, the kinetic interactions among matter particles lead to charge acceleration and dipole oscillation. The electrodynamic generation of coupled electric and magnetic fields causes photons or radiation emission away from the region [46].

To determine the radiative flux into a surface or at any point inside the medium requires the knowledge of the radiative intensity at that point, for different directions and wavelengths, which is derived from conservation of radiative energy along pathway, and it is a fundamental equation in RTE. By investigating solar radiative intensity within a small volume element, over a small path length $dL$ along $L$, within a small solid angle $d\Omega$ around the direction $(\theta, \phi)$, and within a small wavelength interval $d\lambda$ around a given wavelength, the steady-state RTE equation can be expressed as [45]:

$$\frac{\partial I_\lambda(L,\Omega)}{\partial L} = \alpha_\lambda I_\lambda(L) - (\alpha_\lambda + \sigma_{s,\lambda}) I_\lambda(L,\Omega) + \frac{\sigma_{s,\lambda}}{4\pi} \int_{\Omega_i=4\pi} I_\lambda(L,\Omega_i) \Phi_{\lambda}(\Omega_i,\Omega) d\Omega_i$$

(2-1)

where $\alpha_\lambda$ is spectral absorption coefficient, $\sigma_{s,\lambda}$ is spectral scattering coefficient, $I_\lambda$ is the intensity, and $\Phi_\lambda$ is phase function. Figure 2.1 shows the schematics of coordinate system under consideration.

The term on the left-hand side in Eq. (2-1) is the change of radiative energy. The first two terms on the right-hand side stand for the contribution of medium emission and radiation attenuation due to scattering and absorption. The third term on the right-hand
side in Eq. (2-1) is the in-scattering term. This term makes the transfer equation an integro-differential form and the solution a formidable task in high-dimensional problems.

![Figure 2.1 Schematics of coordinate system [47].](image)

### 2.2 Mie scattering theory

Mie scattering theory addresses the scattering effect of an electromagnetic plane wave by a homogeneous sphere, and it is the solution to Maxwell's equations. It takes the form of an infinite series of spherical multipole partial waves.

The optical properties of a single micro/nanoparticle, including the absorption/scattering efficiency factors, can be generally calculated using the Mie scattering theory [48], though the theory originated from the assumption of spherical particles. The extinction/scattering/absorption efficiency is the ratio of an
extinction/scattering/absorption cross-section to a particle's geometric cross-sectional area. The complex index of refraction of a substance, \( m \), is given by:

\[
m = n - ik
\]

(2-2)

where \( k \) is the absorptive index and \( n \) is the refractive index. When the particles are dispersed in a base fluid, the relative complex index of refraction for the nanofluid is

\[
m_{rel} = \frac{m_p}{m_f}
\]

(2-3)

where subscript \( p \) represents particle while subscript \( f \) represents base fluid.

From the Mie scattering theory, the scattering efficiency, \( Q_{sca} \), is

\[
Q_{sca} = \frac{2}{\pi^2} \sum_{n=1}^{\infty} (2n+1) \left( |a_n|^2 + |b_n|^2 \right)
\]

(2-4)

where \( x \) is the size parameter defined as \( \pi D/\lambda \); \( a_n \) and \( b_n \) are the Mie scattering coefficients, expressed as

\[
a_n = \frac{\psi_n'(mx)\psi_n(x) - n \psi_n(mx)\psi_n'(x)}{\psi_n(mx)\zeta_n(x) - n \psi_n(mx)\zeta_n'(x)}
\]

(2-5a)

\[
b_n = \frac{m \psi_n'(mx)\psi_n(x) - n \psi_n(mx)\psi_n'(x)}{m \psi_n'(mx)\zeta_n(x) - n \psi_n(mx)\zeta_n'(x)}
\]

(2-5b)

where \( \psi_n \) and \( \zeta_n \) are the Riccati-Bessel functions, related to the Bessel and Hankel functions by

\[
\psi_n(z) = \left( \frac{\pi z}{2} \right)^{1/2} J_{n+1/2}(z)
\]

(2-6a)

\[
\zeta_n(z) = \left( \frac{\pi z}{2} \right)^{1/2} H_{n+1/2}(z)
\]

(2-6b)

The extinction efficiency, \( Q_{ext} \), is calculated by

\[
Q_{ext} = \frac{2}{\pi^2} \sum_{n=1}^{\infty} (2n+1) \text{Re}\{a_n + b_n\}
\]

(2-7)

The absorption efficiency, \( Q_{abs} \), is calculated by

\[
Q_{abs} = Q_{ext} - Q_{sca}
\]

(2-8)
With a cloud of uniform-size particles, the spectral scattering coefficient, \( \sigma_{s,\lambda} \), absorption coefficient, \( \alpha_{s,\lambda} \), and extinction coefficient, \( \beta_{s,\lambda} \), are calculated by

\[
\sigma_{s,\lambda} = \frac{\pi D^2 N_p Q_{sca,\lambda}}{4} \quad (2-9a)
\]
\[
\alpha_{s,\lambda} = \frac{\pi D^2 N_p Q_{abs,\lambda}}{4} \quad (2-9b)
\]
\[
\beta_{s,\lambda} = \frac{\pi D^2 N_p Q_{ext,\lambda}}{4} \quad (2-9c)
\]

where \( D \) is the particle diameter, and \( N_p \) is the number of particles per unit volume, which can be obtained by

\[
N_p = \frac{6}{\pi D^3} V_p \quad (2-10)
\]

where \( V_p \) is the particle volume concentration.

The asymmetry factor, \( g_\lambda \), can be expressed as

\[
g_\lambda = \frac{1}{4\pi} \int \phi(\theta_{sca}) \cos \theta_{sca} \, d\Omega \quad (2-11)
\]

where \( \theta_{sca} \) is the scattering angle; \( \Omega \) is the solid angle; \( \phi \) is the scattering phase function, shown as

\[
\phi(\theta_{sca}) = 1 + \sum_{n=1}^{\infty} A_n P_n(\cos \theta_{sca}) \quad (2-12)
\]

where the coefficient \( A_n \) is directly related to the Mie scattering coefficients \( a_n \) and \( b_n \); \( P_n \) is the n-th order Legendre polynomial.

For spherical particles, the asymmetry factor, \( g_\lambda \), is readily calculated as

\[
g_\lambda = \frac{4}{x^2 Q_{sca}} \sum_{n=1}^{\infty} \left[ \frac{n(n+2)}{n+1} Re\{a_n^* a_{n+1}^* + b_n^* b_{n+1}^*\} + \frac{2n+1}{n(n+1)} Re\{a_n^* b_n^*\} \right] \quad (2-13)
\]

where * is the complex conjugate.

Guo and Maruyama [49] scaled anisotropic scattering into equivalent isotropic scattering. We utilized and compared the scaled isotropic scattering among different NPs.
in this study given the advantages offered in reducing the complexity of computation and
the uniformity for comparison. The isotropic-scaled spectral scattering coefficient, $\sigma_{s\lambda,i}$, can be calculated for a given anisotropic scattering coefficient as

$$\sigma_{s\lambda,i} = (1 - g_\lambda)\sigma_{s\lambda} \quad (2-14)$$

2.3 Mathematical model

Hardly exact, closed-form analytical solutions to the highly sophisticated integro-differential RTE equation (2-1) exist in multi-dimensional geometric problems. Conventional methods such as the finite difference method and finite element method can solve radiation problems whenever a solution method is applied that transforms the governing equation into sets of partial differential equations. RTE with absorbing participating media problem is too mathematical challenging to solve due to the integro-differential parts. In particular, complicated geometries, radiative properties varying with directions, wavelengths, and anisotropic scattering are involved. Thus, a decent solution by traditional numerical methods seems to be pretty tricky.
The Monte Carlo (MC) method is a class of statistical, computational algorithms that depend on a large number of random samplings to obtain numerical results. The MC method’s underlying concept is to apply repetitions of many random numbers to deal with problems that might be deterministic in principle. MC method is often used in complicated physical and mathematical problems, especially for radiative transfer problems, and is extremely powerful and flexible when other approaches can barely perform.

As the nature of radiative transfer problems, the MC approach is simulated by applying the calculated path length of a statistically large number of photon bundles, which is also named Monte Carlo ray tracing method (MCRT). Each photon bundle trace
from its initial location through the participating medium; it experiences absorption/scattering/reflection/refraction. Upon completing of MCRT, predictions of radiation are determined via the average statistical performance of sets of individual photon bundles. The complexities inherent in the radiation are integro-differential part shown in the RTE equation (2-1) and the difficulty in solving it with the Fresnel reflection and anisotropic scattering.

The most significant advantage of the MCRT method is that even the most challenging problem may be dealt with in a relatively easy way. As a trivial problem, establishing the proper photon bundles alone may require more difficulty than seeking the analytical solution. The conventional numerical methods require much more effort as the complexity of the problem increases. Other advantages of using MC include easy handling of complicated physical processes and conditions based on statistical distributions and easy implementation in computer programs construction without any governing equations. When a problem exceeds certain complexity, the MC method will show its advantages and be desirable. However, the MC method also confronts two shortcomings: they have statistic errors since they are subjected to the statistical nature of the results it generates, and of course, they highly demand computational ability, especially for producing highly accurate and precise results.

For more than a decade, some pioneers and researchers have been extensively utilized this method to simulate radiative transfer problems. MC model is a helpful simulation tool for investigating radiative transfer in complex systems [50-52]. There are a number of excellent papers [53-55] in the literature on MC methods for radiation transfer in participating media under various conditions. In the present solar-louver
system, the solar irradiation on the louver is highly spectral, and the glass and water absorption and refractive index variations are all spectral. Hence, an MC modeling with appropriate spectral properties incorporating reflection, refraction, absorption, and scattering is necessary.

The MC method in this dissertation simulated a spectral solar radiation model through a scattering-absorbing media. Realistic boundary conditions are incorporated, for example, the direct or diffuse solar light, Fresnel reflection at each interface, Snell’s law dealing with the refraction, and so on.

2.4 Simulation method of collimated light

The physical model discussed in this study is a device consisting of a series of transparent louvers that can be installed on one side of a window to change the direction of collimated sunlight to provide natural lighting deeper in the room, as well as to absorb the IR part in solar radiation to heat water inside. The cross-section of the prismatic louver is an equilateral triangle, which is assembled by three pieces of uniform silica glass, each with a thickness (τ) of 0.125 inches and width (W) of 3 inches. The height (H) of the triangle is \(0.5\sqrt{3}W\). A brief illustration of the louver cross-section is given in Fig. 2.3(a). As the louver is very long, its ending effect is generally negligible. The only situation that the end effect cannot be neglected is that both \(\theta\) and \(\phi\) approach to 90°, which consists of a very small solid angle of incidence. In such a small solid angle, the solar incidence is almost negligible as \(\cos\theta\) approaches to zero. Thus, a two-dimensional (2D) geometry is considered in this study. However, the MCRT should be performed in three-dimension with the z-direction being infinite and the z-value at each
reflection/refraction/scattering point being recoiled back to zero. The MC simulation of Chapter 3 is based on this section.

Figure 2.3 A) sketch of the louver cross section with collimated solar irradiation from the top; and b) a representative nodes division.

Figure 2.4 shows the flowchart for tracing one photon bundle in MC modelling. A photon bundle is initiated from a position \((X_0, Y_0, Z_0)\) at the solar incident surface of a uniform distribution:

\[
X_0 = W \ast R - W/2, \quad Y_0 = 0, \quad Z_0 = 0
\]  

(2-15)

where \(R\) is the random number. The collimated solar incident direction has a pair of angles \((\theta_0, \phi_0)\). In the present study, the incident polar angle varies between 0 and 90° and the circumferential angle is fixed at zero for simplicity. Snell’s law is employed to determine the initial polar angle of the refracted photons passing through the air-glass interface.
The flight distance, $L_{B}$, of a photon bundle is

$$L_{B} = \frac{1}{\beta_{\lambda}} \ln \frac{1}{R}$$ (2-16)

where $\beta_{\lambda}$ is the spectral extinction coefficient of the medium from which the photon is initiated. $\beta_{\lambda}$ is a sum of the spectral absorption coefficient, $\alpha_{\lambda}$, and the spectral scattering coefficient, $\sigma_{\lambda}$.

There are six interfaces in the louver as shown in Fig. 1(a), S1- S6. In order to decide which interface the photon bundle will hit or the location the photon will be absorbed/scattered inside the medium, we find the seven possible hitting distances, $L_{j}$, and positions by solving:

$$\begin{cases}
X_{j} = L_{j} \sin \theta_{0} \cos \varphi_{0} + X_{0} \\
Y_{j} = L_{j} \sin \theta_{0} \sin \varphi_{0} + Y_{0} \\
Z_{j} = L_{j} \cos \theta_{0} + Z_{0}
\end{cases}
\quad j = 1, 2, ..., 7$$ (2-17)

with each of the following functions:

For interaction at surface 1: $Z_{1} = 0$ (2-18)

For interaction at surface 2: $Z_{2} = \sqrt{3}X_{2} + \sqrt{3}W/2$ (2-19)

For interaction at surface 3: $Z_{3} = -\sqrt{3}(X_{3} - W/2)$ (2-20)

For interaction at surface 4: $Z_{4} = \tau$ (2-21)

For interaction at surface 5: $Z_{5} = \sqrt{3}(X_{5} + 0.428W) + \tau$ (2-22)

For interaction at surface 6: $Z_{6} = -\sqrt{3}(X_{6} - 0.428W) + \tau$ (2-23)

For scattering/absorption in medium: $L_{7} = L_{B}$ (2-24)

The distance between the middle point $(X'_{j}, Y'_{j}, Z'_{j})$ of surfaces S4-S6 and the emission point obeys the rule as follows:

$$L'_{j} = \sqrt{(X_{0} - X'_{j})^{2} + (Y_{0} - Y'_{j})^{2} + (Z_{0} - Z'_{j})^{2}}, j = 4, 5, 6$$ (2-25)
If $L'_4 \leq L'_5$, $L'_4 \leq L'_6$ and $L'_5 \leq L'_6$, we will check whether the photon will hit S4, S5, S2, S3 and S1 in sequence. If $L'_4 \leq L'_5$, $L'_4 \leq L'_6$ and $L'_6 \leq L'_5$, we will check whether the photon will hit S4, S6, S3, S2 and S1 in sequence. If $L'_5 < L'_4$, $L'_5 \leq L'_6$ and $L'_4 < L'_6$, we will check whether the photon will hit S5, S4, S3, S1 and S2 in sequence. If $L'_5 < L'_4$, $L'_5 \leq L'_6$ and $L'_6 < L'_4$, we will check whether the photon will hit S5, S6, S3, S1 and S2 in sequence. If $L'_6 < L'_4$, $L'_6 < L'_5$ and $L'_4 < L'_5$, we will check whether the photon will hit S6, S4, S1, S2 and S3 in sequence. If $L'_6 < L'_4$, $L'_6 < L'_5$ and $L'_5 < L'_4$, we will check whether the photon will hit S6, S5, S2, S1 and S3 in sequence.

Further, if $L_\beta \geq L_4 > 0$ and $X_D \leq X_4 \leq X_E$, the photon will hit S4; if $L_\beta \geq L_5 > 0$ and $X_D \leq X_5 \leq X_F$, it will hit S5; if $L_\beta \geq L_6 > 0$ and $X_F \leq X_6 \leq X_E$, it will hit S6; if $L_\beta \geq L_2 > 0$ and $0 \leq X_2 \leq X_C$, it will hit S2; if $L_\beta \geq L_3 > 0$ and $X_C \leq X_3 \leq X_B$, it will hit S3; if $L_\beta \geq L_1 > 0$ and $0 \leq X_1 \leq X_B$, it will hit S1; otherwise, it will be absorbed or scattered in the glass medium.

If a photon starts from the water medium due to scattering, we justify the followings: if $L_\beta \geq L_4 > 0$ and $X_D \leq X_4 \leq X_E$, it will hit S4; if $L_\beta \geq L_5 > 0$ and $X_D \leq X_5 \leq X_F$, it will hit S5; if $L_\beta \geq L_6 > 0$ and $X_F \leq X_6 \leq X_E$, it will hit S6; otherwise, the photon will be absorbed or scattered in water.
If a photon hits a surface, we need to consider whether the photon will reflect or transmit. For reflection, specular reflection condition is adopted as the air-glass and glass-water interfaces are smooth. If refraction occurs, Snell’s law is employed

\[ n_t \sin \theta_i = n_a \sin \theta_a \]  

(2-26)
where \( n_l \) and \( n_a \) are refractive indices of medium in the incoming and refractive sides, \( \theta_l \) and \( \theta_a \) represent the incident angle and angle of refraction, respectively.

If \( n_l > n_a \), there exists a critical angle, \( \theta_c \), defined by
\[
\theta_c = \sin^{-1}\left(\frac{n_a}{n_l}\right)
\] (2-27)

When \( \theta_l \geq \theta_c \), and the incident radiation is totally reflected with specular reflection condition. The reflectivity of incident radiation on an interface is given by Fresnel equation:
\[
\rho = \frac{1}{2} \left[ \frac{\tan^2(\theta_l - \theta_a)}{\tan^2(\theta_l + \theta_a)} + \frac{\sin^2(\theta_l - \theta_a)}{\sin^2(\theta_l + \theta_a)} \right]
\] (2-28)

where \( \rho \) is the reflectivity. If \( R < \rho \), the photon will reflect; otherwise, it will transmit.

The ray vector \( \vec{r}_l \) after reflection is
\[
\vec{r}_l = \vec{r}_i \cos \theta_l + 2(|\vec{r}_l| \cos \theta_l) \cdot \vec{n}
\] (2-29)

where \( \vec{n} \) is the normal direction outward the hitting surface, \( \vec{r}_i \) is the incoming ray vector.

The ray vector after refraction, \( \vec{r}_a \), is
\[
\vec{r}_a = \frac{\tan \theta_r}{\tan \theta_l} [\vec{r}_l + \vec{n}(\vec{n} \cdot \vec{r}_l)] - \vec{n}(\vec{r}_l \cdot \vec{n})
\] (2-30)

Once we obtained the ray vector after refraction/reflection, we can get \( \theta \) and \( \Phi \).

The scattering albedo was employed to determine whether a photon is absorbed or scattered. If \( R < \omega \), in which \( \omega \) is the scattering albedo, the photon would scatter; otherwise, it would be absorbed. The new scattering direction is determined by isotropic scattering condition in this study, as water scattering is very weak and glass scattering is negligible, given by:
\[
\theta = \cos^{-1}(1 - 2R), \quad \varphi = 2\pi R
\] (2-31)
where $\theta$ is the new azimuthal angle and $\varphi$ is the new circumferential angle. For anisotropic scattering, isotropic scaling [56] or normalization of phase function [57] could be employed.

### 2.5 Simulation method for diffuse light

The simulation method for diffuse light is pretty similar to collimated light, except direct sunlight has an initially fixed incident direction, while the diffuse one has a distribution. We consider a glazing system of water-filled glass louvers. Visible light passing through the louvers, oriented at the proper angle, will be redirected to ceiling and diffusely reflect to room space for improved daylighting. The water and glass will absorb UV and IR light for energy harvesting. The louver cross-section is shown in Fig. 2.5, in which the three uniform silica glasses form an equilateral hollow triangular prism. Water flows inside the hollow louver. Each glass piece changed from 0.125” to 0.1875” thick now due to manufacturing purposes, 3” wide and a few feet long. Thus, it also has a negligible end effect and a two-dimension (2D) cross-sectional geometry is considered in this study. The solar incident surface (assuming the top one in Fig. 2.7) can be adjusted to face direct sunlight consisted of both collimated and diffuse irradiation. This section also optimizes the photon counting algorithm and save more time on computation. The MC simulations of chapters 4 and 5 are based on this section.
Figure 2.5 Sketch of louver cross-section with direct and diffuse irradiation.

The initial direction \((\theta_0, \varphi_0)\) of the diffuse irradiation is randomly generalized as follows:

\[
\theta_0 = \sin^{-1}(\sqrt{R}), \quad \varphi_0 = 2\pi R
\]

where \(R\) is the random number.

There are six interfaces in the louver as shown in Fig. 2.5, S1- S6. It is necessary to justify which interface a photon will hit or whether it is absorbed/scattered inside the medium. Thus, there are seven possible flight distances, \(L_i\), and associated end positions:

\[
\begin{align*}
X_i &= L_i \sin \theta_0 \cos \varphi_0 + X_0 \\
Y_i &= L_i \sin \theta_0 \sin \varphi_0 + Y_0 \\
Z_i &= L_i \cos \theta_0 + Z_0
\end{align*}
\]

For interaction with S1:

\[Z_1 = 0\]  
(2-34a)

For interaction with S2:

\[Z_2 = \sqrt{3}X_2 + H\]  
(2-34b)
For interaction with S3:

\[ Z_3 = -\sqrt{3}(X_3 - W/2) \quad (2-34c) \]

For interaction with S4:

\[ Z_4 = \tau \quad (2-34d) \]

For interaction with S5:

\[ Z_5 = \sqrt{3}(X_5 + 0.5W - \sqrt{3}\tau) + \tau \quad (2-34e) \]

For interaction with S6:

\[ Z_6 = -\sqrt{3}(X_6 - 0.5W + \sqrt{3}\tau) + \tau \quad (2-34f) \]

For absorption/scattering in medium:

\[ L_7 = L \quad (2-34g) \]

The ray vector is set as:

\[ \vec{r} = (\sin \theta \cos \varphi, \sin \theta \sin \varphi, \cos \theta) \quad (2-35) \]

For each surface \(i\) (from 1 to 6), we set a possible hitting parameter \(Ph_i\) as:

\[ Ph_i = \vec{r} \cdot (-\vec{n}_i), \; i = 1, 2, \ldots, 6 \quad (2-36) \]

where \(\vec{n}_i\) is the normal direction outward the surface.

The interfaces 4-6 are tested first: if \(L \geq L_4 > 0, Ph_i > 0\) and \(X_D \leq X_4 \leq X_E\), the photon will hit S4; if \(L \geq L_5 > 0, Ph_i > 0\) and \(X_D \leq X_5 \leq X_F\), it will hit S5; if \(L \geq L_6 > 0, Ph_i > 0\) and \(X_F \leq X_6 \leq X_E\), it will hit S6. Then, the interfaces 1-3 are examined: if \(L \geq L_2 > 0, Ph_i > 0\) and \(0 \leq X_2 \leq X_C\), it will hit S2; if \(L \geq L_3 > 0, Ph_i > 0\) and \(X_C \leq X_3 \leq X_B\), it will hit S3; if \(L \geq L_1 > 0, Ph_i > 0\) and \(0 \leq X_1 \leq X_B\), it will hit S1; otherwise, it will be absorbed or scattered in the glass medium.

If a photon starts inside the water medium due to scattering, the following is justified: if \(L \geq L_4 > 0\) and \(X_D \leq X_4 \leq X_E\), the photon will hit S4; if \(L \geq L_5 > 0\) and
$X_D \leq X_5 \leq X_F$, it will hit S5; if $L \geq L_6 > 0$ and $X_F \leq X_6 \leq X_E$, it will hit S6; otherwise, the photon will be absorbed or scattered in the water medium.

If a photon is absorbed or scattered, we use the scattering albedo to determine whether the photon is absorbed or scattered. If $R < \omega$, in which $\omega$ is the scattering albedo, the photon would scatter; otherwise, it would be absorbed. The new scattering direction is determined by isotropic scattering condition in this study, as water scattering is very weak and glass scattering is negligible, given by:

$$\theta = \cos^{-1}(1 - 2R), \quad \varphi = 2\pi R \quad (2-37)$$

The MC collimate simulation will be adopted in the chapter 3 and MC collimated incorporated with diffuse radiation simulation will be applied in chapters 4 and 5.

### 2.6 Validation

We applied an analytical solution: Beer’s law to validate the MC 7-band model with $10^8$ photons, 7,140 elements, and AM1.5 collimated model in a purely absorbing medium of the physical model. The geometry model is shown in Fig. 2.7. The details of the MC 7-band, $10^8$ photons, 7,140 elements, and AM1.5 collimated model will be covered in chapter 3. Beer's law, also known as Beer–Lambert law, relates the attenuation of light to the properties of the material through which the light is travelling. Explicitly, when a solar light beam of intensity $E_0$ travels in a material for a finite distance $L$, Beer’s law can be expressed as

$$E_{trans} = E_0 \cdot e^{-\alpha L} \quad (2-38)$$

where $\alpha$ is the absorption coefficient of the material, $E_{trans}$ is the energy after traveling through the material. Thus, the absorbed energy, $E_{abs}$, in the material can be expressed as

$$E_{abs} = E_0 \cdot (1 - e^{-\alpha L}) \quad (2-39)$$
The solar light traveling directions are subject to the equations (2-26) to (2-30) if reflection or refraction happens in the surfaces. The reflection or refraction part of solar energy can be shown as

\[ E_i = E \times \rho, \quad E_a = E \times (1 - \rho) \]  

(2-40)

where \( E_i \) is the energy of reflection; \( E_a \) is the energy of refraction.

The solar light will be eventually absorbed in the water/glass medium or transmitted outside the louver.

The efficiency of solar energy harvesting of Beer’s law can be expressed as:

\[ \epsilon_c = \sum_j \sum_{\lambda=280}^{4000} \frac{E_j}{E_t} w \lambda (1 - \rho_{\lambda ag}) \]  

(2-41)

where \( E_t \) is the total solar energy; \( j \) is the number of time traveling in the absorbing medium; \( E_{\lambda j} \) is the sum of \( j \)-th absorbed spectral energy in the absorbing medium; \( \rho_{\lambda ag} \) is the spectral surface reflectivity of light from air to silica glass; and \( w_\lambda \) is the energy weighting factor of a spectral band.

The solar energy absorption efficiency for collimated light of MC method is defined as:

\[ \epsilon_c = \sum_i \sum_{\lambda=280}^{4000} \frac{N_{\lambda i}}{N_{\text{RAY}}} w \lambda (1 - \rho_{\lambda ag}) \]  

(2-42)

where \( i \) is an element division; \( N_{\lambda i} \) is the absorbed spectral photon number in the element; \( N_{\text{RAY}} \) is the total photon bundles number refracted from the inward surface of solar incidence;

We distinguish the solar absorption efficiency in the glass and water regimes, respectively. The total efficiency in the whole louver is a sum of both efficiencies.

We assume there is no scattering in the glass or water medium; the solar light angle is incident to the upper surface (S1 in Fig. 2.7). We compared the solar energy absorption
efficiency and transmittance in 7 points along the S1 surface (Y and Z equal to zero): X=-0.028575m, -0.01905m, -0.009525m, 0m, 0.009525m, 0.01905m, and 0.028575m, respectively, while θ and ϕ are fixed and equal to zero.

Figure 2.6 Comparison between Beer’s law results and MC results for absorption/transmittance efficiencies at seven points along X direction.

From Fig. 2.6, it can be found that the outputs of the analytical method--Beer’s law match with the MC simulations very well. Total /water/glass absorption and light transmittance are symmetric since the geometry of model is also symmetric. Total/water/glass absorptions vary from 55.6%/18.9%/36.7%, 55.7%/23.2%/32.5%,
55.5%/24.9%/30.6%, 50.5%/26.0%/24.5%, 55.5%/24.9%/30.6%, 55.7%/23.2%/32.5%, and 55.6%/18.9%/36.7% at X=-0.028575m, -0.01905m, -0.009525m, 0m, 0.009525m, 0.01905m, and 0.028575m, respectively. Solar light transmittances change from 40.4%, 40.3%, 40.5%, 45.5%, 40.5%, 40.3%, and 40.4%, respectively. Glass absorption is high at the X=0.028575m or -0.028575m due to the total reflection existing at S2 and S3 surfaces.

Beer’s law has a limitation that it is extremely hard to solve the problems when the scattering effect must be considered. However, the MC method can easily solve this issue. Therefore, in this dissertation, we will apply the MC method to calculate solar energy harvesting and light illumination by considering absorption and scattering effects simultaneously.
CHAPTER 3

SPECTRAL MONTE CARLO SIMULATION OF
COLLIMATED SOLAR IRRADIATION TRANSFER IN A
WATER-FILLED PRISMATIC LOUVER

A MC model was developed to simulate collimated solar irradiation transfer and energy harvest in a hollow louver made of silica glass and filled with water. The entire solar spectrum of the AM1.5 database was adopted and divided into various discrete bands for spectral calculations. The band-averaged spectral properties for the silica glass and water were obtained. Ray tracing was employed to find the solar energy harvested by the louver. Computational efficiency and accuracy were examined through intensive comparisons of different band partition approaches, various photon bundles, and element divisions. The influence of irradiation direction on solar energy harvest efficiency was scrutinized. It was found that within 15° polar angle of incidence, the harvested solar energy in the louver was high, and the total absorption efficiency reached to 61.2% under normal incidence for the current louver geometry.

3.1 Introduction

The spectrum-integrated irradiance corresponds to a solar constant of 1366.1 W/m² above Earth’s atmosphere [58]. Though the amount of solar irradiation on Earth’s surface is gigantic, about $3 \times 10^{24}$ J per year, most of which remains unutilized while we keep
depleting traditional fossil fuels [59]. The yearly installation capacity of solar photovoltaic facilities has continuously seen significant increases worldwide in recent years [60].

There is a pressing need for green energy and next-generation net-zero energy buildings. Abundant solar energy can provide natural lighting as well as heating; thus well-utilized solar energy will lead to energy savings; however, windows in the US consume 30% of overall building heating and cooling loads [11], representing an annual impact of 4.1 quadrillions BTU (quads) of primary energy. Before the industrial revolution, the sun was the primary source for lighting and heating. How to efficiently utilize solar irradiation from windows has gained new attention.

The concept of the proposed glass louver (see Fig. 2.5) in a glazing system is based on a prism’s ability to deviate incident light. The collimated solar irradiation will be redirected by the louver to ceiling and reflected diffusely to room space for illumination. This will eliminate “glare effect”; improve natural lighting quality, and increase occupants’ comfort. The concern of “rainbow effect” in an individual louver because of material dispersion to different colors of light can be minimized by installing many louver in a stacked configuration in practical applications. Further, multiple reflections of light inside the louver will also lessen the dispersion effect. Enhanced daylight can reduce energy consumption due to artificial lighting for both residential and commercial buildings. On the other side, the water-filled and flowing inside the hollow louver will absorb the solar energy. The harvested solar energy could be stored in a heat storage tank for secondary use. The present study focuses on investigating solar irradiation transfer and energy harvest using water inside a glass louver.
In terms of the significance of energy, calculated from reference AM1.5 spectra [15], IR and VIS sunlight contain more than 52% and 43% of solar energy, while UV light only takes less than ~5% solar energy. It is important to consider band-average techniques based on the significance and difference of various bands. Patel et al. [61] proposed a highly efficient metasurface absorber in the VIS and IR sunlight parts. Yolalmaz and Yuce [62] split the solar spectrum into two separate bands between 400 nm - 700 nm and 701 nm – 1,100 nm by using diffractive optical elements. Hoyt [63] calculated the global solar insolation using a one-band gray model. Gueymard [64] utilized a two-band model to calculate sky solar irradiance, illuminance, and photosynthetically active radiation. Escobedo et al. [65] used hourly and daily radiometric data to establish several empirical models for predicting three bands’ fractions. Bird and Riordan [66] provided a simple model for calculating spectral solar irradiance on tilted surfaces, producing terrestrial spectra between 300 nm and 4,000 nm with a resolution of approximately 10 nm. Nevertheless, it would be very useful to establish a band partition model that would be computationally efficient and accurate for calculating solar irradiation transfer in glass-water systems.

The incident angle of solar irradiation on a window depends on many factors, such as the zenith angle, season, time, location, window direction, and orientation. Lave and Jan [67] discussed the global irradiance for different longitudes and latitudes in the continental United States. Yan et al. [68] analyzed different tilt angles using one-year-long data recorded in Brisbane. Rolands et al. [69] investigated optimal tilt angle and azimuth for a photovoltaic panel in Ontario, Canada. Papanicolaou et al. [70] numerically studied the effects of inclination angle on natural convective heat transfer in the air inside
an asymmetric, greenhouse-type solar still. Tang and Wu [71] proposed a simple mathematical procedure for estimating of the optimal tilt angle of a collector based on the monthly horizontal radiation and plotted a contour map of the optimal tilt angle for the south-facing collectors in China. Though the currently proposed louver could be adjusted to face the solar irradiation to harvest the most considerable amount of solar irradiation in practical deployment, it is still needed to examine the influence of the incidence angle of solar irradiation.

### 3.2 Simulation Method

After we applied the MC collimated solar radiation modeling mentioned in Chapter 2, the spectral divergence of heat flux, $Q_{\lambda i}$, due to solar collimated irradiation for an element $i$ is calculated by

\[
Q_{\lambda i} = (1 - \rho_{\lambda ag}) \frac{W \times E_{c\lambda} \times N_{\lambda i}}{S_{i} \times NRAY}
\]  

(3-1)

where $N_{\lambda i}$ is the absorbed spectral photon number in the element; $S_{i}$ is the cross-sectional area of the element; $NRAY$ is the total photon bundles number refracted from the inward surface of solar incidence; $E_{c\lambda}$ is the collimated spectral solar heat flux on louver’s out surface; and $\rho_{\lambda ag}$ is the spectral surface reflectivity of light from air to silica glass. The total divergence, $Q_{\lambda}$, is an integral of the spectral value, i.e., the sum of contributions from all the solar bands:

\[
Q_{\lambda} = \frac{W \times E_{c}}{S_{i}} \sum_{\lambda=280}^{4000} \frac{N_{\lambda i}}{NRAY} W_{\lambda} (1 - \rho_{\lambda ag})
\]  

(3-2)

where $E_{c}$ is the collimated solar heat flux on louver’s out surface and $W_{\lambda}$ is the energy weighting factor of a spectral band.
Since the solar heat flux varies with location, season, day and time, it would be more convenient to show the solar energy absorption in terms of normalized energy harvest $Q_l'$ defined as:

$$ Q_l' = \frac{q_l}{E_c} \quad (3-3) $$

As mentioned in the Chapter 2, the solar energy absorption efficiency for collimated light is defined as:

$$ \epsilon_c = \sum_l \sum_{\lambda=280}^{4000} \frac{N_{\lambda l}}{N_{RAY}} w_{\lambda} (1 - \rho_{\lambda ag}) \quad (3-4) $$

We distinguish the solar absorption efficiency in the glass and water regimes, respectively. The total efficiency in the whole louver is a sum of both two efficiencies.

As the louver is designed to pass the VIS light with altered direction, but to absorb UV and IR light as much possible, it would be very useful to distinguish the absorption difference for different light. Thus, the absorption efficiency for collimated light in the range from $\lambda_1$ to $\lambda_2$ is defined as

$$ \epsilon_c(\lambda_1 - \lambda_2) = \frac{\sum_{\lambda=\lambda_1}^{\lambda_2} N_{\lambda l} w_{\lambda} (1 - \rho_{\lambda ag})}{N_{RAY} \sum_{\lambda=\lambda_1}^{\lambda_2} w_{\lambda}} \quad (3-5) $$

Solar irradiation is highly spectral, and so are the properties of water and glass. In the present study, the AM1.5 database from ASTM Standard G173-03 [15] was adopted in calculating the solar irradiation on Earth’s surface. Referring to AM1.5, the solar spectrum spans a range from 280 nm to 4,000 nm. In the whole solar spectrum, scattering is negligible in glass, and extremely weak in water. The spectral properties for glass [72, 73] and water [74] are calculated by:

$$ P_{\lambda 12} = \int_{\lambda_1}^{\lambda_2} \frac{p_{\lambda 1} I_{\lambda 1} d\lambda}{I_{\lambda 1}} \quad (3-6) $$
where \( P_\lambda \) represents a spectral property, \( I_\lambda \) is the spectral solar intensity, and \( P_{\lambda_{12}} \) can be the band-averaged scattering or absorption coefficient, or refractive index in a discrete band between wavelengths \( \lambda_1 \) and \( \lambda_2 \).

The solar spectrum was divided into many discrete bands, and band-averaged spectral properties are used in the present studies. We divided the spectrum in a way such that property profiles are relatively smooth within each band. Another factor considered was that each band contains a close amount of solar energy so that the spectral-weighting factor is not too diverse. In the region with condensed energy, such as the VIS and near-IR regimes, the bandwidth is relatively narrow; while in the IR region, the bandwidth is generally broad. In this study, we compared the results calculated from 1 full band (gray), 3, 7, 20, and 40 bands, respectively. The data for band divisions and associated properties are shown in Table 3-1.

**Table 3-1** Spectral optical properties of different band models

<table>
<thead>
<tr>
<th>Bands</th>
<th>Wavelength (nm)</th>
<th>( n_{\text{glass}} )</th>
<th>( n_{\text{water}} )</th>
<th>( \alpha_{\text{glass}} ) (m)</th>
<th>( \alpha_{\text{water}} ) (m)</th>
<th>( \sigma_{\text{water}} ) (m)</th>
<th>Weight (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>280-4000</td>
<td>1.5216</td>
<td>1.3307</td>
<td>35.0864</td>
<td>381.3735</td>
<td>0.000165</td>
<td>100</td>
</tr>
<tr>
<td>3</td>
<td>280-400</td>
<td>1.5429</td>
<td>1.3421</td>
<td>102.5293</td>
<td>0.009</td>
<td>0.1929</td>
<td>4.575</td>
</tr>
<tr>
<td></td>
<td>400-700</td>
<td>1.5261</td>
<td>1.3338</td>
<td>3.734</td>
<td>0.06265</td>
<td>0.0074</td>
<td>43.77</td>
</tr>
<tr>
<td></td>
<td>700-4000</td>
<td>1.5122</td>
<td>1.3247</td>
<td>47.735</td>
<td>2994.58</td>
<td>0.0016</td>
<td>51.655</td>
</tr>
<tr>
<td>7</td>
<td>280-400</td>
<td>1.5429</td>
<td>1.3421</td>
<td>102.5293</td>
<td>0.1929</td>
<td>0.009</td>
<td>4.575</td>
</tr>
<tr>
<td></td>
<td>400-548</td>
<td>1.53</td>
<td>1.336</td>
<td>4.92</td>
<td>0.0276</td>
<td>0.032</td>
<td>21.288</td>
</tr>
<tr>
<td></td>
<td>548-700</td>
<td>1.522</td>
<td>1.3316</td>
<td>12.823</td>
<td>0.008</td>
<td>0.0264</td>
<td>21.643</td>
</tr>
<tr>
<td></td>
<td>700-850</td>
<td>1.5178</td>
<td>1.3294</td>
<td>34.1597</td>
<td>2.4007</td>
<td>0.0026</td>
<td>16.195</td>
</tr>
<tr>
<td></td>
<td>850-1100</td>
<td>1.5143</td>
<td>1.3268</td>
<td>54.6798</td>
<td>32.3981</td>
<td>0.0013</td>
<td>16.673</td>
</tr>
<tr>
<td></td>
<td>1100-1530</td>
<td>1.5104</td>
<td>1.323</td>
<td>52.0098</td>
<td>435.3489</td>
<td>0.000165</td>
<td>10.088</td>
</tr>
<tr>
<td></td>
<td>1530-4000</td>
<td>1.501</td>
<td>1.3148</td>
<td>54.7049</td>
<td>16225.8</td>
<td>0.000006</td>
<td>9.538</td>
</tr>
<tr>
<td>20</td>
<td>280-400</td>
<td>1.5429</td>
<td>1.3421</td>
<td>102.5293</td>
<td>0.1929</td>
<td>0.009</td>
<td>4.575</td>
</tr>
<tr>
<td></td>
<td>400-450</td>
<td>1.5343</td>
<td>1.338</td>
<td>6.5916</td>
<td>0.0403</td>
<td>0.0503</td>
<td>6.149</td>
</tr>
<tr>
<td></td>
<td>450-500</td>
<td>1.5299</td>
<td>1.336</td>
<td>4.4101</td>
<td>0.0258</td>
<td>0.0294</td>
<td>7.776</td>
</tr>
<tr>
<td>Range</td>
<td>Mean</td>
<td>Std Dev</td>
<td>Mean</td>
<td>Std Dev</td>
<td>Mean</td>
<td>Std Dev</td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>------</td>
<td>---------</td>
<td>------</td>
<td>---------</td>
<td>------</td>
<td>---------</td>
<td></td>
</tr>
<tr>
<td>500-530</td>
<td>1.5271</td>
<td>1.3344</td>
<td>3.8295</td>
<td>0.0292</td>
<td>0.0156</td>
<td>4.559</td>
<td></td>
</tr>
<tr>
<td>530-566</td>
<td>1.5253</td>
<td>1.3332</td>
<td>5.049</td>
<td>0.0468</td>
<td>0.014</td>
<td>5.509</td>
<td></td>
</tr>
<tr>
<td>566-600</td>
<td>1.5236</td>
<td>1.3323</td>
<td>7.9275</td>
<td>0.1323</td>
<td>0.009</td>
<td>5.021</td>
<td></td>
</tr>
<tr>
<td>600-650</td>
<td>1.5219</td>
<td>1.3315</td>
<td>12.9215</td>
<td>0.276</td>
<td>0.077</td>
<td>7.199</td>
<td></td>
</tr>
<tr>
<td>650-700</td>
<td>1.5203</td>
<td>1.3307</td>
<td>19.3064</td>
<td>0.4348</td>
<td>0.0048</td>
<td>6.72</td>
<td></td>
</tr>
<tr>
<td>700-750</td>
<td>1.5189</td>
<td>1.33</td>
<td>26.3851</td>
<td>2.0035</td>
<td>0.0368</td>
<td>6.001</td>
<td></td>
</tr>
<tr>
<td>750-800</td>
<td>1.5177</td>
<td>1.3293</td>
<td>34.9274</td>
<td>2.3347</td>
<td>0.00323</td>
<td>5.316</td>
<td></td>
</tr>
<tr>
<td>800-850</td>
<td>1.5167</td>
<td>1.3287</td>
<td>42.8651</td>
<td>2.9598</td>
<td>0.02497</td>
<td>4.878</td>
<td></td>
</tr>
<tr>
<td>850-930</td>
<td>1.5156</td>
<td>1.3278</td>
<td>50.5189</td>
<td>7.4352</td>
<td>0.00175</td>
<td>6.651</td>
<td></td>
</tr>
<tr>
<td>930-1000</td>
<td>1.5142</td>
<td>1.3267</td>
<td>56.3405</td>
<td>39.1301</td>
<td>0.00114</td>
<td>3.556</td>
<td></td>
</tr>
<tr>
<td>1000-1100</td>
<td>1.5131</td>
<td>1.3258</td>
<td>58.0337</td>
<td>54.3222</td>
<td>0.001</td>
<td>6.465</td>
<td></td>
</tr>
<tr>
<td>1100-1200</td>
<td>1.5117</td>
<td>1.3245</td>
<td>57.1924</td>
<td>90.3071</td>
<td>0.000544</td>
<td>3.152</td>
<td></td>
</tr>
<tr>
<td>1200-1300</td>
<td>1.5106</td>
<td>1.3233</td>
<td>54.0033</td>
<td>410.1431</td>
<td>0.000165</td>
<td>4.305</td>
<td></td>
</tr>
<tr>
<td>1300-1530</td>
<td>1.5086</td>
<td>1.3205</td>
<td>42.4921</td>
<td>893.4837</td>
<td>0.001</td>
<td>2.631</td>
<td></td>
</tr>
<tr>
<td>1530-1700</td>
<td>1.5063</td>
<td>1.3166</td>
<td>29.3908</td>
<td>731.7093</td>
<td>0.0001</td>
<td>4.017</td>
<td></td>
</tr>
<tr>
<td>1700-3000</td>
<td>1.5004</td>
<td>1.3005</td>
<td>30.3508</td>
<td>12595</td>
<td>1.43E-05</td>
<td>4.78</td>
<td></td>
</tr>
<tr>
<td>3000-4000</td>
<td>1.4729</td>
<td>1.3972</td>
<td>351.6867</td>
<td>125250</td>
<td>5.74E-06</td>
<td>0.74</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Range</th>
<th>Mean</th>
<th>Std Dev</th>
<th>Mean</th>
<th>Std Dev</th>
<th>Mean</th>
<th>Std Dev</th>
</tr>
</thead>
<tbody>
<tr>
<td>280-370</td>
<td>1.5459</td>
<td>1.3436</td>
<td>175.3724</td>
<td>0.2741</td>
<td>0.0814</td>
<td>2.465</td>
</tr>
<tr>
<td>370-400</td>
<td>1.5392</td>
<td>1.3402</td>
<td>12.6989</td>
<td>0.0928</td>
<td>0.075</td>
<td>2.11</td>
</tr>
<tr>
<td>400-418</td>
<td>1.5362</td>
<td>1.3387</td>
<td>6.6426</td>
<td>0.0509</td>
<td>0.0477</td>
<td>2.146</td>
</tr>
<tr>
<td>418-434</td>
<td>1.5343</td>
<td>1.338</td>
<td>6.9023</td>
<td>0.0387</td>
<td>0.039</td>
<td>1.899</td>
</tr>
<tr>
<td>434-450</td>
<td>1.5326</td>
<td>1.3373</td>
<td>6.2805</td>
<td>0.0315</td>
<td>0.032</td>
<td>2.243</td>
</tr>
<tr>
<td>450-466</td>
<td>1.5312</td>
<td>1.3367</td>
<td>4.8093</td>
<td>0.0272</td>
<td>0.0295</td>
<td>2.541</td>
</tr>
<tr>
<td>466-484</td>
<td>1.5298</td>
<td>1.336</td>
<td>4.4557</td>
<td>0.0251</td>
<td>0.029</td>
<td>2.871</td>
</tr>
<tr>
<td>484-500</td>
<td>1.5286</td>
<td>1.3353</td>
<td>3.9545</td>
<td>0.025</td>
<td>0.029</td>
<td>2.509</td>
</tr>
<tr>
<td>500-514</td>
<td>1.5276</td>
<td>1.3347</td>
<td>3.7208</td>
<td>0.027</td>
<td>0.0191</td>
<td>2.227</td>
</tr>
<tr>
<td>514-530</td>
<td>1.5267</td>
<td>1.3341</td>
<td>3.9284</td>
<td>0.0311</td>
<td>0.0157</td>
<td>2.451</td>
</tr>
<tr>
<td>530-548</td>
<td>1.5259</td>
<td>1.3336</td>
<td>4.4105</td>
<td>0.037</td>
<td>0.014</td>
<td>2.807</td>
</tr>
<tr>
<td>548-566</td>
<td>1.525</td>
<td>1.333</td>
<td>5.2975</td>
<td>0.0506</td>
<td>0.013</td>
<td>2.767</td>
</tr>
<tr>
<td>566-582</td>
<td>1.524</td>
<td>1.3325</td>
<td>7.1211</td>
<td>0.0848</td>
<td>0.011</td>
<td>2.437</td>
</tr>
<tr>
<td>582-600</td>
<td>1.5232</td>
<td>1.3322</td>
<td>8.6563</td>
<td>0.1751</td>
<td>0.00907</td>
<td>2.674</td>
</tr>
<tr>
<td>600-618</td>
<td>1.5225</td>
<td>1.3318</td>
<td>10.7808</td>
<td>0.2491</td>
<td>0.0077</td>
<td>2.675</td>
</tr>
<tr>
<td>618-634</td>
<td>1.5218</td>
<td>1.3315</td>
<td>13.2685</td>
<td>0.2821</td>
<td>0.007</td>
<td>2.328</td>
</tr>
<tr>
<td>634-650</td>
<td>1.5213</td>
<td>1.3312</td>
<td>15.3588</td>
<td>0.3052</td>
<td>0.00655</td>
<td>2.334</td>
</tr>
<tr>
<td>650-666</td>
<td>1.5208</td>
<td>1.3309</td>
<td>17.1635</td>
<td>0.3492</td>
<td>0.006</td>
<td>2.248</td>
</tr>
<tr>
<td>666-682</td>
<td>1.5203</td>
<td>1.3307</td>
<td>19.4444</td>
<td>0.417</td>
<td>0.0055</td>
<td>2.3</td>
</tr>
<tr>
<td>682-700</td>
<td>1.5198</td>
<td>1.3305</td>
<td>21.2542</td>
<td>0.5357</td>
<td>0.005</td>
<td>2.313</td>
</tr>
<tr>
<td>700-724</td>
<td>1.5192</td>
<td>1.3302</td>
<td>24.1409</td>
<td>1.8999</td>
<td>0.0045</td>
<td>2.941</td>
</tr>
<tr>
<td>724-750</td>
<td>1.5186</td>
<td>1.3298</td>
<td>28.5397</td>
<td>2.103</td>
<td>0.0042</td>
<td>3.034</td>
</tr>
<tr>
<td>750-776</td>
<td>1.518</td>
<td>1.3295</td>
<td>32.8266</td>
<td>2.5025</td>
<td>0.0037</td>
<td>2.618</td>
</tr>
<tr>
<td>776-800</td>
<td>1.5174</td>
<td>1.3292</td>
<td>36.9404</td>
<td>2.174</td>
<td>0.0033</td>
<td>2.714</td>
</tr>
<tr>
<td>800-824</td>
<td>1.5169</td>
<td>1.3288</td>
<td>40.8048</td>
<td>2.3352</td>
<td>0.0032</td>
<td>2.359</td>
</tr>
<tr>
<td>824-850</td>
<td>1.5164</td>
<td>1.3285</td>
<td>44.7769</td>
<td>3.5392</td>
<td>0.0023</td>
<td>2.511</td>
</tr>
<tr>
<td>850–874</td>
<td>1.516</td>
<td>1.3282</td>
<td>48.0565</td>
<td>4.9536</td>
<td>0.002</td>
<td>2.296</td>
</tr>
<tr>
<td>874–896</td>
<td>1.5156</td>
<td>1.3279</td>
<td>50.5921</td>
<td>6.0801</td>
<td>0.0018</td>
<td>2.017</td>
</tr>
<tr>
<td>896–930</td>
<td>1.5151</td>
<td>1.3275</td>
<td>52.8901</td>
<td>11.06</td>
<td>0.0016</td>
<td>2.292</td>
</tr>
<tr>
<td>930–1000</td>
<td>1.5142</td>
<td>1.3267</td>
<td>56.3405</td>
<td>39.1301</td>
<td>0.00114</td>
<td>3.473</td>
</tr>
<tr>
<td>1000–1050</td>
<td>1.5134</td>
<td>1.3261</td>
<td>57.8741</td>
<td>45.9067</td>
<td>0.0012</td>
<td>3.404</td>
</tr>
<tr>
<td>1050–1100</td>
<td>1.5128</td>
<td>1.3255</td>
<td>58.219</td>
<td>64.093</td>
<td>0.0008</td>
<td>2.928</td>
</tr>
<tr>
<td>1100–1200</td>
<td>1.5117</td>
<td>1.3245</td>
<td>57.1924</td>
<td>90.3071</td>
<td>0.00054</td>
<td>3.056</td>
</tr>
<tr>
<td>1200–1250</td>
<td>1.5109</td>
<td>1.3236</td>
<td>55.0663</td>
<td>266.7723</td>
<td>0.00025</td>
<td>2.215</td>
</tr>
<tr>
<td>1250–1300</td>
<td>1.5103</td>
<td>1.3229</td>
<td>52.8308</td>
<td>568.2748</td>
<td>0.00017</td>
<td>2.006</td>
</tr>
<tr>
<td>1300–1530</td>
<td>1.5086</td>
<td>1.3205</td>
<td>42.4921</td>
<td>893.4837</td>
<td>0.0001</td>
<td>2.557</td>
</tr>
<tr>
<td>1530–1700</td>
<td>1.5063</td>
<td>1.3166</td>
<td>29.3908</td>
<td>731.7093</td>
<td>0.0001</td>
<td>3.886</td>
</tr>
<tr>
<td>1700–2050</td>
<td>1.5037</td>
<td>1.3111</td>
<td>27.3</td>
<td>2343.7</td>
<td>0.00006</td>
<td>2.043</td>
</tr>
<tr>
<td>2050–3000</td>
<td>1.4979</td>
<td>1.2924</td>
<td>32.6871</td>
<td>20446</td>
<td>0.000012</td>
<td>2.593</td>
</tr>
<tr>
<td>3000–4000</td>
<td>1.4729</td>
<td>1.3972</td>
<td>351.6867</td>
<td>125250</td>
<td>5.70E-06</td>
<td>0.712</td>
</tr>
</tbody>
</table>

### 3.3 Results and discussion

First, we examined the MC calculations for solar collimated irradiation under different photon numbers, band numbers, and element numbers. Four sets of photon numbers for each spectral band were considered, i.e., $10^6$, $10^7$, $10^8$, and $10^9$ photon bundles, respectively. The 2D cross-sectional louver was also meshed with four different element sets, i.e., 1,086, 4,032, 7,140 and 11,130 elements, respectively. A brief illustration of element division is shown in Fig. 2-1(b).

In all the present calculations, a laptop equipped with Inter® Core™ i-7-4720HQ CPU@ 2.60GHz was used. The specific CPU times used for different cases of various photon numbers, element numbers and band numbers are listed in table 3-2. It is shown that with increasing photons number, the CPU time increases. The relation between the photons number and CPU time is basically linear. The element number does not affect the CPU time too much in this study as the present MC model needs only to trace the incident solar irradiation and record the final position for each absorbed photon. The CPU
time also increases as the partition number of bands increases; however, this is not a simple linear relationship as the photon tracing time depends heavily on the scattering effect. The scattering coefficient, as shown in the table 3-1 varies with band division.

Table 3-2 The CPU times

<table>
<thead>
<tr>
<th>Photons #</th>
<th>Elements #</th>
<th>Bands #</th>
<th>CPU Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^6$</td>
<td></td>
<td></td>
<td>27.67</td>
</tr>
<tr>
<td>$10^7$</td>
<td></td>
<td></td>
<td>279.69</td>
</tr>
<tr>
<td>$10^8$</td>
<td></td>
<td>7</td>
<td>2,727.08</td>
</tr>
<tr>
<td>$10^9$</td>
<td></td>
<td></td>
<td>27,269.25</td>
</tr>
<tr>
<td>$10^8$</td>
<td>7,140</td>
<td>7</td>
<td>2,812.14</td>
</tr>
<tr>
<td></td>
<td>1,086</td>
<td></td>
<td>2,810.30</td>
</tr>
<tr>
<td></td>
<td>4,032</td>
<td></td>
<td>2,727.08</td>
</tr>
<tr>
<td></td>
<td>7,140</td>
<td></td>
<td>2,796.67</td>
</tr>
<tr>
<td></td>
<td>11,130</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$10^8$</td>
<td>7,140</td>
<td>1</td>
<td>206.75</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>1,334.52</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7</td>
<td>2,727.08</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20</td>
<td>8,217.14</td>
</tr>
<tr>
<td></td>
<td></td>
<td>40</td>
<td>18,707.81</td>
</tr>
</tbody>
</table>

Fig. 3.1 compares the normalized energy harvest along the centerline of the louver for different photon numbers, element numbers, and band numbers. Generally a large amount of solar energy will be absorbed in the incident glass layer as the absorption coefficient is usually larger for glass than for water. The absorbed energy decreases significantly as the photon penetrates deep in the water region. However, there exists a bump near the bottom tip of the prism ($Z/H = 0.9 \sim 0.95$), where the absorbed solar energy is large as compared to other water area because photons may be trapped there due to strong reflection from the two tilted glass layers.
(a) Normalized energy harvest/m

Normalized energy harvest/m

$X/H=0$
$\theta=0^\circ$
7140 elements
7 bands

(b) Normalized energy harvest/m

Normalized energy harvest/m

$10^8$ photons
$\theta=0^\circ$
7 bands
$X/H=0$

1086 elements
4032 elements
7140 elements
11130 elements

Z/H

Z/H
Comparing the results in Fig. 3.1(a) for four different photon numbers, it is seen that, except the $10^6$ photons case, all other three larger photon numbers predict similar results. Therefore, $10^8$ photons are recommended for MC simulation of the present solar-louver system. The results in Fig. 3.1(b) show the effect of meshing. It is seen that the element division is more sensitive than the photon number. However, the result with 7,140 elements is reasonable. Fig. 3.1(c) compares the results with different band divisions. It is observed that the results with 1-band (gray) and 3-band deviate largely from other cases; and therefore, these two band approaches are not acceptable. Certainly, the spectral calculation accuracy improves with increasing band number. However, the CPU time for
the 40-band case shown in table 3-2 is nearly sevenfold of that for the 7-band. The results for the 7-band and 20-band do not deviate much from that for the 40-band.

The influence of element division is further examined in Figs. 3.2 and 3.3. Fig. 3.2 plots the solar energy absorption efficiencies in the glass region, water region, and the whole louver against the four different elements. In the calculations, $10^8$ photons and a 7-band model were employed. It is seen that the non-local solar energy absorption efficiency is not much affected by the element division. This is a distinct feature of the present MC model as the solar irradiation photon flight distance does not depend on element division. It is also seen that the absorption is much stronger in the glass than water inside the louver.

![Graph showing solar energy absorption efficiency vs. elements division.](image)

Figure 3.2 Solar energy absorption efficiency vs. elements division.
Figure 3.3 shows the contours of the normalized energy harvest for the four different element divisions. Inspecting the local solar absorption, it is seen that the element division does affect the distribution of solar energy absorption inside the louver. Such local information is important when combining heat transfer with convection is considered. The local peak energy absorption is less with fewer elements because of averaging effect. The contour with 7,140 elements is close to that with 11,130 elements, with a variation generally under 5%. Compromising the computation efficiency and accuracy, the meshing model with 7,140 elements is adopted in the calculations thereafter.

Figure 3.3 Contours of the normalized energy harvest (m\(^{-1}\)) for different divisions.

Band partition is a very important aspect in accurate and efficient modeling of solar irradiation. Fig. 3.4 shows the total/glass/water solar energy absorption efficiencies with
normal solar incidence for different band partitions. It is seen that the absorption efficiency generally decreases with an increasing band number, except the cases from 1 band to 3 bands in glass. However, the variation from 7 bands to 40 bands is very small. For example, the total efficiency is 63.2% for the 7-band model and 61.2% for the 40-band model, with only 3.27% difference between the two cases.

![Image of solar energy absorption efficiency vs. band division](image)

Figure 3.4 Solar energy absorption efficiency vs. band division.

Fig. 3.5 shows the contours of normalized energy harvest in the whole louver for different band division approaches. It indicates that the 1-band model has a large absorption in the glass, i.e., the solar irradiation is heavily attenuated by the incident glass layer. The 3-band model has a deeper solar penetration. The results in Figs. 3.4 and 3.5 indicate that the 1-band and 3-band models are not suitable for solar irradiation in glass-
water system. The 7-band would be a good choice as its result is close to the 20-, and 40-band models, while its CPU time is the least. Therefore, the 7-band model will be adopted for calculations thereafter. The 7-band model includes one band for the UV light, two bands for the VIS light and four bands for IR light as specified in table 3-1.

Figure 3.5 Contours of normalized energy harvest (m⁻¹) with different bands.

Now, the effect of solar incidence angle is investigated, utilizing 7-band, 10⁸ photons, and 7,140 elements. To simplify the problem, the circumferential angle is fixed at zero, while the azimuthal angle varies from 0° (normal) to 90°. Fig. 3.6 compares the contours of normalized energy harvest for six different incident angles. It is seen that the normalized energy harvest decreases as the incident angle enlarges. This is because the radiation penetration in the louver is shorter for a large incident angle. With
increasing angle, the solar heat flux irradiated on the louver surface decreases under the invariant solar constant on the earth’s surface. This further reduces the harvested solar energy in the louver.

![Normalized energy harvest (m⁻¹) for different incident angles.](image)

**Figure 3.6** Normalized energy harvest (m⁻¹) for different incident angles.

Fig. 3.7 depicts the total/glass/water absorption efficiencies vs. the sunlight incident angle. It is seen that the variation of absorption efficiency in the water is smoother than that in the glass. This is because the glass medium is the first layer the sunlight passes and harvests nearly twice the solar energy than the water. Clearly, the total energy absorption efficiency reduces when the solar incidence angle increases. There exist two obvious drops, one occurred from 15° to 20°, and another one occurred around 75°. The first drop is due to the reduction of effective glass area with increasing incident angle. The second drop is because of the increased reflectivity in the first glass/water interface. With normal incidence (0°), the absorption efficiency is the largest, reaching 63.2%. At
the angle of 15°, the total absorption efficiency only slightly reduces to 62.1%, only 1.7% reduction as compared to the normal incidence. At 20°, the efficiency drops to 55.5%. At 75°, the total absorption efficiency further drops to 36.0%.

Finally, it is meaningful to understand the absorption of solar energy under some distinct solar spectral ranges. Those that are not absorbed will be either transmitted into the room space or reflected outside the window. Here we consider three distinct spectra: UV in the range 280 – 400 nm, VIS in the range 400 – 700 nm, and IR in the range 700 - 4,000 nm. To differentiate the three spectra, the 7-band model is adopted in the calculations. Fig. 3.8 shows that all angles have the same absorption tendency. The glass medium absorbs the most UV and VIS light. The water medium absorbs little UV and
VIS light. As for the IR, both the glass and water absorptions are strong. The absorption of the IR solar energy in the louver is very high, about 85.9% for the 0° case, 84.5% for the 15° case, 73.7% for the 30° case, 68.8% for the 45° case, 65.5% for the 60° case and 53.3% for the 75° case. Since more than 50% solar radiation consists of infrared radiation, the water inside the hollow louver is significant for solar energy harvesting, particularly for 30° and 45° cases. For the UV light, all angles cases absorb the majority of UV light, the total absorption reaches 84.9% for the 0° case, 85.4% for the 15° case, 73.4% for the 30° case, 66.0% for the 45° case, 63.6% for the 60° case and 51.8% for the 75° case, respectively. It means that the UV light is well absorbed by the louver, protecting occupants from over-exposure to the UV. With the angle increasing, the absorption efficiency for VIS light drops down. The absorption of VIS in the louver is weak, only about 34.9% for the 0° case, 32.1% for the 15° case, 17.1% for the 30° case, 13.4% for the 45° case, 13.0% for the 60° case and 10.5% for the 75° case. Therefore, most of the VIS light can pass through the louver for natural illumination.
Figure 3.8 Solar energy absorption efficiencies in three distinct spectra with incident polar angle of $0^\circ$, $15^\circ$, $30^\circ$, $45^\circ$, $60^\circ$ and $75^\circ$, respectively.
3.4 Conclusions

The collimated solar irradiation into a silica glass louver filled with water is investigated using the Monte Carlo ray tracing method. The AM1.5 solar irradiation spectrum and spectral properties of materials are considered. The influences of grid meshing, spectral band division, photon number, and solar incident angle are examined. The absorption efficiency against different light regimes of UV, VIS, and IR as well as between the glass and water is distinguished. Some concluding remarks can be drafted as follows:

The total solar energy absorption efficiency in the louver is 61.2% under normal incidence based on the 40-band calculation. The 7-band model gives a slightly higher value at 63.2%, but reduces the CPU time to less than 15% of that by the 40-band model. The 1-band (gray) model and 3-band (splitting UV, VIS, and IR) model are not suitable for modeling solar energy transport in glass-water structures.

The solar energy absorption efficiency decreases as incident polar angle enlarges. From normal incidence to 15°, however, the absorption efficiency only decreases by 1.7%. As the polar angle increases to 20°, the efficiency drops to 55.5%. At 75°, the total absorption efficiency drops to 36.0%.

Both the glass and water in the louver absorb IR strongly. The glass absorbs the most UV and VIS light, and the water absorbs little UV and VIS light. Under normal incidence, about 85% IR and UV solar energy is absorbed by the louver. The absorption of VIS in the louver is weak, about 34.9% for normal incidence; and it drops to 10.5% for the 75° case.
The calculation of overall solar energy harvest in the louver is a weak function of element division. However, the local energy absorption does depend on the element division. A finer mesh will give a better symmetric distribution in the louver. For collimated irradiation, computational accuracy is also a weak function of photon number. With $10^8$ photons for each spectral band, a good compromise between computational efficacy and accuracy can be realized.
A water-filled prismatic glass louver was proposed to save energy consumptions in buildings because such innovative louvers can harvest solar energy as well as improve daylighting quality rather than “block” sunlight like traditional louvers. To enable this technology, the effectiveness of UV and infrared IR energy harvest and VIS light transmittance was investigated via Monte Carlo simulations in this case study. The 7-band spectral model for glass and water was evaluated and adopted for several cases of solar spectra of different AM coefficients with both direct and diffuse irradiation. Absorption and transmittance in different band regimes as well as in water and glass respectively were distinguished and compared. Practical solar data in Phoenix, Flagstaff, and Golden were utilized to demonstrate the performance of the proposed louver under different locations and realistic conditions. Results show that the device facing normally to direct sunlight can harvest around 51-54% of the total solar energy and transmit 74-76% VIS for daylighting in the range of AM1.0 to AM3.0. In particular, for AM1.5, VIS transmittance reaches 76% for both direct and diffuse irradiation; UV absorption achieves 80% and 85%; and IR absorption reaches 64% and 82% for diffuse and collimated irradiation, respectively. In all the three places tested, the device absorbs about 81% IR and 87% UV, and transmits about 76% VIS.
4.1 Introduction

Chapter 3 investigated collimated solar radiation of AM1.5 spectrum through a water-filled louver; however, solar irradiation through windows contains both comparable direct and diffuse components, and a very small portion of circumsolar and horizon brightening. Under cloudy condition the diffuse component increases. The impact of diffuse irradiation is different from that of direct irradiation. The solar spectrum for the diffuse component generally differs from the direct one. The spectrum also varies by location, weather, season, day, and even time.

Chapter 4 takes both direct and diffuse irradiation, and both energy absorption and transmittance into account to enable the practical use of the proposed louvers, i.e., daylighting as well as energy harvesting. The MC method for collimated/diffuse irradiation discussed in chapter 2 will be applied here. The brightening radiation is neglected as its data are not provided in the AM models selected in this case study. It is noticed that Wojcicki [75] derived the effective beam radiation incidence angles for diffuse and reflected solar radiation for single or double glazed flat plate. Nevertheless, the MC method is very flexible and can easily treat radiation from any direction. Different diffuse ratios and various air mass coefficients will be adopted to demonstrate the feasibility and capability of the prismatic louver deployment under various weather and environmental conditions. Discrete spectral bands for different AM spectra will be calculated. We further use practical solar irradiation data obtained from three locations in the US to calculate the solar energy absorption efficiency and VIS transmittance through the water-filled prismatic glass louver. Absorption in water and glass will be scrutinized and differentiated.
It is critical to model the respective contribution of diffuse and direct irradiation properly. Differences between diffuse and direct irradiation exist in terms of incident angle, photon penetration path, and AM spectrum. Kirn and Topic [76] addressed the contribution of diffuse and direct solar irradiance separately to achieve higher accuracy in power rating photovoltaic modules and systems. Aler et al. [77] improved the separation of direct and diffuse solar irradiation using the gradient boost machine learning technique. Rossi et al. [78] described the correlation between global, diffuse and direct daily solar radiation of the total spectrum and the IR spectrum.

Spectral consideration is also necessary as the solar spectrum spans a wide wavelength range and the properties of material are wavelength-dependent [48]. Though line-by-line spectral calculation [79] is the most accurate, it is incredibly time-demanding. Therefore, it is paramount to consider band-average techniques that are based on the significance and difference of various radiation bands [80]. Escobedo et al. [65] used hourly and daily radiometric data to establish several empirical models for predicting the fractions of three bands. A solar spectrum is generally distinguished by three distinct bands, i.e., UV, VIS, and IR. Variation within each distinct band is still appreciable. Thus, a better band partition model that would be computationally efficient as well as accuracy is highly desired for calculating solar radiation in glass-water systems for both direct and diffuse irradiation.
4.2 Simulation model

4.2.1 Absorption efficiency

The louver is meshed into many small elements, shown in Fig. 2.5. After MC modeling of diffuse radiation simulation part in the chapter 2, and the spectral divergence of heat flux, $Q_{\lambda k}$ for an element $k$, due to solar diffuse irradiation calculated by

$$Q_{\lambda k} = \sum_{j=1}^{N_{\lambda k}} (1 - \rho_{\lambda j}) \frac{W \times E_{d \lambda}}{S_k \times NRAY},$$  \hspace{1cm} (4-1)

where $N_{\lambda k}$ is the absorbed spectral photon number in the element; $S_k$ is the cross-sectional area of the element; $NRAY$ is the total photon bundles number refracted from the inward surface of solar incidence; $E_{d \lambda}$ is the spectral diffuse solar heat flux incidence on the outward surface of the louver; and $\rho_{\lambda j}$ is the spectral surface reflectivity of the $j$-th absorbed photon from air to silica glass. The total divergence of heat flux for the diffuse irradiation, $Q_{dk}$, is an integral of the spectral value, i.e., the sum of contributions from all the solar bands:

$$Q_{dk} = \frac{W \times E_d}{S_k} \sum_{\lambda=280nm}^{4000nm} \sum_{j=1}^{N_{\lambda k}} \frac{(1 - \rho_{\lambda j})}{NRAY} W_{\lambda},$$  \hspace{1cm} (4-2)

where $E_d$ is the total diffuse solar heat flux onto the louver and $w_{\lambda}$ is the energy weighting factor of a spectral band.

Since the solar heat flux varies depending on locations, seasons, days and time, it would be more convenient to show the energy absorption in terms of normalized energy harvest $Q'_{dk}$ defined as:

$$Q'_{dk} = \frac{Q_{dk}}{E_d},$$  \hspace{1cm} (4-3)

The energy absorption efficiency for diffuse irradiation, $\epsilon_{d}$, is defined as:
We compare absorption efficiency in the glass and water, respectively. The efficiency for the whole louver is a sum from both two media.

Similarly, the collimated solar irradiation can be calculated. Suppose the ratio of the diffuse component to the total irradiation is $rd$, and $Q_{ck}$ is the contribution due to collimated irradiation, then the local divergence of heat flux, $Q_k$ including both direct and diffuse irradiation, for an element would be

$$Q_k = Q_{ck} + Q_{dk}$$  \hfill (4-5)

The total normalized energy harvest $Q'_{k}$ would be

$$Q'_{k} = rd \times Q'_{dk} + (1 - rd) \times Q'_{ck}$$  \hfill (4-6)

And the total efficiency $\epsilon_{\text{total}}$ for both direct and diffuse irradiation would be:

$$\epsilon_{\text{total}} = rd\epsilon_{d} + (1 - rd)\epsilon_{c}$$  \hfill (4-7)

where $\epsilon_{c}$ is the absorption efficiency corresponding to the collimated irradiation.

Similarly, we can calculate the total transmittance accounting the photons passing through the louver while excluding those directly reflected from and transmitted out of the solar incident surface.

### 4.2.2 Band-averaging method

Solar irradiation is highly spectral, and so are the properties of water and glass in the whole solar spectrum ranging from $280 – 4,000$nm. Both glass and water are highly absorbing medium for solar irradiation. Scattering in the glass is negligible and extremely weak in water. Further, spectral variation in refractive index should be counted for both
glass and water. There exists a mismatch of refractive indices in the interfaces between glass/air and glass/water. For each partition band in the solar spectrum, band-averaged properties are calculated by:

\[
P_{\lambda_{12}} = \frac{\int_{\lambda_1}^{\lambda_2} P_{\lambda} I_{\lambda} d\lambda}{\int_{\lambda_1}^{\lambda_2} I_{\lambda} d\lambda},
\]

where \( P_{\lambda} \) represents a spectral property, \( I_{\lambda} \) is the spectral solar intensity, and \( P_{\lambda_{12}} \) can be the band-averaged scattering or absorption coefficient, or refractive index in a discrete band between wavelengths \( \lambda_1 \) and \( \lambda_2 \).

4.3 Results and discussion

4.3.1 Validity of the 7-band model

All the present MC simulations were run on a laptop equipped with an Intel Core i-7-4720HQ 2.60 GHz CPU. Computational accuracy and efficiency depend on the band division, element division, and photon number. We divide a solar spectrum into discrete bands, and band-averaged properties are used in our calculations. The spectrum was divided in a way such that property profiles are relatively smooth within each band. Another consideration was that each partition band contains a similar amount of solar energy; and thus, the bandwidth of each band is different: in the region with condensed energy, such as the VIS and near-infrared (NIR) regions, bandwidth is narrower; while in the IR region, bandwidth is wider.

Unless otherwise specified, the AM1.5 spectrum from ASTM Standard G173-03 [15] was adopted as a standard in calculating solar irradiation on the earth’s surface. Details about the bands’ division with AM1.5 spectrum for collimated irradiation were described in chapter 3, in which a grey 1-band model, 3-, 7-, 20-, and 40-band models were
considered and compared. The 7-band model was recommended as a compromise of balance between computational accuracy and efficiency. Though the AM1.5 spectrum for diffuse irradiation is somewhat different, we can use the same band partitions as the difference is not remarkable. Regardless, the band-averaged properties are different between the collimated and diffuse irradiation and for different AM models. Thus, we examine the band models for diffuse irradiation at first.

The CPU times used for calculations under different photon numbers, element numbers, and band numbers for diffuse and collimated irradiation are listed in table 4-1 for comparison. The CPU time consumed is generally longer for diffuse irradiation than for collimated irradiation. Comparing the current CPU times for collimated irradiation with those listed in chapter 3, the new photon hitting justification strategy introduced in this study has shortened the calculation time by 30-40%. In agreement with our previous finding for collimated irradiation, we found that CPU time was not sensitive to element division, and $10^8$ photons were sufficient to obtain accurate results for diffuse irradiation. Therefore, 7,140 elements and $10^8$ photon bundles were adopted in all the calculations hereafter.

<table>
<thead>
<tr>
<th>Photon #</th>
<th>Element #</th>
<th>Band #</th>
<th>Diffuse, CPU (s)</th>
<th>Collimated, CPU (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^6$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$10^7$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$10^8$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$10^9$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$10^8$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$10^8$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$10^8$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
A proper band division of the solar spectrum is pivotal for accurate and efficient modeling of solar irradiation. In general, the larger the band partition number, the more precise the calculation is; however, CPU time increases with increasing band number. Figure 4.1 shows the normalized diffuse solar energy harvest distributions along the louver centreline for five different band models. The results from the grey (1-band) and 3-band divisions deviate substantially from the other three models. The 7-band and 20-band models’ profile coincide well and are in a good agreement with the 40-band model except the local peak value around $Z/H=0.08$. In comparison with the result for collimated irradiation, the normalized solar energy harvest for diffuse irradiation is smaller. This is because the collimated irradiation under normal incidence could be attenuated more in the louver.
Figure 4.1 Normalized diffuse solar energy harvest along the louver centreline (x=y=0) for different band models.

Fig. 4.2 shows the glass/water/total solar energy absorption efficiencies and the transmittance for diffuse irradiation with different band divisions. It is seen that the predicted absorption and transmittance efficiencies vary with band partition number until 7 band partitions and then is almost flatten in the range from 7 bands to 40 bands. Thus, the 7-band model provides a good accuracy.
The contours of normalized diffuse solar energy harvest in the whole louver are plotted in Fig. 4.3. The 1-band and 3-band models predict a larger absorption in the glass, i.e., the solar irradiation is heavily attenuated by the glass layer facing solar incidence. The 7-band model is still a good choice as its result is close to the predictions of the 20- and 40-band models. The same conclusion held for collimated irradiation. Therefore, the 7-band model is justified and used hereafter for both collimated and diffuse irradiation.
4.3.2 Absorption/transmittance efficiency

In many practical applications, a solar spectrum is categorized by three distinct sub-spectra: UV in the range 280-400 nm, VIS in the range 400-700 nm, and IR in the range 700-4,000 nm. The water-filled prismatic louver is designed to absorb solar IR and UV radiation for harvesting energy, but pass VIS light through for daylighting. It would be very useful to understand the energy absorption efficiency and transmittance under these three distinct wavelength ranges. In this sub-section, AM1.5 spectrum was adopted in all the calculations.

Fig. 4.4 shows the absorption/transmittance efficiencies in UV, VIS, and IR, respectively, for diffuse and collimated (normal incidence) irradiation. It is observed that the glass medium absorbs the most UV and VIS light; as for the IR, both the glass and
water absorb strongly. The total absorption of IR solar energy in the louver is very high, about 63.8% for the diffuse irradiation and 82.3% for the collimated irradiation. For the UV light, the absorption for both the diffuse and collimated irradiation is strong, and the total absorption reaches about 80% for the diffuse radiation and 84.9% for the collimated one. It means that UV light is well absorbed by the louver, protecting occupants in a room from over exposure to harmful UV irradiation. The absorption of VIS is weak, only about 14.1% for the diffuse light and 19.2% for the collimated light. However, VIS transmittance is quite high, about 76.3% for both the diffuse and collimated light. It well explains that most VIS light can pass through the water-filled glass louver for natural illumination.
Figure 4.4 Solar energy absorption/transmittance efficiencies in three distinct spectra for both diffuse and direct irradiation.
The ratio of diffuse intensity over total irradiation (diffuse + direct) varies with locations, seasons, days, time, and weather conditions. Each air mass value has a diffuse ratio. To simplify the problem and inspect the effect of diffuse ratio, we assumed a varying diffuse ratio from 0.2 to 1.0 in Fig. 4.5, in which the glass/water/total solar energy absorption efficiencies and VIS transmittance are plotted. The collimated irradiation is of normal incidence. A unity diffuse ratio represents an opaque cloud. It is seen that as the diffuse ratio increases, the water absorption efficiency decreases obviously, but the glass absorption efficiency decreases slightly, and the VIS transmittance is nearly constant at 76%. Glass absorption efficiency is much larger than water absorption efficiency. The total energy absorption efficiency increases from 40.6% to 51.9% when the diffuse ratio declines from unity to 0.2. It means that the louver performs better under clearer sky conditions. The louver under overcast clouds absorbs about 22% less solar energy than that under a clear sky.
Fig. 4.6 depicts the absorption/transmittance efficiencies vs. the incident angle of collimated irradiation. In Fig. 4.6 (a), the polar angle of collimated incidence varies from 0° to 90°, and the circumferential angle is fixed at Φ = 0°. It is seen that the variation of absorption efficiency is smoother in the water than in the glass. This is because the glass medium is the first incident layer of the sunlight. The glass has a larger absorption coefficient and harvests nearly twice as much solar energy than that of the water inside the louver. Initially, the total energy absorption efficiency increases, and the VIS transmittance decreases as the polar angle grows from zero to a small value (5°). Then, both the total absorption and VIS transmittance nearly flatten until 15°. After that, the total energy absorption efficiency reduces with increasing polar angle. For the VIS
transmittance, however, the efficiency starts to increase after 15° to a maximum around 45°. After that, the VIS transmittance drops as the angle increases. Both the absorption efficiency and transmittance drop rapidly after 75°. Under normal incidence (0°), the total absorption efficiency reaches 55.5%. At 5°, the total absorption efficiency reaches a maximum of 56.8%, and remains about 56% from 5° to 15°. This is because the incident light at 5° can travel longer distance inside the glass medium than the normal and other incident angles; and thus, more energy can be absorbed by the glass layer. At 20°, the efficiency drops to 51.1%. This drop is due to the reduction of effective glass area with an increasing incident angle. At 75°, the total absorption efficiency further falls to 31.7%. After 75°, an abrupt drop occurs because of the increased reflectivity in the first glass-water interface. As for the VIS transmittance, it remains around 75% from 5° to 15°, and reaches a maximum of about 83.4% at 45°.

In Fig. 4.6(b) the circumferential angle of collimated incidence varies between 0° and 90° and the polar angle is fixed at θ = 20°. Because the louver geometry is symmetric, we only need to investigate the influence on circumferential angle in one octant. It is seen that as the circumferential angle enlarges, the glass/water/total absorption efficiencies slightly increase, but the VIS transmittance slightly falls. The water/glass/total absorption and VIS transmittance efficiencies are 19.9%, 37.5%, 57.4%, and 72.9%, respectively at ø = 90°, and 18.8%, 32.4%, 51.1%, and 78.4%, respectively at ø = 0°. This is attributed to the fact that the incoming light travels longer distance in the glass medium when the circumferential angle increases.
Figure 4.6 Effects of incident angle of the collimated irradiation on solar energy absorption and VIS transmittance: a) polar angle; and b) circumferential angle.
4.3.3 Effect of air mass spectrum

In addition to AM1.5, we further developed the 7-band model to incorporate AM1, AM2, and AM3, and listed the spectral band-averaged properties of water and glass for the four air mass coefficients in table 4-2 for both diffuse/collimated irradiation. In the calculations, we used the spectral data of water from Hale and Querry [74] and those of silica glass from Herzberger [72] and Rubin [73]. As scattering is negligible in glass and very weak in water, the values for scattering coefficients are not listed in table 4-2. The simple model of SMARTS developed by Dr. Christian Gueymard computes clear-sky spectral irradiances. In this and following sub-section, we obtained the solar spectra data from NREL SMARTS code (https://www.nrel.gov/grid/solar-resource/smarts.html) and calculated the diffuse ratio for each air mass spectrum. The diffuse ratio is 0.2635, 0.2232, 0.2426, and 0.2802, corresponding to AM1.0, 1.5, 2.0, and 3.0, respectively.
Table 4-2 Spectral properties of material in the 7-band model for AM1.0 to AM3.0 spectra. (D/C = Diffuse/Collimated)

<table>
<thead>
<tr>
<th>AM#</th>
<th>λ (nm)</th>
<th>n_{glass} D/C</th>
<th>n_{water} D/C</th>
<th>a_{glass}(m^{-1}) D/C</th>
<th>a_{water}(m^{-1}) D/C</th>
<th>w(%) D/C</th>
</tr>
</thead>
<tbody>
<tr>
<td>280–400</td>
<td>1.5440/1.5430</td>
<td>1.3427/1.3421</td>
<td>178.8291/122.8164</td>
<td>0.2288/0.1957</td>
<td>15.8004/4.3827</td>
<td></td>
</tr>
<tr>
<td>400–548</td>
<td>1.5302/1.5300</td>
<td>1.3360/1.3360</td>
<td>5.1404/4.9238</td>
<td>0.0332/0.0322</td>
<td>32.3281/20.9044</td>
<td></td>
</tr>
<tr>
<td>548–700</td>
<td>1.5218/1.5225</td>
<td>1.3312/1.3313</td>
<td>12.4456/12.8232</td>
<td>0.2540/0.2645</td>
<td>21.0546/21.4920</td>
<td></td>
</tr>
<tr>
<td>700–850</td>
<td>1.5179/1.5177</td>
<td>1.3292/1.3300</td>
<td>33.7586/34.2335</td>
<td>2.3779/2.4048</td>
<td>12.5021/15.8989</td>
<td></td>
</tr>
<tr>
<td>850–1100</td>
<td>1.5144/1.5142</td>
<td>1.3265/1.3268</td>
<td>54.4810/54.7346</td>
<td>31.0781/32.5442</td>
<td>10.3138/16.6866</td>
<td></td>
</tr>
<tr>
<td>1100–1530</td>
<td>1.5101/1.5105</td>
<td>1.3227/1.3300</td>
<td>52.5434/51.8163</td>
<td>414.4431/445.388</td>
<td>5.0196/10.7063</td>
<td></td>
</tr>
<tr>
<td>1530–4000</td>
<td>1.5028/1.5004</td>
<td>1.3114/1.3155</td>
<td>36.8057/58.4255</td>
<td>2.3592/2.4007</td>
<td>13.3306/16.195</td>
<td></td>
</tr>
</tbody>
</table>

The air mass effect on solar energy absorption and transmittance in the respective UV, VIS and IR regions is shown in Fig. 4.7. Both UV and IR absorption in the louver is very strong for all the four AM spectra. The IR absorption efficiency is 80.3%, 79.8%, 76.8%, and 80.1% for AM1.0, 1.5, 2.0, and 3.0, respectively. The corresponding UV
absorption efficiency is 86.2%, 83.5%, 70.9%, and 69.8%, respectively. Thus, the influence of air mass on IR absorption efficiency is weak; but the UV absorption efficiency decreases as air mass value increases. This is because the glass absorption coefficient for UV reduces as AM value increases. The VIS absorption in the louver is weak, all below 20% for the four AM values; but VIS transmittance is quite high, reaching 75.4%, 76.3%, 74.0%, and 74.4% for AM1.0, 1.5, 2.0, and 3.0, respectively. Thus, the AM does not affect much VIS transmittance.
Figure 4.7 Effects of air mass spectrum on solar energy absorption and transmittance in UV, VIS, and IR regions, respectively.
Fig. 4.8 displays the effect of air mass value on water/glass/total absorption efficiencies and VIS transmittance. With increasing AM value, the water absorption efficiency increases, but the glass absorption efficiency decreases. The total absorption efficiency changes slightly, ranging from 51.8% to 53.9% for the four AM coefficients. The variation on VIS transmittance is also small. VIS transmittance varies between 74.4% and 76.3%. It should be mentioned that during the calculations, the collimated irradiation was assumed of normal incidence and the circumsolar and horizon brightening was ignored. When the louver is adjusted to face the direct sunlight, it will perform well for all air mass conditions.

Figure 4.8 Solar energy absorption efficiency and VIS transmittance vs. air mass coefficient.
4.3.4 Proof-of-concept study

As a proof-of-concept study to enable practical installation of the water-filled prismatic glass louvers, we calculated and compared the louver performance at three locations: Phoenix (P) and Flagstaff (F) in Arizona, and Golden (G) in Colorado, using solar data from the NREL SMARTS code. The spectral solar irradiances are plotted in Fig. 4.9 for both direct and diffuse irradiation. All the band-averaged properties for the three places are listed in Table 4-3. The diffuse ratio is 0.1046, 0.08633, and 0.1107 for P/F/G, respectively.
Figure 4.9 Spectral solar irradiances at Flagstaff, Golden and Phoenix during summer time.

Table 4-3 Spectral properties of material for the three selected locations. $^a$

<table>
<thead>
<tr>
<th>Place</th>
<th>$\lambda$ (nm)</th>
<th>$n_{\text{glass}}$</th>
<th>$n_{\text{water}}$</th>
<th>$\alpha_{\text{glass}}$ D/C</th>
<th>$\alpha_{\text{water}}$ (m$^{-1}$) D/C</th>
<th>$\omega$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flagstaff, AZ</td>
<td>280–400</td>
<td>1.5447/1.5429</td>
<td>1.3431/1.3420</td>
<td>187.7624/121.8088</td>
<td>0.2347/0.1966</td>
<td>17.375/4.550</td>
</tr>
<tr>
<td></td>
<td>400–548</td>
<td>1.5307/1.5300</td>
<td>1.3363/1.3359</td>
<td>5.1926/4.9302</td>
<td>0.0334/0.03229</td>
<td>30.029/21.058</td>
</tr>
<tr>
<td></td>
<td>548–700</td>
<td>1.5227/1.5221</td>
<td>1.3314/1.3317</td>
<td>12.5969/12.8139</td>
<td>0.2582/0.2644</td>
<td>19.783/21.397</td>
</tr>
<tr>
<td></td>
<td>700–850</td>
<td>1.5179/1.5179</td>
<td>1.3291/1.3302</td>
<td>33.9149/34.2280</td>
<td>2.3852/2.4041</td>
<td>12.367/15.787</td>
</tr>
<tr>
<td></td>
<td>850–1100</td>
<td>1.5147/1.5145</td>
<td>1.3275/1.3267</td>
<td>54.5382/54.7290</td>
<td>31.272/32.5010</td>
<td>10.632/16.574</td>
</tr>
<tr>
<td></td>
<td>1100–1530</td>
<td>1.5103/1.5103</td>
<td>1.3227/1.3229</td>
<td>52.1497/51.7478</td>
<td>20.223/22.11</td>
<td>5.542/10.793</td>
</tr>
<tr>
<td></td>
<td>1530–4000</td>
<td>1.5032/1.5001</td>
<td>1.3165/1.3156</td>
<td>55.9517/59.4039</td>
<td>22437.77/25388.48</td>
<td>4.272/9.841</td>
</tr>
</tbody>
</table>

| Phoenix, AZ | 280–400        | 1.5457/1.5427      | 1.3427/1.3418      | 183.0197/122.7706             | 0.2307/0.1960                          | 21.449/4.537 |
|             | 400–548        | 1.5308/1.5296      | 1.3363/1.3356      | 5.1831/4.9229                 | 0.0333/0.03229                         | 40.383/21.532 |
|             | 548–700        | 1.5225/1.5215      | 1.3319/1.3311      | 11.9715/12.8030               | 0.2409/0.2369                          | 20.223/22.11 |
|             | 700–850        | 1.5187/1.5174      | 1.3294/1.3290      | 33.4706/34.2330               | 2.3658/2.4073                          | 8.981/15.992 |
|             | 850–1100       | 1.5143/1.5141      | 1.3271/1.3267      | 54.1861/54.7311               | 29.514/32.6616                         | 5.882/16.370  |
|             | 1100–1530      | 1.5109/1.5103      | 1.3233/1.3228      | 53.0507/52.0093               | 390.391/443.6420                       | 2.001/9.825  |
|             | 1530–4000      | 1.5032/1.5004      | 1.3129/1.3147      | 38.5970/55.7801               | 45320.17/14727.21                      | 1.081/9.634  |

| Golden, CO  | 280–400        | 1.5441/1.5429      | 1.3428/1.3421      | 177.1455/118.5965             | 0.2302/0.1949                          | 19.893/4.424 |
|             | 400–548        | 1.5310/1.5230      | 1.3365/1.3359      | 5.1493/4.9157                 | 0.0332/0.0321                          | 38.456/20.663 |
|             | 548–700        | 1.5217/1.5221      | 1.3304/1.3316      | 12.1313/12.8914               | 0.2455/0.2665                          | 20.450/21.299 |
|             | 700–850        | 1.5185/1.5178      | 1.3309/1.3294      | 33.6100/34.3250               | 2.3641/2.4061                          | 9.878/15.865 |
|             | 850–1100       | 1.5138/1.5143      | 1.3259/1.3268      | 54.2891/54.7780               | 29.879/32.7004                         | 6.947/16.793 |
|             | 1100–1530      | 1.5132/1.5104      | 1.3289/1.3229      | 52.8717/51.7180               | 405.263/451.1257                       | 2.775/10.989 |
|             | 1530–4000      | 1.5021/1.5005      | 1.3132/1.3153      | 44.5994/57.5710               | 31650.01/25722.35                      | 1.601/9.967  |


The solar spectrum for Flagstaff in a dry, desert-like environment was generated for AM1.2 at an elevated site at 34° latitude. The same summer atmosphere was used (20°C temperature, 30% relative humidity), but a default humidity-dependent aerosol model was selected. The UV irradiance was calculated on a receiver tilted 34° towards South (i.e., tilt = latitude). This geometry is such that near normal incidence is reached at the
equinoxes. Because AM1.2 corresponds to a zenith angle of 33.59°, the incidence angle at solar noon on equinox days is 0.41°.

Solar noon time for specific mid-summer day, July 15, 2000, was considered in generating the solar spectrum for Phoenix (latitude 33.433N, longitude 112.007W). All gaseous abundances were defaulted from the reference atmosphere selected (MLS).

The spectrum for Golden was the output of a spectroradiometer under realistic conditions. The experiment took place at NREL, Golden, Colorado, during the Summer of 2001. The basic atmospheric profiles were assumed to be described by the default MLS reference atmosphere. The site being relatively close to various pollution sources within the Denver urban area; thus the light pollution option was selected. The type of aerosol is not known, but is probably close to a rural model.

Fig. 4.10 shows and compares the absorption efficiency and transmittance in the three places. The collimated irradiation to the louver is assumed to be normally incident. It is seen that the louver performs very well at all three places. The device absorbs 87.2%, 88.3%, and 86.9% UV light, and 80.9%, 82.2%, and 81.9% IR radiation in P/F/G, respectively. The VIS absorption is weak, about 18.9%, 19.2%, and 19.4% in P/F/G, respectively. The VIS transmittance is high, achieving 75.9%, 75.8%, and 75.5% in P/F/G, respectively. We also calculated the total solar energy absorption efficiency, which is 53.2%, 55.4%, and 56.1% in P/F/G, respectively.
Figure 4.10 Absorption/transmittance efficiencies in three places with practical solar data.

4.4 Conclusion

In this chapter, the aim of this case study is to develop the 7-band spectral model for spectral investigation of solar irradiation under various solar spectra and conditions as well as to evaluate the performance of a water-filled prismatic glass louver to enable its practical use. Other innovations in this study include uses of various AM spectra and associated band averaging data, practical solar data and realistic conditions in three places, and VIS transmittance, etc. The ray tracing process is the same for diffuse and collimated irradiation. As compared with direct irradiation, a difference is that the direct irradiation has an initially fixed incident direction, while the diffuse one has a distribution. Their initial reflectance from the incident surface and solar spectrum are also different. In
the present study, diffuse irradiation is assumed to be isotropic, ignoring circumsolar and horizon brightening. Such irregularity could be dealt with by the MC method if data were available.

The louver has dual-purpose: solar energy harvesting and daylighting. Both direct and diffuse irradiation were considered and compared. Differences of absorption and transmission between water and glass and among the three distinct spectral regions, i.e., UV, VIS and IR, were examined and scrutinized. Performance under practical solar data at three places with realistic conditions was demonstrated. Important conclusions can be summarized as follows:

1. The proposed louver can be used to harvest solar energy and improve daylighting effectively in different places under different conditions. The three practical examples in Phoenix and Flagstaff, Arizona, and Golden, Colorado show that the device can absorb 87-88% UV and 81-82% IR radiation energy, and transmit about 76% VIS light. The total solar energy absorption efficiency reaches 53-56% in the three places under testing conditions.

2. The influence of AM value on the total absorption efficiency and VIS transmittance is very small. We considered AM1.0, 1.5, 2.0, and 3.0 spectra, and found that the total solar energy absorption efficiency ranges from 51.8% to 53.3%, and the VIS transmittance varies between 74.4% and 76.3%. The air mass does affect the UV absorption efficiency, which is 86.2%, 83.5%, 70.9%, and 69.8% for AM1.0, 1.5, 2.0, and 3.0, respectively. The corresponding IR absorption efficiency is 80.3%, 79.8%, 76.8%, and 80.1%, respectively.
3. The change of solar energy absorption efficiency and VIS transmittance is very slight as the diffuse ratio varies. This further justifies the fact that the proposed louver would work well in any locations, seasons, and under any weather conditions.

4. Both the glass and water media absorb IR radiation strongly. The glass absorbs the UV strongly and some VIS light. The water absorbs little UV and VIS light. VIS transmittance is very high and the majority of the UV light can be blocked by the louver, reducing the risk of UV overexposure of occupants.

5. The incident polar angle of direct sunlight affects the solar energy absorption and VIS transmittance. The total energy absorption efficiency increases, and the VIS transmittance decreases slowly as the polar angle grows from 0° to 5°. Then, both the efficiencies nearly flatten until 15°. After that, the energy absorption efficiency reduces with an increasing polar angle; but the VIS transmittance starts to increase until a maximum around 45°. After that, the VIS transmittance drops with an increasing angle. In practice, a louver can be adjusted to face the sunlight within a small variation of polar angle (e.g., <15°); and thus, the effect of incident angle should not be a concern. Further, the effect of the circumferential angle for the collimated incidence is not appreciable. With increasing circumferential angle, the energy absorption efficiency slightly increases, while the VIS transmittance slightly drops.

6. Through intensive comparisons among different spectral band models, treating the solar spectrum as grey or simply dividing it into 3 bands is not good enough for accurately simulating solar radiation transfer through glass and water. With 20 and 40 bands, the
accuracy improves, but the computation is time-consuming. The 7-band model works well as a compromise of balance between computational efficiency and accuracy.
CHAPTER 5

ENHANCED ABSORPTION OF SOLAR ENERGY IN A DAYLIGHTING LOUVER WITH Ni-WATER NANOFLUID

It is well known that the addition of some NPs to a base fluid can enhance solar radiation absorption; however, its influence on simultaneous solar energy harvesting and daylighting is rarely studied. Water is nearly transparent to VIS light but highly absorbing of UV and IR. It is necessary to examine water-based nanofluid performance in a glass louver for dual purpose – illumination and energy harvesting. First, we investigated the absorption and scattering efficiencies of NPs commonly used in solar energy research, including Ni, SiO₂, Fe₂O₃, Al₂O₃, TiO₂, and ZnO; and found that Ni NPs are the most desirable because they have an excellent balance between UV and IR absorption and VIS transmission. Then the spectral coefficients of absorption and scaled isotropic scattering with different NP sizes and concentrations in Ni-water nanofluids were scrutinized. Results show that the higher the NP size or concentration is, the higher absorption and scaled isotropic scattering coefficients are. A dilute 0.00004 vol% Ni-water nanofluid with a particle diameter of 80 nm was found to absorb more solar energy and provide required daylighting. Under the AM1.5 model, a glass louver filled with such a nanofluid can transmit 46.5% solar VIS for daylighting and harvest 65.7% of the total solar energy, which is a 25.9% increase as compared to pure water.
5.1 Introduction

Chapter 4 investigated natural illumination (daylighting) and solar energy absorption through a liquid/water-filled prismatic glass louver. Water was mainly used to split the solar spectrum (280 – 4,000 nm) and to store and transport solar/thermal energy given its excellent spectral property: deficient absorption to VIS (400-700 nm) light but extremely strong absorption of UV (280-400 nm) and IR (700-4,000 nm). Such prismatic louvers can transmit and redirect VIS direct (collimated) sunlight to room ceiling such that the room space can be illuminated. This will eliminate the “glare effect” in daylighting through windows and improve natural lighting quality and comfortableness. On the other side, the liquid/water filled inside the hollow glass louver will absorb UV and IR solar irradiation and convert and store the solar energy into thermal energy for heating purposes or other usages. Though nanofluids were initially proposed to the National Science Foundation in 2014 (NSF Grant #ECCS-1505706) as the filling material inside such a kind of hollow louver by Dr. Guo, the impacts of the use of nanofluid on the performance of daylighting and solar energy harvesting have never been studied quantitatively.

According to Monthly Energy Review (April 2019) published by U.S. Energy Information Administration, renewable energy occupied only 11% of the U.S. primary energy consumption in 2018; and of the renewable energy source, solar energy accounts for just 8%. The deployment of the proposed innovative louvers in buildings will substantially save electrical power and protect the environment as well as increase the utilization of renewable solar energy. It is well known that the building sector is the largest energy consumer in the U.S. “We spend more than $400 billion each year to
power our homes and commercial buildings, consuming approximately 74% of all
electricity used in the United States, about 40% of our nation's total energy bill...U.S.
buildings account for nearly 40% of the nation's human-made carbon dioxide emissions,
18% of the nitrogen oxide emissions, and 55% of the sulfur dioxide emissions. These
emissions - primarily from electricity generation - in turn, contribute to smog, acid rain,
haze, and global climate change.”, quoted from

Nanofluids have been extensively explored for enhancing heat transfer [81-85] as
the addition of NPs is generally reported to improve the thermal properties of
conventional heat-transfer fluids such as ethanol, heating oil, and water [86-89].
Nanofluids have been widely adopted in solar energy research to enhance either solar
radiation, heat convection or both [90-93]. In addition, some controversial results and
challenging issues on nanofluids (especially discrepancies and inconsistencies in property
predictions and measurements) have also been reported [94-96]. It is worth to mention
that Guo [40] provided a comprehensive review on the prospects, challenges, and
contradictions with the use of nanofluids for heat transfer enhancement in applications to
cooling technology, renewable energy, and building technology.

Various NPs, such as Ni, SiO₂, Fe₂O₃, Al₂O₃, TiO₂, or ZnO, among many others,
were commonly considered for applications to solar energy systems. Sundar et al. [97]
investigated experimentally the heat transfer and friction factor of Ni-water nanofluid
flowing in a tube. Karimi et al. [98] measured the thermal conductivity of water-based Ni
ferrite nanofluid. Navas et al. [99] utilized experimental and molecular dynamics
methods to study enhanced heat transfer of concentrating solar power with use of Ni-
mixture of diphenyl oxide and biphenyl nanofluid. Jumphokul et al. [100] conducted experiments to determine the maximum efficiency index in turbulent flow of SiO$_2$-water nanofluid. Hu et al. [101] analyzed the effect of NP size and concentration on boiling performance of SiO$_2$-ethylene glycol and water mixture nanofluid. Milanese et al. [102] measured the optical absorption of Fe$_2$O$_3$-water nanofluid in direct absorption solar power systems. Shen et al. [103] investigated ultrasonic waves’ effect on heat transfer in Al$_2$O$_3$-water nanofluid under natural convection and pool boiling. Sundar et al. [104] explored the effectiveness of solar flat plate collector with Al$_2$O$_3$-water nanofluids and with longitudinal strip inserts. Said et al. [105] evaluated the optical properties of TiO$_2$-water nanofluid for a direct absorption solar collector. Kaya et al. [106] investigated experimentally the thermal performance of an evacuated U-tube solar collector with ZnO/Ethylene glycol-pure water nanofluids. Taylor et al. [107] optimized the nanofluid-based optical filter for PV/T system.

This chapter investigated and compared the spectral properties of absorption and scattering of some common NPs applied to solar energy research. The Ni-water nanofluid was identified and established as the desired nanofluid to fulfill our solar louver device’s dual purposes, i.e., daylighting and solar energy harvesting. The effects of particle size and volume concentration were examined. The total radiation absorption for solar energy harvesting and VIS transmittance for daylighting was calculated under various conditions. The enhancement of solar energy harvesting via use of Ni-water nanofluid is found to be significant.
5.2 NP radiation modeling

Figure 5.1 is the two-dimensional (2-D) sketch of the proposed nanofluid-filled prismatic glass louver. For performance comparison with water-filled louver, the same louver dimensions as in the previous studies are adopted. The difference in the present study is that NPs are added to the water flowing through the louver; and the primary purpose of this study is to investigate the enhancement of solar energy absorption when the daylighting requirement is met. As established in section 2.5, each glass piece forming the louver is 0.1875” thick, 3” wide, and 39.4” long; and the end effect in the solar radiation calculation is negligible. One of the prismatic louver surfaces can be adjusted to face direct sunlight, assuming the top one in Fig. 5.1 for simplicity.

Figure 5.1 Sketch of nanofluid-filled louver cross-section with direct and diffuse irradiation.
The MCRT method established in our previous studies of water-filled glass louver could be employed to investigate solar radiation through the present nanofluid-filled glass louver. The significant difference in solar radiation heat transfer calculation is that radiation scattering exists and is comparable to absorption in the present nanofluid case while it is negligible in pure water case. However, our previous method and code have already incorporated scattering effect; thus, the details on collimated/diffuse MC modeling can be found in chapters 2, 3, and 4. It should be noticed that the spectral optical properties of water-based nanofluids deviate substantially from those of pure water. Water is the most-common heat-transfer medium and works well for absorbing solar UV and IR radiation but transmitting VIS light. Therefore, alteration of base fluid is not considered here. Details about the method validation on bands’ division, elements’ division, photon bundles’ selection, and selection of AM1.5 spectrum for direct and diffuse irradiation were described in chapters 3 and 4. In the present work, we still adopted the 7-band spectral model, 7,140 elements, $10^8$ photon bundles, and AM1.5 if not otherwise specified.

The required VIS transmittance for daylighting, $\eta_m$, is calculated by

$$\eta_m = \frac{q_{\text{lum}}}{286 \times q_v \times S},$$  \hspace{1cm} (5-1)

where $q_{\text{lum}}$ is the desired luminous flux; $q_v$ is the VIS power; 286 lm/W is an appropriate average spectral luminance; and $S$ is the surface in which the luminous flux flowed onto, i.e., the product of the number of louvers installed and the louver solar irradiation surface area. The optical properties of a nanofluid are the superposition of the base fluid property and that of the NPs. For water based nanofluid, water scattering is negligible; but its spectral absorption is paramount.
In the present study, AM1.5 database from ASTM Standard G173-03 [15] was adopted as the standard in calculating the solar irradiation on the Earth’s surface, whose spectral distributions of both the direct and diffuse irradiances are shown in Fig. 5.2, together with the water spectral absorption coefficient. Solar irradiation is highly spectral, and so are the properties of water-based nanofluid and glass in the whole solar spectrum ranging from 280 – 4,000 nm. Both glass and water are highly absorbing against solar UV and IR irradiation. Scattering is negligible in the glass but very strong in the nanofluid because of the presence of NPs. There exists a mismatch of refractive indices in the interfaces between glass/air and glass/nanofluid, where radiation refraction/reflection must be appropriately incorporated.
5.3 Results and discussion

5.3.1 Properties of nanoparticles

The absorption and isotropic-scaled scattering efficiency factors of some common NPs (Ni, SiO$_2$, Fe$_2$O$_3$, Al$_2$O$_3$, TiO$_2$, and ZnO) are calculated and compared in Fig. 5.3 (a) and (b), respectively. The data of particle complex refractive index used in the calculations were from https://refractiveindex.info/. Since water has weak absorption in the wavelength range from 0.28 $\mu$m to 1.1 $\mu$m, covering UV, VIS, and near-infrared (NIR) light, it would be more realistic using NPs to enhance the absorption in this spectrum range as this range occupies about half of the solar energy. In Fig. 5.3, the absorption/scaled isotropic scattering efficiency factors of SiO$_2$, Fe$_2$O$_3$, Al$_2$O$_3$, TiO$_2$, and ZnO NPs are relatively lower than those of the Ni NP in the range from 0.28 $\mu$m to 2.5 $\mu$m. More important, it would be better that the absorption efficiency factor be higher than the scaled isotropic scattering efficiency; otherwise, the solar incidence will be easily lost through back reflection. It is noticed that the scaled isotropic scattering efficiency factors of some NPs are higher than the corresponding absorption efficiency factors in some situations: in the spectra from 0.28 $\mu$m to 1.0 $\mu$m for SiO$_2$, from 0.6 $\mu$m to 1.2 $\mu$m for Fe$_2$O$_3$, from 0.28 $\mu$m to 0.425 $\mu$m for Al$_2$O$_3$, from 0.28 $\mu$m to 0.975 $\mu$m for TiO$_2$, and from 0.375 $\mu$m to 0.4 $\mu$m for ZnO; whereas the absorption efficiency factor of Ni NP is higher than its scaled isotropic scattering efficiency in the whole solar spectrum. Further, the Ni NP has a reasonable scaled isotropic scattering efficiency in the
VIS range, i.e. neither too weak nor too strong as compared with its absorption efficiency factor. This is helpful to scatter some collimated light into diffuse light and transmit sufficient VIS light for daylighting. Therefore, we select Ni NP to form a nanofluid to enhance solar energy absorption and maintain a reasonable daylighting condition.
Figure 5.3 Spectral efficiency factors for different NPs: a) absorption; and b) isotropic-scaled scattering.

Fig. 5.4 compares the spectral absorption and scaled isotropic scattering efficiency factors of the Ni NPs of different diameters (20, 40, and 80 nm). The absorption and scaled isotropic scattering efficiencies are the ratios of an absorption and scaled isotropic scattering cross-section to a particle's geometric cross-sectional area, respectively. The scattering efficiency factor decreases with increasing wavelength for all three particle sizes, whereas the scattering efficiency for the particle of 80 nm in diameter has a slight increase when wavelength increases in the narrow range from 0.28 μm to 0.425 μm. It is seen that the absorption and scattering efficiencies for the 80 nm NP are greater than those for the 40 nm and 20 nm ones. It is also noticeable that the magnitude of the
absorption efficiency factor is much higher than that of the scattering absorption efficiency in the whole solar spectrum, which means that the absorption of Ni NPs dominates over scattering. This feature is desirable for enhancing solar energy absorption.

Figure 5.4 Spectral absorption/scaled isotropic scattering efficiency factor for different Ni NP diameters.

The spectral variation of asymmetry factor of Ni NPs of different sizes is plotted in Fig. 5.5. The asymmetry factor is the first moment of the scattering phase function, which can be positive or negative corresponding to forward or backward dominant scattering. It is seen that the asymmetry factor drops rapidly in the UV and VIS regions, and nearly
flattens in the IR region. The variation is more substantial for larger particles than for smaller particles. The scattering is forward in the UV and VIS spectrum, and becomes weakly backward in the IR.

![Figure 5.5 Spectral asymmetry factor for different Ni NP diameters.](image)

5.3.2 Optical properties of Ni-Water nanofluid

Fig. 5.6 depicts the spectral absorption and scaled isotropic scattering coefficients of Ni-water nanofluids of various particle sizes at same particle concentration 0.00004 vol%, where the properties for pure water are also plotted for comparison. It is seen that the nanofluid absorption coefficient is much greater than pure water absorption coefficient in
the spectrum from 0.28 μm to 1.1 μm. For the spectrum beyond 1.1 μm, however, water absorption dominates over Ni particles and both the nanofluid and water absorptions are similar. Thus, the use of Ni-water nanofluid will enhance solar UV, VIS and near-infrared (NIR, 700-1,100 nm) absorption; but has little effect on solar IR above 1.1 μm. Also, it can be found that the scattering of the water-based nanofluid is determined by the scattering property of the NPs. Scattering in the nanofluid is not negligible like the pure water case. The scaled isotropic scattering coefficient of the Ni-water nanofluids decreases with increasing wavelength. The relatively stronger scattering for 80 nm NP helps not only convert more direct light into diffuse light to reduce the “glare effect”, but also might absorb more solar energy because of increased path length of solar light in the nanofluid. Further, the 80-nm particle has higher absorption in the NIR region, which can enhance solar energy absorption as compared to pure water or smaller particle sizes. Spectral properties of material in the 7-band model for different particle sizes at 0.00004 vol% concentration were shown in table 5-1.
Figure 5.6 Comparison of spectral absorption/scattering coefficients of Ni-water nanofluids for different particle sizes.

Table 5-1 Spectral properties of material in the 7-band model for different particle sizes at 0.00004 vol% concentration. (Df/C = Diffuse/Collimated)

<table>
<thead>
<tr>
<th>D/nm</th>
<th>λ (nm)</th>
<th>( \sigma_{nano\ fluid} (m^{-1}) ) Df/C</th>
<th>( \sigma_{glass} (m^{-1}) ) Df/C</th>
<th>( \sigma_{nano\ fluid} (m^{-1}) ) Df/C</th>
<th>( w(%) ) Df/C</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>280–400</td>
<td>0.2593/0.3472</td>
<td>140.8555/102.5293</td>
<td>21.5428/21.0570</td>
<td>14.0626/4.575</td>
</tr>
<tr>
<td></td>
<td>400–548</td>
<td>0.1138/0.1332</td>
<td>5.1727/4.9200</td>
<td>12.0445/11.4946</td>
<td>32.2913/21.288</td>
</tr>
<tr>
<td></td>
<td>548–700</td>
<td>0.0168/0.0412</td>
<td>12.0604/12.8230</td>
<td>5.4310/5.4012</td>
<td>21.5228/21.643</td>
</tr>
<tr>
<td>20</td>
<td>700–850</td>
<td>0.0031/0.0162</td>
<td>33.4190/34.1597</td>
<td>4.9977/4.9943</td>
<td>13.3306/16.195</td>
</tr>
<tr>
<td></td>
<td>850–1100</td>
<td>0.0009/0.0078</td>
<td>54.1478/54.6798</td>
<td>30.1100/32.3981</td>
<td>10.6064/16.673</td>
</tr>
<tr>
<td></td>
<td>1100–1530</td>
<td>0.0001/0.0020</td>
<td>53.1602/52.0098</td>
<td>410.5200/435.3489</td>
<td>5.0399/10.088</td>
</tr>
<tr>
<td></td>
<td>1530–4000</td>
<td>4.24e-6/0.0002</td>
<td>41.6509/54.7049</td>
<td>4820.23/16225.80</td>
<td>3.1464/9.538</td>
</tr>
<tr>
<td>40</td>
<td>280–400</td>
<td>2.4824/2.3623</td>
<td>140.8555/102.5293</td>
<td>23.4431/23.0333</td>
<td>14.0626/4.575</td>
</tr>
<tr>
<td></td>
<td>400–548</td>
<td>548–700</td>
<td>700–850</td>
<td>850–1100</td>
<td>1100–1530</td>
</tr>
<tr>
<td>--------</td>
<td>---------</td>
<td>---------</td>
<td>---------</td>
<td>----------</td>
<td>-----------</td>
</tr>
<tr>
<td></td>
<td>1.0720/1.0053</td>
<td>0.3066/0.3034</td>
<td>0.1172/0.1156</td>
<td>0.0549/0.0543</td>
<td>0.0148/0.0135</td>
</tr>
<tr>
<td></td>
<td>5.1727/4.9200</td>
<td>12.0604/12.8230</td>
<td>33.4190/34.1597</td>
<td>54.1478/54.6798</td>
<td>53.1602/52.0098</td>
</tr>
</tbody>
</table>

|        | 0.3066/0.3034 | 12.0604/12.8230 | 33.4190/34.1597 | 54.1478/54.6798 | 53.1602/52.0098 | 41.6509/54.7049 |
|--------| 0.1172/0.1156 | 0.0549/0.0543 | 0.0148/0.0135 | 0.0017/0.0010 | 0.0017/0.0010 |
|        | 0.0148/0.0135 | 0.0017/0.0010 | 0.0017/0.0010 |
|        | 9.2741/3.4937 | 5.1727/4.9200 | 1.3560/0.4138 | 3.5875/1.1090 | 0.6148/0.1908 | 0.1578/0.0464 |
|        | 5.1727/4.9200 | 12.0604/12.8230 | 33.4190/34.1597 | 54.1478/54.6798 | 53.1602/52.0098 | 41.6509/54.7049 |
| 80     | 212.840/212.8343 | 12.0604/12.8230 | 33.4190/34.1597 | 54.1478/54.6798 | 53.1602/52.0098 | 41.6509/54.7049 |
|        | 1.0843/1.0667 | 6.4125/6.3924 | 30.1100/32.3981 | 410.5200/435.3489 | 4820.23/16225.80 | 4820.23/16225.80 |
|        | 7.4003/7.1701 | 5.1727/4.9200 | 0.4906/0.4849 | 0.1260/0.1150 | 0.0135/0.0084 |
|        | 5.1727/4.9200 | 12.0604/12.8230 | 54.1478/54.6798 | 53.1602/52.0098 | 41.6509/54.7049 |
|        | 15.0479/14.8152 | 5.8040/5.7922 | 30.1100/32.3981 | 410.5200/435.3489 | 4820.23/16225.80 | 4820.23/16225.80 |

The spectral absorption and scaled isotropic scattering coefficients with different particle volume concentrations are illustrated in Fig. 5.7. It is evident that with increase of the particle concentration, both the absorption and scattering coefficients rise. There is a significant increase in absorption between the spectrum from 0.28 μm to 1.1μm. This is desirable for enhancing UV and NIR absorption, but a sacrifice of VIS transmission for daylighting. Therefore, it is critical to find a balance between illumination and energy absorption to realize the dual-purpose of the louver. Table 5-2 shows spectral properties of material in the 7-band model for different particle volume concentration at diameter of 80 nm nickel particle.
Figure 5.7 Comparison of spectral absorption/scattering coefficients of Ni-water nanofluids for different NP concentrations.

Table 5-2 Spectral properties of material in the 7-band model for different particle volume concentration at diameter of 80 nm nickel particle. (Df/C = Diffuse/Collimated)

<table>
<thead>
<tr>
<th>Vol (%)</th>
<th>λ (nm)</th>
<th>$\sigma_{\text{nano fluid}}$ (m$^{-1}$)</th>
<th>$\sigma_{\text{glass}}$ (m$^{-1}$)</th>
<th>$\alpha_{\text{nano fluid}}$ (m$^{-1}$)</th>
<th>w(%) Df/C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Df/C</td>
<td>Df/C</td>
<td>Df/C</td>
<td></td>
</tr>
<tr>
<td>0.00001</td>
<td>280–400</td>
<td>2.0735/2.0996</td>
<td>140.8555/102.5293</td>
<td>3.9982/4.0312</td>
<td>14.0626/4.575</td>
</tr>
<tr>
<td></td>
<td>548–700</td>
<td>0.7210/0.7130</td>
<td>12.0604/12.8230</td>
<td>2.2274/2.2200</td>
<td>21.5228/21.643</td>
</tr>
<tr>
<td>0.00001</td>
<td>700–850</td>
<td>0.2725/0.2689</td>
<td>33.4190/34.1597</td>
<td>3.1828/3.1927</td>
<td>13.3306/16.195</td>
</tr>
<tr>
<td>850–1100</td>
<td>0.1238/0.1221</td>
<td>54.1478/54.6798</td>
<td>30.1100/32.3981</td>
<td>10.6064/16.673</td>
<td></td>
</tr>
<tr>
<td>1100–1530</td>
<td>0.03182/0.0291</td>
<td>53.1602/52.0098</td>
<td>410.5200/435.3489</td>
<td>5.0399/10.088</td>
<td></td>
</tr>
<tr>
<td>1530–4000</td>
<td>0.0034/0.0021</td>
<td>41.6509/54.7049</td>
<td>4820.23/16225.80</td>
<td>3.1464/9.538</td>
<td></td>
</tr>
</tbody>
</table>
The use of nanofluid rather than pure water in the present louver is aimed to absorb as much solar energy but meet the required natural daylighting condition. The addition of NPs will undoubtedly degrade the amount of the transmitted VIS. A criterion for illumination must be established, i.e., how much VIS light should not be “blocked” going through the louver.

In general, illumination per room square footage is determined by the amount of luminance or VIS power, and the required luminance varies with room type. For example, a 100 square-foot kitchen requires about 7,000-8,000 lumens, a living room of same size just needs 1,000 – 2,000 lumens, and a standard 100-W incandescent light bulb produces...
about 1,500 – 1,700 lumens (https://www.alconlighting.com/blog/residential-led-lighting/how-do-i-determine-how-many-led-lumens-i-need-for-a-space/). Here we use a top value of 8,000 lumens for 100 square-foot room to justify the requirement of natural daylighting using the proposed louvers, assuming 9 such louvers (total irradiation surface is 0.686 m²) are installed per such a room size. This is for comparison purpose in parametric study of nanofluid conditions; and in real practice, more or fewer louvers can be installed to adjust the need.

Corresponding to the 8,000 lumens under the above-stated assumptions, table 5-3 lists the required VIS transmittance under four typical solar irradiation conditions, i.e., AM1.0, 1.5, 2.0, and 3.0 models, respectively. Since the extremely shaded AM3.0 solar irradiation contains the least VIS solar power, it requires the largest VIS transmittance, which is 45%. To enable the louver device under all-weather conditions, we adopt 45% VIS transmittance as the minimum criterion for daylighting in the following investigations.

<table>
<thead>
<tr>
<th>AM#</th>
<th>VIS power (W/m²)</th>
<th>Luminous flux (lm)</th>
<th>Louvers#</th>
<th>Required VIS transmittance (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>133.6</td>
<td>8,000</td>
<td>9</td>
<td>29.9</td>
</tr>
<tr>
<td>1.5</td>
<td>114.4</td>
<td>8,000</td>
<td>9</td>
<td>34.9</td>
</tr>
<tr>
<td>2.0</td>
<td>103.4</td>
<td>8,000</td>
<td>9</td>
<td>38.6</td>
</tr>
<tr>
<td>3.0</td>
<td>88.8</td>
<td>8,000</td>
<td>9</td>
<td>45.0</td>
</tr>
</tbody>
</table>

### 5.3.4 Effects of nanofluids

Since AM1.5 is the most widely used solar irradiation model in the USA, the discussions below are based on calculations with this model but assume the 45% VIS
transmittance requirement, although this value is obviously larger than the 34.9% listed in table 5-1 for AM1.5. This is because we want to ensure that the louver device can provide sufficient natural illumination under various conditions.

Fig. 5.8 displays the louver solar energy absorption and transmittance efficiencies with different Ni NP sizes but with a constant 0.00004 vol% concentration. It is seen that as the NP diameter increases, the absorption efficiency in the nanofluid increases. Thus, the total solar energy absorption efficiency increases with increasing particle size; and it is 62.1%, 63.5%, 64.6%, and 65.7% for particle diameter at 20, 40, 60, and 80 nm, respectively. However, the VIS transmittance decreases with increasing particle size, which is 53.0%, 49.7%, 48.0%, and 46.5% for particle diameter at 20, 40, 60, and 80 nm, respectively. With 0.00004 vol% Ni particles of 80 nm diameter, the minimum VIS transmittance criterion is satisfied and the absorbed solar energy is the highest; and thus, such a nanofluid is recommended.
The contours of the normalized solar energy harvest in the whole louver for the three different Ni particle diameters at 0.00004 vol% are plotted in Fig. 5.9. A very good symmetry of energy distribution exists, indicating the convergence of the MC calculations. It is seen from the figure that the glass medium and nanofluid are critical to solar energy absorption. With increasing NP diameter, the nanofluid harvests more solar energy.

Figure 5.8 Effect of particle size on solar energy absorption and transmittance efficiencies.
The particle size effect on solar energy absorption and transmittance efficiencies in the three distinct UV, VIS and IR regions is shown in Fig. 5.10. The concentration remains at 0.00004 vol%. It is seen that both UV and IR absorption in the louver are very strong for the three particle sizes. The IR absorption efficiency is 79.8%, 79.9%, and 80.4% for 20, 40, and 80 nm, respectively, which means that the IR light is well-absorbed. The UV absorption efficiency is around 87.2% for the three particle sizes. The VIS absorption efficiency is 40.1%, 42.6%, and 47.3% and VIS transmittance is 53.0%, 49.7%, and 46.5% for the 20, 40, and 80nm particles, respectively.
Fig. 5.10 Effect of Ni NP diameters on solar energy absorption and transmittance efficiencies in different spectra.

Fig. 5.11 demonstrates the effect of particle (80 nm) concentration on solar energy absorption efficiency and VIS transmittance. With increasing particle volume concentration, the nanofluid absorption efficiency increases; but the glass absorption efficiency decreases. The glass absorbs more energy than the nanofluid at low particle concentration since the glass medium is the first sunlight incident layer and the glass has a larger absorption coefficient. The total absorption efficiency is 55.7%, 59.5%, 65.7%, 68.2%, 73.9%, and 76.5% for concentration at 0.00001 vol%, 0.00002 vol%, 0.00004 vol%, 0.00005 vol%, 0.00008 vol%, and 0.0001 vol%, respectively. The VIS transmittance is 65.0%, 56.8%, 46.5%, 41.2%, 29.8%, and 25.3% at 0.00001 vol%, 0.00002 vol%, 0.00004 vol%, 0.00005 vol%, 0.00008 vol%, and 0.0001 vol%.
respectively. Since the VIS transmittance has a minimum 45% criterion, the ideal concentration of the 80-nm Ni-water nanofluid is around 0.00004 vol%.

![Graph showing solar energy absorption efficiency and VIS transmittance vs. Ni NP concentrations.]

Figure 5.11 Solar energy absorption efficiency and VIS transmittance vs. Ni NP concentrations.

The solar energy absorption and VIS transmittance efficiencies in the three distinct spectra for three different particle volume concentrations at D=80 nm are shown in Fig. 5.12. The louver absorbs 83.9%, 87.2% and 88.7% UV light, 27.5%, 47.3%, and 67.7% VIS light, and 80.0%, 80.4% and 83.2% IR solar irradiation at 0.00001 vol%, 0.00004 vol%, and 0.0001 vol% particle volume concentration, respectively. The VIS
transmittance varies from high to low, achieving 65.0%, 46.5%, and 25.3% at 0.00001 vol%, 0.00004 vol%, and 0.0001 vol%, respectively. It should be mentioned that with the increase of the particle volume concentrations, the nanofluid takes more percentage of whole spectral absorption, especially for the VIS part: the glass medium absorbs 17.8%, 16.0%, and 13.5% of VIS part energy, while nanofluid absorbs 9.7%, 31.0%, and 54.2% of VIS light at 0.00001 vol%, 0.00004 vol%, and 0.0001 vol%.

![Figure 5.12](image)

Figure 5.12 Absorption and transmittance efficiencies in three distinct spectra for three different Ni NP volume concentrations.

Fig. 5.13 presents the solar energy absorption and transmittance efficiencies in three distinct spectra for diffuse and direct irradiation, respectively. The particle concentration is 0.00004 vol% and the particle diameter is 80 nm. It is observed that the glass medium
absorbs the most UV light; as for the VIS and IR light, both the glass and nanofluid absorbs significantly. The total solar energy absorption efficiency is 68.6% for the direct light and 55.8% for the diffuse light, respectively. For the UV light, the absorption for both the diffuse and direct irradiation is strong, reaching about 79.6% for the diffuse radiation and 90.6% for the direct one. The UV light is well absorbed by the louver, protecting occupants in a room from overexposure to the harmful UV irradiation. The total absorption of IR solar energy is very high, about 68.6% and 82.6% for the diffuse irradiation and direct irradiation, respectively. The VIS absorption is 44.0% for the diffuse light and 49.0% for the direct one. Meanwhile, the VIS transmittance is about 46.7% for the diffuse light and 46.0% for the direct one. It well illustrates that the louver can pass through sufficient VIS light for the natural illumination.

Figure 5.13 Solar energy absorption and transmittance efficiencies in three distinct spectra for direct and diffuse irradiation, respectively.
Finally, we compare the performance between the Ni-water of 80 nm NP diameter nanofluid-filled prismatic louver at two different concentrations (0.00001 and 0.00004 vol%) and the purely water-filled prismatic louver in table 5-4. It is observed that the total energy absorption efficiency is increasing significantly for the nanofluid-filled louver, from 52.2% for water to 65.7% for 0.00004 vol% nanofluid, which is enhanced by 25.9%. Certainly the VIS transmittance dropped, but it still meets the natural illumination requirement. In the UV, VIS and IR regions, the absorption efficiency of the 0.00004 vol% nanofluid-filled louver improved by 4.4%, 165.7%, and 0.8%, respectively. Thus, the biggest improvement of energy absorption is in the VIS. When the nanofluid concentration is 0.00001 vol%, the enhancement in solar energy absorption efficiency is 0.5%, 54.5%, and 0.3% in the UV, VIS, and IR regions, respectively; and the total solar energy absorption efficiency is improved by 6.7%.

Table 5-4 Comparisons between water-filled and Ni-water (D=80 nm) nanofluid-filled louvers

<table>
<thead>
<tr>
<th></th>
<th>Water-filled louver</th>
<th>Nanofluid-filled louver (10^{-5} vol% / 4x10^{-5} vol%)</th>
<th>Relative enhancement (10^{-5} vol% / 4x10^{-5} vol%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UV (abs.)</td>
<td>83.5%</td>
<td>83.9% / 87.2%</td>
<td>0.5% / 4.4%</td>
</tr>
<tr>
<td>VIS (abs.)</td>
<td>17.8%</td>
<td>27.5% / 47.3%</td>
<td>54.5% / 165.7%</td>
</tr>
<tr>
<td>IR (abs.)</td>
<td>79.8%</td>
<td>80.0% / 80.4%</td>
<td>0.3% / 0.8%</td>
</tr>
<tr>
<td>Total (abs.)</td>
<td>52.2%</td>
<td>55.7% / 65.7%</td>
<td>6.7% / 25.9%</td>
</tr>
<tr>
<td>VIS Trans.</td>
<td>76.2%</td>
<td>65.0% / 46.5%</td>
<td>-14.7% / -39.0%</td>
</tr>
</tbody>
</table>
5.4 Conclusion

The innovation of this chapter is to find a suitable NP with an appropriate size and concentration to enhance solar energy absorption while maintaining a daylighting requirement. Nanofluids are evaluated to enable simultaneous daylighting and energy harvesting. To this end, the illumination criterion for the proposed louver device is established. Through the spectral absorption/scaled isotropic scattering efficiency factor analyses of several commonly utilized NPs, we found that the Ni-water nanofluid is a preferred choice as it has a high absorption efficiency factor and reasonable scaled isotropic scattering efficiency factor. The optical properties of NPs, mainly the absorption/scaled isotropic scattering efficiency factors/coefficients, are obtained through Mie scattering theory. Performance comparisons between water and nanofluid louvers are scrutinized. Parametric studies concerning NP type, size, and concentration are conducted. VIS light transmittance is related to lumen requirement for natural illumination. Important conclusions are summarized as below:

1. To meet the requirement of illumination under various room and atmospheric situations, 45% VIS transmittance through the proposed louver device is suggested and justified.

2. The Ni NP absorption efficiency factor is the greatest among the studied NPs, including SiO$_2$, Fe$_2$O$_3$, Al$_2$O$_3$, TiO$_2$, and ZnO in the wavelength range from 0.28 µm to 2.5 µm. Since pure water has a weak absorption from 0.28 to 1.1 µm, but over half of the solar energy comes from this spectrum, addition of Ni NPs into water to enhance solar energy absorption is desirable. Further, the Ni NP has a
reasonable scaled isotropic scattering efficiency. Therefore, Ni NP is a preferred choice.

3. The absorption efficiency of Ni NPs and Ni-water nanofluid increases with increasing particle size and concentration. Under the illumination criterion and assumed conditions, a Ni-water nanofluid with 0.00004 vol% NPs of 80 nm diameter is recommended as the filling heat-transfer medium into the proposed glass louver.

4. The calculated VIS transmittance with this nanofluid under AM1.5 is 46.5%, sufficiently satisfying the illumination requirement; and the total solar energy absorption efficiency reaches 65.7%, which is an enhancement of 25.9% as compared with the use of pure water.
CHAPTER 6
SUMMARIES AND CONTRIBUTIONS

6.1 Summaries

A comprehensive study of spectral solar radiation harvesting and VIS transmission of water-filled or Ni-water nanofluid-filled prismatic louver is achieved in this dissertation. The Monte Carlo simulation incorporated with direct/diffuse solar light, band-average optical properties, and different AM models is complemented. Some concluding remarks can be drafted as follows:

1) The novel prismatic louver filled with liquid is intensively studied, based on the Monte Carlo ray tracing method that is applied to calculate the solar radiative transfer. The device can help us split solar light and even redirect the sunlight to reduce the “glare effect”.

2) Division of the solar spectrum into 7 bands is proposed for the first time. The spectral properties, such as absorption coefficients and scattering coefficients of water/Ni-water nanofluid/glass were explored. The 7-band spectral MC method can tremendously reduce the computational time and maintain accuracy in the meantime.

3) The research also shed a light on a new way to achieve a high efficiency of solar light utilization: improve the natural illumination and harvest the most solar energy.

4) Different incident angles and circumferential angles of the solar light are considered for modeling. The MC simulation is applied with realistic boundary conditions such as direct
or diffuse solar light, Fresnel reflection at each interface, Snell’s law dealing with the refractions.

5) The spectral irradiance of AM1.0, AM1.5, AM2.0, and AM3.0 are analyzed and jointly utilized by the MC method. The real data in Flagstaff, Phoenix, and Golden with spectral MC method are also investigated. This can validate the outstanding performance of the novel prismatic louver.

6) The spectral optical properties, including absorption/scattering efficiency factors, asymmetric factors of commonly used NPs such as Ni, SiO2, Fe2O3, Al2O3, TiO2, and ZnO, have been explored based on Mie scattering theory. The comprehensive comparisons among different types of nanoparticles are provided for the first time.

7) A criterion of illumination is given for optimal design of the innovative louver such that it meets this criterion and harvests the most solar energy.

6.2 Contributions

The significant investigations and contributions of this research are as follows:

1) The first investigation simulated the collimated solar light of a water-filled prismatic louver. This investigation mainly discussed the spectral MC model’s mathematical modeling. The simulation results’ accuracy and consuming time of the spectral MC model are highly dependent on the photon bundle numbers, band partitions, and element divisions. After compared with $10^6$, $10^7$, $10^8$, and $10^9$ photons, 1-, 3-, 7-, 20-, 40-band, and 1,086, 4,032, 7,140, and 11,130 elements, this research chose $10^8$, 7-band, and 7,140 elements for the MC model. It achieved high computational performance and results accuracy. The solar incident angle effects were also analyzed: set circumferential
angle fixed at zero, and the azimuthal angle changes from 0° to 90°. The result shows that the maximum energy harvesting angle ranges from 0° to 15°. It is a novel idea to check the exact solar energy absorption efficiency under some distinct solar spectral ranges. We considered the solar harvesting efficiency and transmission through three distinct spectra: UV, VIS, and IR, of glass and water regions. Glass medium absorbed the most UV and VIS light, while water medium absorbs little UV and VIS light. The glass and water medium could harvest IR strongly.

2) The subsequent investigation was the spectral analysis of solar energy absorption and light transmittance in a water-filled prismatic glass louver. This investigation first revised the real geometric parameters of the glass louver due to manufacturing requirements and improved the mathematical algorithm to reduce the computational time. It also adopted 10^8 photon bundles, 7-band, and 7140 elements to simulate both direct and diffuse solar light. We also explored the incident angles ranging from 0° to 90° and circumferential angle ranging from 0° to 90° as well. Besides the AM1.5 involved in the MC simulation, we extended the AM 1.0, AM 2.0, and AM 3.0 in the modeling. The spectral absorption and scattering coefficients in different AM numbers are listed in tables. The results showed that UV and IR absorption in the louver are very strong for all four AM spectra. Although the VIS absorption is weak in all four AM models, the VIS transmittance is high. It means there would be sufficient VIS light transmitted into the room for natural illumination. In order to validate the practical installation of the prismatic louver, this research calculated and compared the louver’s performance at Phoenix, Flagstaff, and Golden. The results showed that the performances of the louver at all three places are
extraordinary well, which means the louver can transmit VIS light into the room and harvest most of the solar energy.

3) The final set of simulations investigated a novel harvesting medium, i.e., Ni-water nanofluid. Use of Ni-water nanofluid aims at enhancing solar energy harvest and transmitting sufficient solar VIS light for natural illumination. The previous part discussed that VIS can only absorb 22% energy due to the low absorption coefficient of water. Here we compared and calculated different absorption and isotropic-scaled scattering efficiency of commonly used NPs such as Ni, SiO$_2$, Fe$_2$O$_3$, Al$_2$O$_3$, TiO$_2$, and ZnO. Ni NP is the most desirable in this research because it has higher absorption efficiency, especially in the VIS spectra. Next, the spectral absorption and scaled isotropic efficiency factors of the Ni NPs of different diameters (20, 40, 80 nm) have been analyzed. We compared spectral absorption/scattering coefficients with different NPs’ sizes and volume concentrations. In this dissertation, we created an illumination criterion that satisfies the daylighting demand. Therefore, we tried to improve the solar energy harvesting by using the Ni-water nanofluid inside the louver under the illumination criterion. The results showed that D=80 nm with 0.00004 vol% Ni-water nanofluid has the best performance. The detailed solar absorption and transmittance efficiencies in UV, VIS, and IR spectra for different Ni NP sizes, different Ni NP volume concentrations, and direct/diffuse irradiation were also scrutinized.
REFERENCES


Kafka, J. L., Solar energy collection in complex radiation fields: implications for large and infrastructure-constrained panel arrays, (2020). (Rutgers, The State University of New Jersey, School of Graduate Studies)


