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The Volumetric Absorption Solar Collector

Philibert Girurugwiro
THE VOLUMETRIC ABSORPTION SOLAR COLLECTOR

By

PHILIBERT GIRURUGWIRO

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The members of the supervisory committee were:

Juan Carlos Ordonez  
Professor Directing Thesis

Anjaneyulu Krothapalli  
Committee Member

Patrick Hollis  
Committee Member

The Graduate School has verified and approved the above-named committee members, and certifies that the thesis has been approved in accordance with university requirements.
To my sisters Henriette, Flash, Lilian
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ABSTRACT

In a continuing effort to advance the use of solar energy and to improve the efficiency of existing technologies, a new type of solar energy collector is presented. This method builds upon the principles of a natural phenomenon found in solar ponds and the principles of common flat plate collector (FPC). This type of collector, made out of a semitransparent material, was given the name of a Volumetric Absorption Solar Collector.

A model for a Volumetric Absorption Solar Collector (VASC) accounting for lateral heat losses has been developed and it has been experimentally validated. The model can be used to determine the collector performance, assuming one-dimensional heat conduction and steady state operating conditions. It is based on several dimensionless numbers, each of them having a clear physical significance and playing a key role in the analysis of the collector. Preliminary results suggest that with a radiation of 1000 W/m\(^2\), it is possible to obtain temperatures above 100°C using a glass rod collector of 15 cm diameter and 15 cm length while extracting 200 W/m\(^2\).

The use of a VASC in conjunction with a FPC is one of the feasible applications of the VASC. This joint system was analyzed and the results showed the possibility of increasing the efficiency of a common FPC by a factor of 3 for temperatures around 100°C. Other potential applications as well as suggestions to improve the performance of the VASC are also presented in this work.
CHAPTER ONE

1 INTRODUCTION AND MOTIVATION

Energy has always been one of the world’s most important and valuable commodities. This is all the more evident as energy is becoming an integral part of people’s everyday lives. The availability of modern day energy allows the use of the increase of the level of comfort in homes through heating, ventilation and air conditioning, and the access to medical care. In addition, agriculture, construction, transportation, computing, telecommunications, and many other essential activities would not be possible without access to energy. Undoubtedly, energy is not just an accessory, it is essential in order to survive. Today, this statement is more applicable than it has ever been due to several reasons that will be presented in detail below such as the increase in energy needs, unsure security of supply and its economic consequences and the general concern about climate change.

According to The World Energy Outlook 2009 [1], the global energy demand grew by 66% over the past 30 years. An increase of this scale or higher should be expected for the forthcoming years. The global population is expected to grow to almost 9 billion by the year of 2030 and the standards of living for many people in developing countries are expected to increase. The industrial development itself is expected to grow even faster than ever and, in addition, an increasing shortage of fresh water will call for energy-intensive desalination plants, and in the longer term hydrogen production for transport purposes will need large amounts of electricity and/or high temperature heat. All of these events will lead to increased energy consumption overall and in particular a doubling of electricity consumptions by the year of 2030 [1].

The security of supply and its consequences to the economy is another factor that make energy the world’s most controversial and prestigious commodity. In the winter of 1973, the Egyptian army raged the Suez Canal, causing an international oil supply crisis, and for the first time oil proved itself to be a threatening weapon. Immediately after, the prices of crude oil were raised by 70% by the Organizations of Petroleum Exporting Countries (OPEC) [2]. This incident
led countries to realize how vulnerable they are to interrupted deliveries of traditional fossil fuels and their ever increasing prices. Historical data proves that there is a close relationship between the availability of energy resources and the health of economic activities. This is confirmed by the lack of vibrant economies in the developing nations of the world, which is mainly due to the lack or misuse of energy resources. Since the fossil fuels reserves are exhaustible, the price of these fuels will continue to increase as the reserves are decreased. It can be expected that at one point the fossil fuels will be unaffordable, which will have a significant negative impact on world economies.

Finally, increased awareness of environmental problems such as acid rain, stratospheric ozone depletion, and the global climate change has led decision makers, media and the public to realize that the use of fossil fuels, which contribute most to these environmental problems, must be reduced and replaced by low-emission or zero-emission sources of energy. The daily consumption of oil is estimated at 85 million barrels today but expected to increase to 123 million barrels per day by the year of 2025[3]. With this increase of consumption, it can be expected that the pollution will be much greater. In light of this, it is critical that an immediate plan of action be taken to counter these environmental problems and to insure a sustainable development, which is a development that meets the needs of the present without compromising the ability of future generations to meet their own needs, and to insure a sustainable planet, which is an environment free of life threatening pollution.

Policies must be put in place to ensure that energy consumption to satisfy today’s needs does not affect tomorrow’s generation access to the energy resources. One of the ways this can be done is by improving the efficiency of today’s energy consuming equipment and to adopt what is now known as the ‘fifth fuel’[4]. The fifth fuel is another word for conservation, energy efficiency, energy productivity or energy ingenuity. It is indeed a fuel that has a long term impact on the overall fuel consumption. The other four fuels are coal, petroleum, nuclear and alternative energy. However, it should be pointed out that the adoption of the fifth fuel requires intensive studies, investment in research and in educating energy consumers. Another way to achieve economic and environmental sustainability is to increase the use of clean alternative sources of energy, the most promising of which is solar energy.

Different technologies have been developed over the years to harness the energy from the sun. Most of this energy is used for heating applications, water desalination, and electricity
production. This work proposes a method of collecting solar energy using a semitransparent solid medium that was given the name of Volumetric Absorption Solar Collector (VASC) [5]. In this work, a model of the VASC has been developed and experimentally validated. The model is based on several dimensionless numbers, each of them having a clear physical significance and playing a key role in the analysis of the collector and the determination of the collector’s performance. Before presenting the model and results, it is useful to review some of the existing solar energy collection technologies, and the development of solar energy throughout history.
2 HISTORY AND REVIEW OF SOLAR ENERGY TECHNOLOGIES

2.1 History of Solar Energy

The idea of harnessing energy from the sun in order to perform useful work has been around since prehistory. The first recorded attempt to use solar energy was by the Greek philosopher Socrates (470-399) who might have taught how to correctly orient dwellings in order to have houses which were cool in summer and warm in winter; this is recorded in Socrates memorabilia by Xenophon [6]. Legend also has it that in the year of 212 B.C. the physicist Archimedes attempted to develop a method to burn the Roman fleet by using a concave mirror to reflect all the incoming radiation on one ship. Whether or not the Greek scientist’s attempt actually succeeded is a subject of controversy. It is also suggested that in ancient Mesopotamia, the priests may have used highly polished bowls as parabolic mirrors to ignite fires on the altar. What is certain is that around the year of 1000 AD, the work of the Egyptian mathematician Ibn al-Haytham (965-1039AD) in optics catapulted the developments in concave mirrors (burning mirrors). Around the year of 1515 AD, the Italian artist and scientist Leonardo Da Vinci proposed to build a large 6.5-kilometer diameter concave mirror to focus the sunlight and provide enough heat for commercial enterprises. The focal point was located at a distance of 4 meters. He conducted experiments to validate his design using large silver-vanished concave mirrors [7].

In the late 1700, Germans were able to build large focusing mirrors that were used to burn objects at a distance of 10 meters. The mirrors had the capacity of focusing the sun rays to an area of less than 30 square centimeters. The focused rays had enough heat to melt Copper ores in seconds [7].
Solar energy technologies saw major advances in the late 19th century and early 20th century. In 1878, Augustin Mouchot presented a solar device at the Universal Exposition in Paris. He had built a prototype a decade before that led Napoleon III to fund his project. This device had a form of a cone with a total reflecting surface area of 5 m$^2$. A boiler was placed along the axis of the device and provided steam to drive a 0.5 hp engine at 80 rpm.

In 1880, John Ericsson built an engine to run on solar heat. The driving force from the pistons could push the flywheel at the speed of 400 rpm [7].

The largest solar undertaking in the early 20th century was accomplished by Frank Shuman in 1914, in Egypt by building the largest pumping plant in the world. This solar-powered plant produced approximately 45kW continuously for a 5 hour period. It was abandoned due to the immediate availability of cheaper fuel. His original plan was to build 50,000 km$^2$ in the Sahara desert. If today’s technology was to be used, this surface could provide as much as 2.5 TW of electricity [7].

The years that followed, the world of energy was dominated by fossil fuel until the year of 1975 when a subtle rebirth of solar energy was experienced. In the summer of 1975, President Jimmy Carter held the first ever press conference on the rooftop of the White House. At this occasion, a new solar heating system, worth $28,000, was inaugurated. President Carter made it clear that the system would pay of itself in less than a decade. He made a promise that the United States would get 20 percent of its total energy needs from solar by the end of the 20th century and also promised to spend $1B to get it started. In the year of 1980, President Carter lost his reelection campaign to Ronald Reagan who ended all of Carter’s solar energy promises. In the year of 2009, solar energy constituted less than 1.5 percent of the U.S. energy supply; no advances had been made since the Carter’s times [8].

Today, more than any other time in history, leaders worldwide have started to realize the inevitable need to put more effort in developing solar energy technologies along with other renewable sources of energy. President Barack Obama, in his effort to promote the renewable sources of energy, has said that “the nation that leads the world in creating new energy sources will be the nation that leads the twenty-first-century global economy.” And in his most recent state of the union address, he highlighted his energy vision when he said: “I will not run away from the hope of renewable energies”. President Hu Jintao of China also said that “China must seize the preemptive opportunities in the new round of the global energy revolution,” also
referring to the rise of renewable energies [8]. The European Union has a 20 percent renewable energy goal by the year of 2020 and Germany in particular has set a new target to increase the renewables’s share of electricity from 17 percent to 35 percent by the year of 2020. Also referring to the renewables, David Cameron of Great Britain has promised the most dramatic change in Britain’s energy policy. From these statements from the world’s most prominent leaders, it is fair to say that the train of renewable energies has left the station [8].

2.2 Viability of Solar Energy

It’s common to wonder if the solar energy could ever be enough to satisfy all the global energy needs. To remove all doubt, it may be useful to present some of the facts regarding the sun. The sun is a large sphere located $1.5 \times 10^{11}$ meters away from the earth with a diameter of $1.39 \times 10^9$ meters. The overall temperature of the sun is estimated at 5762 K, although it get as high as $40 \times 10^6$ K at the sun’s core [9]. The sun radiates its energy in all directions and only a small portion of it is intercepted by the earth. Even though this portion is small, estimated at $1.7 \times 10^{14}$ kW, 30 minutes of solar radiation befalling the earth contains the same amount of energy equal to the world energy demand for one year [9]. Nate Lewis of the California Institute of Technology proved that there is enough radiation from the sun to meet all energy needs on planet earth, which are estimated at 2 kW per person [10]. By selecting 6 rectangular spaces on earth with a high solar radiation like those shown in figure 2-1, which are mostly deserts and unexploited, and applying a conversion efficiency of 10%, it is possible to collect as much as 20 TW of electrical power, which is enough to satisfy the energy needs of 10 billion people, the projected world population in the year of 2050.

With higher conversion efficiency, more energy would even be collected to fully and cleanly solve every problem regarding energy in the world [10]. If the current advances in solar energy exploitation continue to grow, it is expected that electricity from solar will have quadrupled by the mid of the 21st century as shown in figure 2-2.
Figure 2-1. Six boxes at 3.3TW each can provide 20TW – Nate Lewis, CIT

Figure 2-2. Sustainable Energy vision 2050 - Gunnar B. Olesen.
2.3 Solar Energy Technologies

In the recent years, solar power technology has seen important improvements, both in solar heating technologies and solar photovoltaic technologies. This discussion will mainly focus on solar heating technologies. There are two criterions commonly used to classify solar heating technologies: the solar radiation received per surface area of the collector distinguishes concentrating collectors from non-concentrating collectors; the tracking of the sun distinguishes stationary collectors from sun-tracking collectors. Non-concentrating collectors only absorb solar radiation that is intercepted by their surface area. Examples of these include flat plate collectors, evacuated tube collectors, solar fences, etc. Concentrating collectors receive solar radiation and redirect it on a point-focus to heat a working fluid. The working fluid, also known as the transport medium, which can be water, oil or air runs through the collector and receives the energy accumulated in the collector. This energy is then transported to a thermal energy storage for later use or can be directly used for water heating or space heating applications and several other applications. Examples of this category include parabolic trough systems, parabolic dish, power towers, etc... [11]. Both concentrating and non-concentrating collectors can either be stationary or sun-tracking.

The list of solar heating technologies is long. Each technology has also been a subject to important improvements over the years. This brief discussion will highlight three of the major solar heating technologies, namely flat plate collectors (FPC), parabolic trough collectors (PTC) and evacuated tube collectors (ETC). Also presented, is a discussion of another unpopular but important solar heat collecting technology, the solar pond, which is closely related to the VASC presented in this work.

2.3.1 Flat Plate Collectors

Flat plate collectors are a very widely used type of collectors. They are mostly used for low temperature applications up to 100°C. Recent advances have been made in improving insulation materials and special coatings that allow FPCs to reach temperatures of 200°C or higher. The main parts of a FPC include the flow tubes, the absorber plate and glazing (figure 2-3). Solar radiation passes through the semitransparent cover and is absorbed by the absorber
plate which has a very high absorptivity. The energy absorbed is then transferred to the transport fluid (air, oil or water) in the flow tubes and carried away for storage or direct use.

The objectives in the design of flat plate collectors are to absorb as much energy as possible from the sun’s radiation and to minimize the heat losses: conduction heat losses, convection heat losses as well as radiation heat losses. In order to capture the maximum possible radiation from the sun, the choice of the material and coating plays an important role. By using the appropriate electrolytic and chemical treatments, it is possible to produce surfaces with high absorptance and low longwave emittance. There’s also the use of a thin upper layer that’s deposited on the absorber surface. This thin layer is highly absorbent to shortwave solar radiation but relatively transparent to longwave thermal radiation, while the surface on which it is deposited has a high reflectance and a low emittance for longwave radiation. Most commercial absorbers are made by electroplating, anodization, evaporation, sputtering and by applying solar selective paints [9]. The use of a transparent cover helps in reducing the energy losses from the absorber plate by holding in place the air between the plate and the glass. It also reduces radiation losses from the collector as the glass is transparent to the short wave radiation received by the sun but it is nearly opaque to long-wave thermal radiation emitted by the absorber plate.

Figure 2-3. Flat Plate Collector with main elements (Credit: US DOE).
[9]. The conduction losses are minimized by putting the flow tubes and the absorber plate in a well insulated enclosure. Figure 2-4 shows the configuration of flat plate collectors for solar water heating.

![Figure 2-4. Solar water heating with FPC - J. Fergusson.](image)

### 2.3.2 Parabolic Trough Collectors

Parabolic trough collectors are one of the four main types of concentrating solar collectors. The other three are heliostat field collectors, linear Fresnel reflectors, and parabolic dish collectors. They all receive the incoming solar radiation and through a sequence of internal reflections, focus it on a receiver which has a much smaller surface area, hence the name of concentrating collector.

Concentrating collectors have more advantages compared to flat plate collectors. They perform at higher temperatures and often have greater efficiencies. There are different ways to concentrate solar energy and concentrations as high as 10,000 suns have been achieved. This increases the operation temperature and the amount of heat collected per area, therefore increasing the efficiency of the collector. In several cases, optical and sun tracking devices are mounted on these collectors to improve the performance throughout the day. These advantages of a concentrating collector come with a higher price tag. Also, a good selection of materials for light concentration, absorption, heat transfer storage, and power conversion cycles plays an
important role in improving the efficiency of the system. Figure 2-5 shows a typical parabolic trough collector.

![Figure 2-5. National Solar Energy Center, Beersheba, Israel - David Shankbone.](image)

Today, Solar Electric Generating Systems (SEGS) a field of parabolic trough collector systems in California is the largest PTC power plant in the world with a capacity of 345 MW [12].

In many PTC systems, pressure control and temperature control methods are used in order to maintain a constant steam output. There is a Once-Through mode and a Recirculation mode in the parabolic trough collector systems. In the former, preheated water fed to the collector and is evaporated into steam as it travels through the receiver channel. In the Recirculation mode, there is a water-steam separator that is placed at the end of the collector. The excess water is fed back into the collector’s inlet and mixed with the preheated water [12].
2.3.3 **Evacuated Tube Collectors**

The evacuated tube solar collector (ETC) technology is another popular solar energy collecting technology. In fact, in some areas of the globe, the ETC technology dominates the industry of solar water heating. When compared to flat plate collectors, ETC have a better thermal efficiency at temperatures above 80°C [13]. The ETC also presents the advantage of a much steadier efficiency as the temperature increases. It has experimentally been shown that when the average temperature is increased from 50 to 90°C, the efficiency of the ETC only decreased from 60 to 50% [14]. This allows for the use of ETC for high temperature applications, such as power generation at a small expense of the thermal efficiency. He W. et al have proposed to use the ETC in conjunction with thermoelectric modules to produce electricity in addition to heating water [15].

There are two types of evacuated tube collectors: single-phase evacuated tube collectors and two-phase evacuated tube collectors. The evacuated tube designed for single-phase is made of two concentric borosilicate glass tubes sealed at one end. The space between the two tubes is evacuated to minimize the conduction and convection losses. Radiation heat losses are minimized by a selective coating applied to the outer surface of the inner tube. This coating also contributes to the maximization of heat absorption. The heat absorbed by the inner tube warms up the water (working fluid) which develops a buoyant flow up the tube and is displaced by an inflow of cold water from the storage [16].

The two-phase evacuated tubes collectors consist of a heat pipe inside a glass tube. The heat pipe contains a small amount of fluid that undergoes evaporating-condensing cycles. The solar heat received by the tube evaporates the small amounts of liquid found in the heat pipe (figure 2-6). The vapor then travels to the heat sink where it releases its latent heat by condensing back to the fluid state. The fluid returns to the hot end of the heat pipe and the cycle restarts. The latent heat from the heat pipes is transferred to the transfer fluid, which is typically a liquid-vapor phase change material (water or water and anti-freeze mix), for water heating or space cooling application [17].
Figure 2-6. Evacuated Tube Collector with heat pipe.
CHAPTER THREE

3 THE VOLUMETRIC ABSORPTION SOLAR COLLECTOR: THEORETICAL ANALYSIS

3.1 Introduction

A Volumetric Solar Absorption (VASC) is a semitransparent solid medium used to collect and store solar radiation and deliver it as heat transfer [18-20]. Several factors influence the temperatures that can be reached within the VASC. These factors vary from the amount of solar radiation received to the size of the collector and the collector’s material properties. Some VASC might have physical limitations regarding the maximum temperatures they can withstand.

This work will focus on a solid semitransparent material. The solid material has a higher melting point and presents an advantage over liquid material for high temperature applications. The physics of a VASC have been studied and model has been derived and implemented. The model contains several dimensionless parameters, each of which has a clear physical significance. The objective of this work is to determine which of these factors are critical to the performance of the collector and ways in which the performance can be improved by varying the dimensionless numbers.

This work is a continuation of a previous analysis of VASC model that did not take into account lateral heat losses [18]. A perfectly insulated VASC provides the maximum achievable temperatures in the collector and can therefore be used for comparison purposes. In practice, even with the most efficient insulation, there are still heat losses on the sides of the collector. This new model takes into account and studies the effect of these losses.
3.2 Heat Transfer Analysis

The VASC studied in this paper has a cylindrical form and is made out of a semitransparent solid material such as glass or acrylic. The lateral surface of the cylinder is covered by an insulating material. The top surface is exposed to incident solar radiation and the energy is extracted from the bottom surface. Figure 3-1 shows a schematic of the VASC.

![Figure 3-1. The layout of a VASC.](image)

This model assumes steady state conditions, one dimensional heat conduction and constant properties. It also takes into consideration lateral heat losses due to convection.

The analysis is made on a differential element of the collector as seen in figure 3-2. The exposed surface receives solar radiation \( G \) which is then transmitted into the material. The transmitted radiation, \( G_{\text{trans}} \), results in heat \( Q_{x} \) being conducted through the collector. \( Q_{\text{conv}} \) is added to account for the lateral heat losses through convection.
Using the law of conservation of energy we obtain

\[- \frac{dQ_x}{dx} - A_T \frac{dG_{\text{trans}}}{dx} - Q_{\text{conv}} = 0 \]  \hspace{1cm} (3-1)

Applying the Fourier’s law of conduction,

\[ Q_x = -kA_T \frac{dT}{dx} \]  \hspace{1cm} (3-2)

Newton’s law of cooling

\[ Q_{\text{conv}} = h_L A_L (T - T_\infty) \]  \hspace{1cm} (3-3)

and the Beer’s law of transmissivity [21],

\[ G_{\text{trans}} = Q^* e^{-\mu x} \]  \hspace{1cm} (3-4)

Equation 3-1 becomes

\[ \frac{d^2T}{dx^2} + \frac{Q^* \mu}{k} e^{-\mu x} - \frac{h_L P}{k A_T}(T - T_\infty) = 0 \]  \hspace{1cm} (3-5)
where $Q^*$ is the incident solar radiation, $T$ is the temperature of the collector, $k$ is the thermal conductivity of the material, $\mu$ is the material’s extinction coefficient, $h_L$ is the convection coefficient between the material and the insulation, $A_T = \pi D^2/4$ is the top area of the collector, and $P = \pi D$ is the perimeter.

The convection coefficient $h_L$ can be determined from the knowledge of the effective thermal resistance $R$ between the collector and the external medium.

$$R = \frac{\ln\left(\frac{D_{\text{ins}}}{D}\right)}{2\pi k_{\text{ins}} L} + \frac{1}{h_{A_{\text{ins}}}} = \frac{1}{h_{L}A_{L}} \quad (3-6)$$

Rearranging (3-6), the equivalent convection coefficient is

$$h_L = \frac{1}{\frac{D_{\text{ins}}}{2\pi k_{\text{ins}} L} \ln\left(\frac{D}{D_{\text{ins}}}\right) + \frac{D}{h_{A_{\text{ins}}}}} \quad (3-7)$$

where $D$ and $D_{\text{ins}}$ are the diameters of the collector and insulation respectively, $k_{\text{ins}}$ is the thermal conductivity of the insulation material, $h$ is the convection coefficient with the external medium.

Eq. 3-5 can be written in a non-dimensional form by dividing it by $T_\infty \mu^2$

$$\frac{d^2\theta}{d\bar{x}^2} + A e^{-\bar{x}} - C^2 (\theta - 1) = 0 \quad (3-8)$$

where

$$\bar{x} = \mu x \quad \text{(Dimensionless position)} \quad (3-9)$$

$$\theta = \frac{T}{T_\infty} \quad \text{(Dimensionless temperature)} \quad (3-10)$$

$$A = \frac{Q^*}{\mu k T_\infty} \quad \text{(Material property number)} \quad (3-11)$$
\[
C^2 = \frac{4h_\ell}{kD\mu^2} \quad \text{(Lateral heat loss number)} \quad (3-12)
\]

Eq. 3-8 is a second order ordinary differential equation with the general solution

\[
\theta = K_1 e^{c\bar{x}} + K_2 e^{-c\bar{x}} - \frac{A}{1-c^2} e^{-\bar{x}} + 1 \quad (3-13)
\]

The constants \(K_1\) and \(K_2\) are determined by applying the appropriate boundary conditions. For this particular case, the boundary conditions are known at \(\bar{x} = 0\) and \(\bar{x} = \mu L\).

At \(\bar{x} = 0\),

\[
\frac{d\theta}{d\bar{x}} = \frac{A}{B}(\theta - 1)
\]

where

\[
B = \frac{Q^*}{hT_\infty} \quad \text{(Heat loss number)} \quad (3-14)
\]

At \(\bar{x} = \mu L\)

\[
\frac{d\theta}{d\bar{x}} = A(e^{-\bar{x}} - \eta)
\]

\[
\eta = \frac{Q}{Q^*} \quad \text{(Efficiency)} \quad (3-15)
\]

\(Q\) is the energy extracted at the bottom. The efficiency \(\eta\) is the ratio between the extracted energy and the incident solar radiation. The more energy extracted the greater the efficiency and the lower the temperature of a VASC.

Applying these boundary conditions, the constants \(K_1\) and \(K_2\) are

\[
K_1 = \frac{A(BC+A)[e^{-\mu L}(\frac{c^2}{1-c^2})+\eta]-AC(A+B)e^{-\mu L}C(1)}{C(BC-A)e^{-\mu L}C(BC+A)e^{\mu L}} \quad (3-16a)
\]
By replacing \( x \) with \( L \) in equation 3-9, a new dimensionless variable \( \varepsilon = \mu L \) can be defined, called the dimensionless depth. Replacing \( \overline{x} \) with \( \varepsilon \) in equation 3-13, the resulting equation represents the temperature of the collector’s bottom and is given by the following identity

\[
\theta_B = K_1 e^{C \varepsilon} + K_2 e^{-C \varepsilon} - \frac{A}{1-C^2} e^{-\varepsilon} + 1
\] (3-17)

### 3.2.1 Temperature Distribution

The form of temperature distribution is shown in figure 3-3 for constant values of \( B = 0.22 \) and \( C = 0.2 \). The value of \( B \) was obtained using \( Q^* = 1000 \, W/m^2 \), \( h = 20 \, W/m^2K \), and \( T_{\infty} = 300K \). The value of \( C \) was fixed for specific insulation material properties and size as well as the collector material properties. The constants \( A = 5 \) and \( A = 10 \) are used to observe the behavior with respect to \( A \).
Figure 3-3 illustrates the variation of the collector temperature as a function of the position (or the collector’s bottom temperature as a function of depth) for different efficiencies and material property number. For each combination of efficiency and the group A there is a maximum temperature. The value of $\varepsilon$ at which $\theta$ reaches one represents the maximum depth for which the collector can operate at the given efficiency. Observe that the maximum depth is independent from A but is strongly dependent on the efficiency. For higher efficiencies, the maximum depth is smaller. The depth at which the bottom temperature reaches its maximum value also depends on the efficiency. For a constant A, the higher the efficiency the smaller the depth needed to reach this temperature. It is also possible to see that for a constant depth, the higher temperatures are reached with the lower efficiencies, meaning that the lesser the heat extracted by the user the higher the temperature distribution of the collector. It may be useful to point out that the form of this temperature distribution matches the form of the popular volumetric solar receivers [9].

It is also important to study the effects of lateral heat losses. The material properties and size of the collector and insulation play an important role in the determination of the lateral heat losses. All of these properties are embodied in one non-dimensional heat loss number called C. Small values of C result in reduced amounts of heat losses, and as shown in figure 3-4, the maximum temperatures that can be achieved for given efficiencies get smaller as the value of C gets bigger. In the following chapter, an analysis will be done on collectors for which the C value is reduced to zero.
Figure 3-4. Variation of collector's efficiency with respect to maximum temperature.

It may also be useful to see the variation of the bottom temperature with respect to both the efficiency and depth. This can be used to know what depth of the collector to choose and at what efficiency it should operate in order to provide a desired temperature. Figure 3-5 below shows the level curves with respect to efficiency and depth for the bottom temperatures ($\theta_B$) of 1.5, 2.5, 4 and 6.
3.2.2 Exergy Output

When designing for a desired collector’s output, it’s important to characterize its performance. The collector will not necessarily perform better at higher temperatures or higher efficiencies. High temperatures are a result of low efficiencies, and high efficiencies cause low temperatures in the collector. It is therefore useful to determine the optimal temperature and efficiency for a better performance of the collector. The exergy extracted from the collector is an indicator of the relationship between the efficiency and the bottom temperature. It can therefore be used to determine the optimal efficiency and temperature that maximize the exergy output. The exergy extracted from the collector’s bottom is given by the equation

$$E_Q = Q \left(1 - \frac{T_0}{T_B}\right)$$

(3-18)

where \(T_0\) is the temperature of the dead state and will be assumed to be equal to \(T_x\), and \(E_Q\) is the exergy extracted from the collector. Equation 3-18 can be rewritten in dimensionless form as
\[ \Xi = \eta \left( 1 - \frac{1}{\theta_B} \right) \]  \hspace{1cm} (3-19)

where
\[ \Xi = \frac{E_q}{Q} \]  \hspace{1cm} (3-20)

\( \Xi \) is the exergy output number and symbolizes the exergy extracted from the collector’s bottom in a dimensionless form. It represents the fraction of the solar energy that is available to be transformed into work. It is a function of A, B, C, \( \theta \), and \( \epsilon \).

Figure 3-6 shows the variation of \( \Xi \) with respect to \( \eta \) for specific depths of the collector. It can be noticed that, for a given depth, the exergy increases with the efficiency until it reaches the maximum value and then decreases until it reaches zero. It is also important to notice that for each collector’s depth, there is a maximum efficiency for which the collector is useful; above this efficiency, the collector’s results would not be practical. It can also be seen that the smaller the depth of the collector, the greater the exergy number that can be achieved for a given efficiency.

![Figure 3-6. Variation of exergy with collector's efficiency.](image)

The material number A also plays an important role in the exergy production. It can be seen from the figure that, for a given collectors depth or efficiency, the exergy increases with the increase in A. This maximum exergy number can never be greater than the efficiency of the collector.
Figure 3-7 below shows the level curves for selected exergy output numbers (0, 0.1, 0.2 and 0.3) for any desired efficiency and depth. This is very useful especially in the process of designing a collector. From this analysis, it is easy to determine the range of depths to use in conjunction with the range of efficiencies in order to obtain a desired output from the collector. As an example from the figure below, if an exergy output number of 0.3 is desired for this specific type of material used in the analysis, it can be seen that depths values ranging from 0.4 to 0.8 can be used with efficiencies of 0.45 to 0.6.

![Figure 3-7. Level curves of exergy output with respect to depth and efficiency.](image)

From both figures 3-6 and 3-7 in the case study above, it can be observed that for a given depth, there is an optimal efficiency that should be used to maximize the exergy output. This leads to the next discussion topic.

3.2.3 Maximization of Extracted energy
The performance of the collector can be optimized by finding the efficiency and depth that maximize the extraction of exergy. The optimization seeks the equilibrium point between the extracted heat and the collector’s bottom temperature to maximize the extracted heat. As it was seen in figure 3-6, for every given depth, there’s an optimal efficiency value, $\eta_{opt}$, that provides the maximum exergy extracted. The optimal efficiency can be found analytically by solving the equation $\frac{\partial \Xi}{\partial \eta} = 0$ but discrete values of $\eta_{opt}$ can also be computed numerically. Figure 3-8 below shows the optimal efficiency as a function of the depth of the collector for $B=0.22$ and $C=0.2$. Again, it can be seen that higher values of $A$ allow for extraction high amounts of exergy while keeping a higher efficiency.

![Figure 3-8. Variation of optimal efficiency with depth.](image)

### 3.3 Improving the performance of the VASC
3.3.1 Optimizing System’s Parameters

It has been shown that a number of factors play key roles in the performance of a volumetric absorption solar collector. The most important of these factors are: the dimensionless number \( A \), which is a material property number, the dimensionless number \( B \), which is a heat loss number and the dimensionless number \( C \), which is a lateral heat losses number.

- **The material property number, \( A \) (Eq. 3-11)**

\[
A = \frac{Q^*}{\mu k T_{\infty}}
\]

In the expression above for \( A \), the \( Q^* \) value, which represents the amount of solar radiation being received, cannot be modified in the design process since it depends on environmental conditions. The same argument applies to \( T_{\infty} \) value, which is the ambient temperature of the VASC surrounding. The only variables that can be modified are the \( \mu \) and \( k \) values. \( \mu \) is the extinction coefficient of the material. The lower this value is the more transparent the material is and can therefore transmit more radiation and improve the performance of the collector. \( k \) is the thermal conductivity of the material. Materials with low values of \( k \) will take longer to reach steady state but have the advantage of keeping the thermal energy and reducing conduction heat losses. In fact, the minimization of the product \( \mu k \) leads to an increase in the value of \( A \), which in turn, increases the performance of the collector. For this particular application, materials with a high value for \( A \) must also be capable to withstand high temperatures. Figure 3-9 below shows how the increase in the value of \( A \) increases the performance of the collector.
The heat loss number $B$ (Eq. 3-14)

$$B = \frac{Q^*}{hT_\infty}$$

This heat loss number does not play a major role in the optimization of the performance of the volumetric absorption solar collector. The solar radiation and ambient temperature cannot be freely modified in the design since they depend on the weather conditions. The convection coefficient can be altered to reduce the heat losses but it would require additional energy to increase the convection coefficient.
• The lateral heat loss number $C$ (Eq. 3-12)

$$C = \frac{4h_L}{\sqrt{kD\mu^2}}$$

This work studied a cylindrical VASC with a diameter $D$. It was shown that the increase in the value of $C$ results in the increase of the lateral heat losses which negatively affect the performance of the collector. Therefore, it is important to design a VASC that has the minimum possible value of $C$. From the expression above (Eq. 3-12), it can be seen that the $C$ value could be minimized by increasing the values of $k$, $\mu$ and $D$ or decreasing the value of $h_L$. However, choosing materials with high values of $k$ and $\mu$ is not an option since this will lower the value of $A$ and negatively affect the performance. Therefore, only $D$, the diameter of the collector, and $h_L$ can be manipulated. $h_L$ represents the convection coefficient between the collector and the surrounding. The value of $h_L$ depends heavily on the quality and size of material chosen for insulation as shown in equation 3-12. If the insulation material has a low thermal conductivity and a large diameter, the $h_L$ value will be reduced. The advantage of a large diameter for a VASC is two-fold: the larger the diameter is the more surface area and therefore more radiation is collected; the second advantage is that for larger diameters, the values of $C$ are increasingly lower, which means that less heat is lost through the lateral surfaces of the collector. Figure 3-10 shows the variation of the collector’s bottom temperature with respect to the depth of the collector for $C \cong 0$, $C = 0.5$, $C = 2$ and for $C = 10$. From the figure, it can be seen that lower values of $C$ lead to less heat losses and result in higher temperatures of the collector.
3.3.2 Heat transfer analysis of a VASC without lateral heat losses

Applying the conservation of energy principle to the differential element in figure 3-2,

\[
 k \frac{d^2 T}{dx^2} = \frac{d(Qe^{-\mu x})}{dx}
\]

Applying the boundary conditions at \( x = 0 \) and at \( x = L \),

\[
 -k \frac{dT}{dx} \bigg|_{x=0} = -h(T|_{x=0} - T_\infty) \quad (3-22)
\]

\[
 Q^*e^{-\mu L} - k \frac{dT}{dx} \bigg|_{x=L} = Q \quad (3-23)
\]

Solving equation (3-21) with the boundary conditions (3-22) and (3-23), the temperature distribution in the VASC is

\[
 T(x) = \frac{-Q^*e^{-\mu x}}{\mu k} - \frac{Q}{k} x + Q^* \left( \frac{1}{h} + \frac{1}{\mu k} \right) - \frac{Q}{h} + T_\infty
\]

Figure 3-10. Temperature distribution for different lateral heat loss numbers.
which, in dimensionless form, can be written as

$$\theta = A(1 - \eta x' - e^{x'}) + B(1 - \eta) \quad (3-25)$$

And the temperature at the bottom of the collector ($x = L$) is

$$\theta_B = A(1 - \eta \varepsilon - e^{\varepsilon}) + B(1 - \eta) \quad (3-26)$$

Equation 3-26 can be rearranged to find the efficiency of a VASC as a function of the material property number, A, heat loss number, B, dimensionless depth number $\varepsilon$ and the bottom temperature of the collector $\theta_B$

$$\eta = \frac{A - A\varepsilon + B}{A\varepsilon + B} - \frac{1}{A\varepsilon + B}(\theta_B - 1) = \frac{Q}{Q^*} \quad (3-27)$$

With careful selection of parameters, the dimensionless number C can be driven to almost zero. When the C value is approximately equal to zero, the effects of lateral heat losses are minimized or reduced to zero, resulting in the optimum performance of the collector: higher temperatures can be reached at high efficiencies. The following analysis studies the performance of the collector without lateral heat losses. The efficiency with respect to the temperature for different depths of the collector is presented for three different cases. The first case assumes normal operating conditions, with the sun providing radiation at 1000 W/m² and at an ambient temperature of 300 K, with a low quality glass material such as the one used in the experimental analysis section. The second case tries to maintain the same operating conditions but uses a better quality of glass for this application. A glass material is considered high quality if the product of its coefficient of conduction, $k$, and its extinction coefficient, $\mu$, is very small. The third case seeks to improve the performance of the collector by using a good quality glass material and reducing the convection heat losses by installing a glass cover on top of the collector, which lowers the value of $h$. Below is a summary of the three cases in a table.
Table 3-1 Parameters for the analysis of the efficiency of the VASC.

<table>
<thead>
<tr>
<th></th>
<th>Q*</th>
<th>T_{inf}</th>
<th>µk</th>
<th>h</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(W/m²)</td>
<td>(K)</td>
<td>(W/m²K)</td>
<td>(W/m²K)</td>
</tr>
<tr>
<td>Case I</td>
<td>1000</td>
<td>300</td>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>Case II</td>
<td>1000</td>
<td>300</td>
<td>1.25</td>
<td>20</td>
</tr>
<tr>
<td>Case III</td>
<td>1000</td>
<td>300</td>
<td>1.25</td>
<td>5</td>
</tr>
</tbody>
</table>

From figure 3-11, if a VASC with a depth of 10 centimeters is considered, and under the conditions stated in case I, temperatures of around 100°C can be reached with an efficiency of 20%. It can also be noticed from the same figure that thinner VASCs reach higher efficiencies for low temperature applications but the efficiency decreases fast with the increase of temperature. VASC with a bigger depth have a lower but relatively steady efficiency and are more practical for higher temperature applications.
For case 2 (figure 3-12), the same VASC of 10 centimeters reaches the temperatures of around 100°C with a much bigger efficiency of 60%. It’s very clear that minimizing the product $\mu k$ improves dramatically the performance of the collector. In this particular case, a 200% increase in efficiency was achieved by reducing the value of $\mu k$ to 25%. Like in the previous case (case 1), it can be seen that the thicker the VASC is the steadier the efficiency and the better the performance at high temperatures.

In the third case (figure 3-13), a 17% increase in the efficiency over case 2 and 250% increase over case 1 can be observed for the same VASC of a 10-cm depth, proving that the reduction of convection effects does play a significant role in improving the performance of the collector.

Figure 3-14 below summarizes the comparisons of the three cases for the 10-cm VASC. It can be noticed that a significant increase in the performance of the VASC can be achieved by making a right choice of the material and under favorable conditions.
A volumetric absorption solar collector of 10 centimeters of depth, with a very low $\mu k$ and operating in ideal conditions, with minimal convection heat losses and zero lateral heat losses, performs better than the common solar heat collector technologies. Figure 3-15 below compares this VASC with three other types of technologies, flat plate collector (FPC), advanced
flat plate collector (AFP), compound parabolic collector (CPC), and evacuated tube collector (ETC) [9]. All the collectors operate under the same conditions with an incident solar irradiation of 1000 W/m$^2$. It’s important, however, to keep in mind that this is an ideal case where a highly efficient glass material is used and all the heat losses are neglected.

![Figure 3-15. Case III compared with other solar collector technologies.](image)

Figure 3-15. Case III compared with other solar collector technologies.
CHAPTER FOUR

4 THE VOLUMETRIC ABSORPTION SOLAR COLLECTOR: EXPERIMENTAL ANALYSIS

4.1 Introduction

In order to validate the model discussed above, a series of laboratory experiments were set up using a semitransparent material. The choice for the material was a one foot long Borosilicate Glass rod with 1.2 inch diameter. This material was chosen due to its off-the-counter availability in retail stores and relatively cheap cost. It also comes with the manufacturer’s estimated thermodynamic properties such as the coefficient of thermal conductivity, the melting point and the specific heat capacity. Experiments were carried out to determine two main quantities: the extinction coefficient of the material and the temperature distribution. The top surface of the rod was exposed to a light source in such a way that the radiation is normal to the surface. Incident radiation was measured at the top surface of the rod and transmitted radiation was measured at the bottom of the rod. To measure the temperature, six calibrated high precision thermistors were uniformly attached to the cylinder to measure the temperature. A Labview program was used to record temperature data from the thermistors. In this experimental setup, precaution was taken to minimize the energy losses in the lateral surface of the cylinder and fiberglass was used to achieve this insulation. The experimental results were found to be only within a 2% difference with the theoretical prediction.

4.2 Determination of the extinction coefficient

The surface of the borosilicate cylinder was exposed to a light source. It is important to note that this radiation hitting the surface has spectral as well as directional distribution determined by \( I(\lambda, \theta, \phi) \). This quantity is defined as the rate at which radiant energy of wavelength \( \lambda \) is incident from the \((\theta, \phi)\) direction, per unit area of the intercepting surface.
normal to this direction, per unit solid angle about this direction, and per unit wavelength interval $d\lambda$ about $\lambda$ [21].

At the surface of this semitransparent material, a portion of the incoming irradiation is reflected back while the remaining penetrates the material. Of the penetrated radiation, a portion is absorbed by the material while the remaining is transmitted through the bottom of the material. The incoming radiation is equal to the sum of the reflected, absorbed and transmitted radiations ($G = G_{\text{ref}} + G_{\text{abs}} + G_{\text{trans}}$). The absorbed radiation contributes to the rising of the temperature of the material. Figure 4-1 below summarizes the three types of radiations.

![Figure 4-1. Different types of radiations.](image)

In this experimental setup, the directional distribution of radiation was minimized by placing the center of the light source on an axis normal to the surface ($\theta = 0, \varphi = 0$), resulting in the radiation being normal to the surface (See figure 4-4). The top surface of the collector was polished using a fine sand paper to minimize the effects of reflections. The incoming light intensity was measured at the top surface of the semitransparent material and the transmitted light intensity was measured at the bottom surface of the material as shown in Fig 4-2. The ratio of these two quantities (incident and transmitted radiations) gives the value of the transmittance of the material. The Beer’s law (equation 3-4) can be used to determine the material’s extinction
coefficient with the knowledge of the transmittance. Measurements were taken using a SP110 Model Pyranometer from Apogee (see figure 4-3). This pyranometer was chosen due to its relatively cheap price, its simplicity of use. It is also self powered which allows measuring the light intensity with ease under various outdoors conditions without the need to carry a power supply. Pyranometers are usually used to measure the total radiation (beam and diffuse) and are responsible for most of available solar radiation data. They can collect measurements for the entire spectrum from 280 to 2800 nm.

![Figure 4-2. Experimental setup: Determining the extinction coefficient.](image)

All Apogee precision pyranometer models have a standard calibration of exactly 5.00 W/m² per mV. This conversion is used to convert the mV signal from the sensor to shortwave
radiation in W/m$^2$. In the experiment, a mV signal of 200 mV was used, which is equivalent to a radiation of 1000 W/m$^2$, the normal radiation of the sun (figure 4-7). In a typical pyranometer, the detector comprises of black and white surfaces whose temperature difference is measured using thermopiles. The detector’s response is independent from the wavelength and the angle of incidence of the radiation.

In this experimental analysis a wide range of light intensities were achieved by using different sources of light. A 300 W lamp, a regular 100 W light bulb, and the sunlight were the major sources of light. Shading was used in conjunction with these light sources to vary the intensity and provide more data. The sample results are tabulated below.

**Table 4-1. Incident and transmitted radiation values for two different light sources.**

<table>
<thead>
<tr>
<th>Incident Radiation (W/m$^2$)</th>
<th>Transmitted Rad.$^1$ (W/m$^2$)</th>
<th>Transmitted Rad.$^2$ (W/m$^2$)</th>
<th>Transmittance$^1$</th>
<th>Transmittance$^2$</th>
<th>Extinction Coefficient$^1$ (m$^{-1}$)</th>
<th>Extinction Coefficient$^2$ (m$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>495.5</td>
<td>146</td>
<td>107.5</td>
<td>29%</td>
<td>22%</td>
<td>4.06</td>
<td>4.97</td>
</tr>
<tr>
<td>374</td>
<td>100.5</td>
<td>83</td>
<td>27%</td>
<td>22%</td>
<td>4.30</td>
<td>4.97</td>
</tr>
<tr>
<td>252</td>
<td>66</td>
<td>54.5</td>
<td>26%</td>
<td>22%</td>
<td>4.42</td>
<td>4.97</td>
</tr>
<tr>
<td>124.5</td>
<td>29</td>
<td>29.5</td>
<td>24%</td>
<td>22%</td>
<td>4.68</td>
<td>4.97</td>
</tr>
<tr>
<td>Average Extinction Coefficient</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4.36</td>
</tr>
</tbody>
</table>

$^1$using a 300W lamp as a light source $^2$using a 100W lamp as a light source

From the results in Table 1, it can be noticed that the results are fairly consistent for each light source regardless of the intensity. However, the results differ for the two light sources. It can be seen that with the 300W lamp, on average, 20% more light was transmitted compared to the 100 lamp.

This phenomenon generated interest in determining whether the difference might be due to the difference in the spectral distribution of incident radiation. A spectrophotometer was used to determine the relative intensity of the incident and transmitted radiation per wavelength. One drawback with the spectrophotometer used is the wavelength range since it is only capable to measure for wavelengths in the visible spectrum and much of the radiation in the thermal
radiation spectrum cannot be viewed. This instrument still gave good results for observation purposes.

![Incident radiation per wavelength graph](image)

**Figure 4-4. Incident radiation distribution per wavelength.**

From figure 4-3 above, it can be seen that the relative incident radiation varies with the wavelength. However, there is no apparent difference between the spectral distribution of the incident light from the 300W lamp and the 100W lamp. Figure 4-4 shows the same spectral distribution for the transmitted radiation. It can be noticed that even though the distribution has the same pattern, the intensity of the radiation is smaller for the 100W lamp compared to the 300W lamp. As it was mentioned before, this instrument is only capable to detect the light within the visible spectrum. Much of the light heat is in the infrared region and could be the cause of the differences observed in the measurement since the two light sources, 100W and 300W, emit at different temperatures.
Figure 4-5. Transmitted radiation distribution per wavelength.

The 300W lamp was chosen to pursue with further experiments and its transmittance measurements were used in the analysis.

4.3 Determination of the temperature distribution and maximum temperature

The setup for measuring the temperature distribution is similar to the setup for the determination of the extinction coefficient. The 300 W lamp was used and placed at a distance in such a way that 1000 W/m² reached the surface of the glass rod. Six thermistors were uniformly attached to the rod to measure the temperature. A LabVIEW program was used to collect temperature data from the thermistors as shown in figures 4-6 and 4-7. In practice, the temperature near the surface of the collector would be close to the temperature of the surrounding. To achieve this, fans were used to blow air on the collector in order to maintain this
temperature as close as possible to the surrounding temperature and to also achieve a uniform convection coefficient throughout.

The insulation of the lateral surface of the cylinder was achieved by using fiberglass insulation material. The first sets of experiments were performed with the bottom surface of the collector insulated. In this case, no energy is extracted and it can be assumed that all the transmitted radiation is kept within the collector and heat losses are minimized. The second runs of experiments were accomplished with the bottom surface of the cylinder exposed to the surrounding. In this setting, it can be assumed most of the energy getting transmitted to the bottom is transferred to the surrounding. With the knowledge of the cylinder’s extinction coefficient, it is possible to determine how much heat reaches the bottom of the collector.

Figure 4-6. Experimental setup: Measuring the temperature distribution.

Figure 4-7. LabView channels measuring the temperature.
4.4 Experimental Results and Discussion

For observation and experimental purposes a borosilicate glass cylinder of 0.038 m of diameter and 4.36 m$^{-1}$ extinction coefficient and a thermal conductivity of 1.14 W/mK was used. This glass rod of length 0.3 m was thermally insulated with an insulating material (fiberglass) of a low thermal conductivity of 0.04 W/mK and thickness of 0.05 m. An approximate value for convection coefficient of 18 W/m$^2$K on top and sides of the insulated collector was assumed. The 300 W light source was placed at an adequate distance to provide 1000 W/m$^2$ of radiation at the surface of the rod (figure 4-8).

![Pyranometer measuring the radiation at the surface of the rod]

![The light source placed at a distance to provide exactly 1000 W/m$^2$ at the surface of the rod]

![Light source properly aligned with the collector for radiation to reach the bottom and minimize internal reflections]

Figure 4-8. Experiment Setup.
In this experiment, additional considerations were taken into account. The $I_c = 1000 \text{ W/m}^2$ radiation reaching the surface of the glass doesn’t enter the collector entirely. Using the material’s index of refraction, an approximate value of 4% was determined as the fraction of reflected radiation. Therefore,

$$Q^* = I_c (1 - 4%) = 960 \frac{\text{W}}{\text{m}^2}$$

Another consideration was made regarding the absorbed energy at the bottom of the rod. In this experiment, the absorption surface was simply achieved by coloring the bottom surface with black ink. An absorption coefficient of 0.5 was assumed for this case (figure 4-9).

Figure 4-9. VASC accounting for reflection on the top and absorption on the bottom.

A more detailed theoretical analysis of a VASC system with reflections and absorption will be discussed in the following chapter.

Below is a table summarizing all the important parameters used in the model to generate the temperature distribution along the VASC.

<table>
<thead>
<tr>
<th>$Q^*$</th>
<th>$T_\infty$</th>
<th>$k$</th>
<th>$k_{\text{ins}}$</th>
<th>$L$</th>
<th>$D$</th>
<th>$D_{\text{ins}}$</th>
<th>$h$</th>
<th>$\mu$</th>
<th>$R$</th>
<th>$\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{W/m}^2$</td>
<td>$\text{K}$</td>
<td>$\text{W/mK}$</td>
<td>$\text{W/mK}$</td>
<td>$\text{m}$</td>
<td>$\text{m}$</td>
<td>$\text{m}$</td>
<td>$\text{W/m}^2\text{K}$</td>
<td>$\text{m}^{-1}$</td>
<td>$%$</td>
<td>$%$</td>
</tr>
<tr>
<td>960</td>
<td>294</td>
<td>1.14</td>
<td>0.04</td>
<td>0.3</td>
<td>0.038</td>
<td>0.11</td>
<td>18</td>
<td>4.36</td>
<td>4</td>
<td>50</td>
</tr>
</tbody>
</table>
Figure 4-10 shows the transient temperature distributions across the cylinder starting from T1 at 0.5 inches, to T2 at 2.5 inches, T3 at 4.5 inches, T4 at 7 inches, T5 at 9.5 inches and T6 at 12 inches, which is the bottom of the cylinder. It can be seen from the figure that the bottom temperature is the highest at steady state conditions. At the beginning of the experiment, the point closest to the surface (0.5 inch) has the highest temperature since it is located closer to the light source. As time increases, the heat from the light source diffuses down in the rod and reaches the bottom where a portion of it is absorbed. At a given point in time, as heat keeps being diffused in the cylinder, all the other temperatures, T2, T3, T4, T5 and T6 catch up and exceed T1. It can be seen that T1 is the lowest temperature at steady state conditions.

Figure 4-10. Transient temperature distribution.

The experiment with the bottom of the rod insulated was repeated three times and the steady state temperatures were very close in all of the runs. Their values are reported in table 4-3. The steady state temperature distribution is shown in figure 4-11. Also in the same figure is the temperature distribution predicted by the model, using the parameters in table 4-2. It can be seen that the theoretical values and the experimental values are in close agreement and only an average difference of 1.21% exists between the two categories.
Table 4-3. Steady state temperature distribution (Insulated bottom).

<table>
<thead>
<tr>
<th>Thermistor Position (inch)</th>
<th>T1</th>
<th>T2</th>
<th>T3</th>
<th>T4</th>
<th>T5</th>
<th>T6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1</td>
<td>30.15</td>
<td>32.49</td>
<td>32.77</td>
<td>32.21</td>
<td>32.10</td>
<td>33.78</td>
</tr>
<tr>
<td>Run 2</td>
<td>30.29</td>
<td>32.58</td>
<td>32.83</td>
<td>32.28</td>
<td>32.17</td>
<td>33.81</td>
</tr>
<tr>
<td>Run 3</td>
<td>30.30</td>
<td>32.55</td>
<td>32.78</td>
<td>32.23</td>
<td>32.11</td>
<td>33.79</td>
</tr>
<tr>
<td>Average</td>
<td>30.25</td>
<td>32.54</td>
<td>32.79</td>
<td>32.24</td>
<td>32.13</td>
<td>33.80</td>
</tr>
<tr>
<td>STDEV</td>
<td>0.09</td>
<td>0.05</td>
<td>0.03</td>
<td>0.04</td>
<td>0.04</td>
<td>0.02</td>
</tr>
<tr>
<td>Model Values</td>
<td>29.67</td>
<td>32.39</td>
<td>32.52</td>
<td>31.67</td>
<td>31.53</td>
<td>33.92</td>
</tr>
<tr>
<td>% Difference</td>
<td>1.92</td>
<td>0.45</td>
<td>0.85</td>
<td>1.78</td>
<td>1.89</td>
<td>0.38</td>
</tr>
</tbody>
</table>

Figure 4-11. Experimental and theoretical data temperature distribution (insulated bottom).
The second runs of experiments were performed with the bottom of collector exposed to the surrounding. Figure 4-12 shows the transient temperatures for the six selected location on the cylinder at 0.5 inch, 2.5 inch, 4.5 inch, 7 inch, 9.5 inch and 12 inch marks. As expected, the 0.5 inch-mark has the highest temperature at the beginning but is quickly exceeded by T2 and T3. The bottom temperature, also high at the beginning of the experiment, ends up being the lowest temperature due to its contact with the surrounding.

![Figure 4-12. Transient temperature distribution (exposed bottom).](image)

Table 4-4 contains steady state temperatures from the three sets of experiments and their averages. It can be seen that the measurements are close with a very low standard deviation. Also in the table, are the theoretical values predicted by the model. The same parameters in table 4-2 have been used to this case with one exception of absorption at the bottom. The absorptance coefficient has been reduced to almost zero ($\alpha = 0.01$), since most heat reaching the bottom is quickly lost to the environment. Figure 4-13 shows the temperature distribution at the selected locations for both experimental and theoretical data.
Table 4-4. Steady state temperature distribution (exposed bottom).

<table>
<thead>
<tr>
<th>Thermistor</th>
<th>T1</th>
<th>T2</th>
<th>T3</th>
<th>T4</th>
<th>T5</th>
<th>T6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position (inch)</td>
<td>0.5</td>
<td>2.5</td>
<td>4.5</td>
<td>7</td>
<td>9.5</td>
<td>12</td>
</tr>
<tr>
<td>Run 1</td>
<td>30.27</td>
<td>32.00</td>
<td>31.43</td>
<td>30.26</td>
<td>28.41</td>
<td>26.96</td>
</tr>
<tr>
<td>Run 2</td>
<td>30.29</td>
<td>32.04</td>
<td>31.42</td>
<td>30.31</td>
<td>28.45</td>
<td>26.98</td>
</tr>
<tr>
<td>Run 3</td>
<td>30.74</td>
<td>32.53</td>
<td>32.03</td>
<td>30.77</td>
<td>28.95</td>
<td>27.44</td>
</tr>
<tr>
<td>Average</td>
<td>30.44</td>
<td>32.19</td>
<td>31.63</td>
<td>30.45</td>
<td>28.60</td>
<td>27.13</td>
</tr>
<tr>
<td>STDEV</td>
<td>0.27</td>
<td>0.30</td>
<td>0.35</td>
<td>0.28</td>
<td>0.30</td>
<td>0.27</td>
</tr>
<tr>
<td>Model Values</td>
<td>29.55</td>
<td>32.14</td>
<td>32.01</td>
<td>30.50</td>
<td>28.80</td>
<td>27.61</td>
</tr>
<tr>
<td>% Difference</td>
<td>2.94</td>
<td>0.16</td>
<td>1.22</td>
<td>0.16</td>
<td>0.70</td>
<td>1.77</td>
</tr>
</tbody>
</table>

Figure 4-13. Experimental and theoretical temperature distribution data (exposed bottom).
CHAPTER FIVE

5 LOCATING POTENTIAL APPLICATIONS OF THE VOLUMETRIC ABSORPTION SOLAR COLLECTOR

5.1 Introduction

It was proven that the volumetric absorption solar collector has the potential to accumulate significant amounts of heat and therefore it can be used for applications such as water heating, space heating and all other applications for which flat plate collectors are normally used. In different cases, the analysis showed that a VASC system allows for more heat to be extracted than the flat plate collector and is therefore thermodynamically superior.

One potential application of the VASC is to use it in conjunction with the flat plate collector. In this configuration, a well selected depth of the VASC could be mounted on the absorber surface of the flat plate collector. The radiation received by the volumetric absorption solar collector would be collected and then transferred to the flat plate collector’s absorber surface. This would increase the temperature values that are normally achieved by using the flat plate collector alone. Figure 5-1 illustrates this idea. The sun’s radiation hits the surface of the VASC at ambient temperature and increase temperature of the collector at the bottom by n times the ambient temperature. The same phenomenon happens with the FPC, where the temperature is increased m times. When combined, the overall increase of temperature is m+n.

Figure 5-1. VASC mounted on the FPC.
This process is, however, not as straightforward as it might look. In reality, there are different kinds of heat losses, reflection losses, convection losses to name a few. This would make the overall increase of the temperature not $m+n$ but a fraction of $m+n$ that is still bigger than $m$ and $n$ individually.

The following analysis is a mathematical study of real case where a VASC is used in conjunction with a FPC and a comparison of the performance of the system with the performance of the FPC individually is made.

### 5.2 Heat transfer analysis of a VASC-FPC system

This configuration takes a normal flat plate collector like the one shown in figure 2-3 and mounts a layer of glass (VASC) on top of the absorber plate. Everything else remains the same. A layout of this system is shown in figure 5-2. An incoming solar radiation $I_C$ hits the glazing and a portion of it, $I_C \tau_S$, is transmitted to the VASC. After a series of internal and external reflections, $R$, $I_C \tau_S e^{-\mu L}(1 - R)^2$ reaches the absorber plate. The quantity $I_C \tau_S e^{-\mu L}(1 - R)^2 \alpha_S$ represents the amount of heat absorbed in the plate. The term $1/U_C A_C$ represents the thermal resistance between the VASC and the ambient temperature.

![Figure 5-2. VASC-FPC layout.](image-url)
Applying the conservation of energy principle to the VASC, we get

\[ k \frac{d^2T}{dx^2} = \frac{d(I_c \tau_s (1-R)e^{-\mu x})}{dx} \]  

where \( I_c \) is the incident radiation hitting the glazing surface, \( \tau_s \) is the reflection coefficient and \( R \) is the reflected radiation. This is similar to equation 3-21, with \( Q^* = I_c \tau_s (1-R) \)

Applying the boundary conditions at \( x = 0 \) and at \( x = L \),

\[ -k \frac{dT}{dx} \bigg|_{x=0} = -U_c (T|_{x=0} - T_\infty) \]  
\[ I_c \tau_s (1-R)e^{-\mu L}(1-R)\alpha_s - k \frac{dT}{dx} \bigg|_{x=L} = Q_u \]  

where \( U_c \) is the equivalent convection coefficient between the glass material and the ambient, and \( \alpha_s \) is the absorptance of the glass. These boundary conditions are similar to the ones found in equations 3-22 and 3-23.

The equation can be solved to arrive at the final form of the heat conducted in the absorber plate, which is

\[ Q = Q_u + Q^* e^{-\mu L}(1-\alpha_s(1-R)) \]  

where \( Q \) is the total heat reaching the bottom of the glass, \( Q^* \) is the radiation entering the glass material, and \( Q_u \) is the heat extracted and ready to be used.

**5.2.1 The efficiency of the system**

For the VASC component of the system,

\[ \eta = \frac{Q}{Q^*} = \frac{Q_u + Q^* e^{-\mu L}(1-\alpha_s(1-R))}{Q^*} \]  

\[ 50 \]
The overall efficiency of the system VASC-FPC is the ratio between the energy extracted from the absorber plate \( Q_u \) and the incident radiation that hits the top surface \( I_c \)

\[
\eta_{\text{VASC-FPC}} = \frac{Q_u}{I_c} = \frac{Q_u}{Q} \tau_s (1 - R) \tag{5-6}
\]

Combining equations 5-5 and 5-6 with equation 3-27, the overall efficiency of a combined VASC-FPC as a function of the temperature difference can be found to be

\[
\eta_{\text{VASC-FPC}} = \tau_s (1 - R) \left[ \frac{A - A e^E + B}{A e + B} - e^{-\varepsilon} \left( 1 - \alpha_s (1 - R) \right) \right] - \frac{\tau_s (1 - R)}{(A e + B) T_\infty} (T_B - T_\infty) \tag{5-7}
\]

The equation 5-7 is a straight line in the \( \eta - \Delta T \) plane.

If the effects of reflections are disregarded and the \( \varepsilon \) value is set to \( \varepsilon = 0 \), the above equation is reduced to

\[
\eta_{\text{FPC}} = \tau_s \alpha_s - \frac{I_c}{I_c} (T_B - T_\infty) \tag{5-8}
\]

which is the normal equation for the efficiency as a function of the temperature difference between the plate and the ambient for a common flat plate collector [22].

The efficiency can also be expressed in terms of fixed losses (\( F_L \)) and variable losses (\( V_L \)) as follows:

\[
\eta = 1 - F_L - V_L \tag{5-9}
\]

For a common flat plate collector

\[
F_L = 1 - \tau_s \alpha_s \tag{5-9a}
\]

and

\[
V_L = \frac{I_c}{I_c} (T_B - T_\infty) \tag{5-9b}
\]
And for the VASC-FPC system

\[ F_L = 1 - \tau_s (1 - R) \left[ \frac{A - A e^B}{A e + B} - e^{-e} (1 - \alpha_s (1 - R)) \right] \quad (5-9c) \]

and

\[ V_L = \frac{\tau_s (1 - R)}{(A e + B) T_\infty} (T_B - T_\infty) \quad (5-9d) \]

Finally, the efficiency can be expressed in terms of the temperature difference between the fluid entering the collector and the ambient temperature, as it is usually done for the flat plate collectors. The \( F_L \) and \( V_L \) values become:

For a common flat plate collector, the fixed losses and variable losses become

\[ F_L = 1 - F_R \tau_s \alpha_s \quad (5-9e) \]

and

\[ V_L = \frac{F_R U_c}{I_c} (T_{f,in} - T_\infty) \quad (5-9f) \]

And for the VASC-FPC system

\[ F_L = 1 - F_R \tau_s (1 - R) \left[ \frac{A - A e^B}{A e + B} - e^{-e} (1 - \alpha_s (1 - R)) \right] \quad (5-9g) \]

and

\[ V_L = \frac{F_R \tau_s (1 - R)}{(A e + B) T_\infty} (T_{f,in} - T_\infty) \quad (5-9h) \]

where \( T_{f,in} \) is the temperature of the fluid entering the plate and \( F_R \) is the heat removal factor.

The equation resulting from 5-9, 5-9e and 5-9f

\[ \eta = 1 - (1 - F_R \tau_s \alpha_s) - \frac{F_R U_c}{I_c} (T_{f,in} - T_\infty) \quad (5-9i) \]

is known as the Hottel-Whillier-Bliss equation [22], which is the equation for the efficiency of a flat plate collector in terms of fixed losses and variable losses and temperature difference between the fluid and ambient.
5.2.2 Comparison between a FPC and a VASC-FPC

The comparison between the performances of the two systems can be based on their efficiencies. But these efficiencies depend on the fixed losses and variable losses. Comparing fixed losses and variable losses can give an idea of how the two systems perform.

Comparing fixed losses

From equations 5-9e and 5-9g, \( \alpha_{s,eq} \) can be defined as the equivalent absorptance of the VASC-FPC system, therefore

\[
\alpha_{s,eq} = (1 - R) \left[ \frac{A - Ae^{-B}}{Ae^{-B}} - e^{-\varepsilon} \left( 1 - \alpha_s (1 - R) \right) \right] \tag{5-10}
\]

Making substitution and rearranging the equation above, the equivalent absorptance can also be written as

\[
\alpha_{s,eq} = \alpha_s (1 - R) e^{-\mu L} + \frac{1 - R}{\alpha_s \left( \frac{1}{\mu k} + \frac{1}{U_c} \right)} \left[ \left( \frac{1}{\mu k} + \frac{1}{U_c} \right) (1 - e^{-\mu L}) - \frac{L}{k} e^{-\mu L} \right] \tag{5-11}
\]

And the ratio, \( \gamma \), between the equivalent absorptance of the VASC-FPC system, \( \alpha_{s,eq} \), and the absorptance of the common FPC, \( \alpha_s \), can be determined

\[
\gamma = \frac{\alpha_{s,eq}}{\alpha_s} = (1 - R) e^{-\mu L} + \frac{1 - R}{\alpha_s \left( \frac{1}{\mu k} + \frac{1}{U_c} \right)} \left[ \left( \frac{1}{\mu k} + \frac{1}{U_c} \right) (1 - e^{-\mu L}) - \frac{L}{k} e^{-\mu L} \right] \tag{5-12}
\]

If \( \gamma \) is greater than 1, then more energy is absorbed by the VASC-FPC system’s absorber plate than the FPC alone, which increases the amount of heat delivered to the end user, \( Q_u \).

If this is the case, the VASC-FPC system has a better performance compared to the FPC in terms of the fixed losses. If \( \gamma \) is less than 1, the VASC-FPC performance is poorer compared to FPC alone in terms of the fixed losses.
Comparing variable losses
From equations 5-9h and 5-9f, \( U_{c,eq} \) can be defined as the equivalent \( U_c \) for the VASC-FPC system, therefore

\[
\frac{F_R U_{c,eq}}{I_C} = \frac{F_R \tau_s (1-R)}{(A\varepsilon+B)T_\infty}
\]  

(5-13)

Rearranging the equation above and making substitutions, the equivalent thermal resistance of the overall VASC-FPC system is

\[
\frac{1}{U_{c,eq}} = \frac{L}{k} + \frac{1}{U_c}
\]

(5-14)

The ratio, \( \rho \), between the equivalent resistance of the combined system and the flat plate collector alone is

\[
\frac{1}{U_{c,eq}} \left( \frac{1}{U_c} \right) = \rho = 1 + \frac{\mu l}{\mu k}U_c
\]

(5-15)

If \( \rho \) is greater than 1, the VASC-FPC thermal resistance is higher, which reduces the amount of variable heat losses of the system and increases the overall performance. And if \( \rho \) is less than 1, the VASC-FPC system is poorer than FPC in terms of variable losses.

The figures 5-3 and 5-4 show the variation of the ratios \( \gamma \) (figure 5-3) and \( \rho \) (figure 5-4) with respect to the depth of the collector, for different types of glasses (\( \mu k \)) and for fixed \( U_c = 7.5 \text{ W/m}^2\text{K} \), \( R = 4\% \), and \( \alpha_s = 95\% \).

It can be seen from figure 5-3 that the ratio \( \gamma \) is always less than 1 for the all the given glass materials. This means that the fixed losses are larger for the VASC-FPC system compared to the FPC alone. This puts the combined VASC-FPC system at a competitive disadvantage in comparison to the common flat plate collector.
In figure 5-4, the ratio $\rho$ is always greater than 1, which means that the variable heat losses of the combined VASC-FPC are smaller than the FPC alone. This puts the VASC-FPC system at a competitive advantage in comparison to the normal FPC.
From the two figures above, it can be concluded that the fixed losses are larger for the combined system and the variable losses are lower. This cannot provide a definite insight on which collector has a better performance, even though it can be seen that the variable losses are more decreased than fixed losses are increased. This results in the overall performance being greater for the combined system in comparison to the flat plate collector alone.

The figures below 5-5 and 5-6, show the variation of the collector efficiency as a function of the temperature difference between the entering fluid and ambient. This is an all-inclusive technique of comparing the VASC-FPC with the FPC.

Three different depths of the VASC are used and compared to a common flat plate collector. The following parameters have been used in figure 5-5 and are typical for a common flat plate collector [22]. The same parameters were used to reproduce the efficiency curve for the flat plate collector (FPC) in figure 3-16 which was taken from [9]. In this case, the heat transfer coefficient is assumed to be constant for all temperature ranges. In reality, it is a weak function of temperature.

\[
\mu k = 1 \frac{W}{m^2 K}
\]
\[
I_c = 1000 \frac{W}{m^2}
\]
\[
F_R = 0.9
\]
\[
\tau_s = 0.92
\]
\[
U_c = 7.5 \frac{W}{m^2 K}
\]
\[
R = 4\%
\]

Figure 5-5. Comparison of the efficiency of a FPC with different VASC-FPC systems.
It can be noticed that for temperature differences below $20^\circ C$, the effects of fixed losses cause the efficiency of a normal collector to be greater than the efficiencies of the combined system, but for higher temperatures, the effects of lower variable losses lead to a higher efficiency of the combined system. For this case in particular, it can be seen that for a temperature difference of $100^\circ C$, the efficiency of a flat plate collector with a relatively small depth VASC component is three times higher than the flat plate collector alone.

The figure below shows the same phenomenon for an advanced flat plate collector (AFC). Two parameters were changed to improve the performance of the flat plate collector and the combined VASC-FPC. These values reproduce the curve presented before for an advanced flat plate collector (AFP) in figure 3-16, which was taken from [9].

\[
F_R = 0.915 \\
U_c = 5.2 \text{ } W/m^2K
\]

All the other parameters values were kept. In this case, it can be seen that for the same temperature difference of $100^\circ C$, the efficiency can be significantly improved.

![Comparison of an advanced FPC with various VASC-FPC systems.](image)

Figure 5-6. Comparison of an advanced FPC with various VASC-FPC systems.
5.3 Locating materials

In chapter 3, an experimental analysis of the model was presented. A borosilicate glass cylinder was used to carry out the experiments and the experimental results matched the theoretical prediction of the VASC model to an appreciable degree. The highest temperature that was measured in the material at steady state conditions was about 330°C. In an effort to improve the performance of the collector, it is commendable to locate other potential materials for this application. The search would focus on materials whose material number, A, is high and that can withstand high temperatures. The material used in the experiment had an A value of approximately 0.58. Higher values of A would provide higher temperatures. Optical glass materials were deemed to be best for this application due to their relatively high values of A. A sample of some of these glass materials is shown in the table below. These are different optical glasses from Schott. A longer list of these materials as well as other glasses from Hoya Optics is shown in appendix A.

Figure 5-7 shows the cost of different types of materials. It can be seen that there is a big range of materials with a low $\mu_k$ (high A) that are relatively lowly priced. Therefore, for this application, the best materials are not necessarily the most expensive ones.

![Figure 5-7. Price levels for different optical glasses.](image-url)
Table 5-1 Schott optical glass properties.

<table>
<thead>
<tr>
<th>Glass</th>
<th>$\mu$ (1/m)</th>
<th>$k$ (W/mK)</th>
<th>$\mu k$ (W/m²K)</th>
<th>$T_{\text{max}}$</th>
<th>$A$</th>
</tr>
</thead>
<tbody>
<tr>
<td>F2</td>
<td>1.59</td>
<td>0.78</td>
<td>1.24</td>
<td>434</td>
<td>2.69</td>
</tr>
<tr>
<td>F2HT</td>
<td>1.38</td>
<td>0.78</td>
<td>1.08</td>
<td>434</td>
<td>3.09</td>
</tr>
<tr>
<td>F5</td>
<td>1.67</td>
<td>0.88</td>
<td>1.47</td>
<td>438</td>
<td>2.27</td>
</tr>
<tr>
<td>K10</td>
<td>1.43</td>
<td>1.12</td>
<td>1.60</td>
<td>459</td>
<td>2.08</td>
</tr>
<tr>
<td>LF5</td>
<td>1.47</td>
<td>0.87</td>
<td>1.28</td>
<td>419</td>
<td>2.61</td>
</tr>
<tr>
<td>LLF1</td>
<td>1.31</td>
<td>0.99</td>
<td>1.29</td>
<td>431</td>
<td>2.58</td>
</tr>
<tr>
<td>N-BAK1</td>
<td>1.18</td>
<td>0.80</td>
<td>0.94</td>
<td>592</td>
<td>3.56</td>
</tr>
<tr>
<td>N-BAK2</td>
<td>1.23</td>
<td>0.92</td>
<td>1.13</td>
<td>554</td>
<td>2.95</td>
</tr>
<tr>
<td>N-BAK4</td>
<td>1.88</td>
<td>0.88</td>
<td>1.65</td>
<td>581</td>
<td>2.02</td>
</tr>
<tr>
<td>N-BALF4</td>
<td>2.08</td>
<td>0.85</td>
<td>1.77</td>
<td>578</td>
<td>1.88</td>
</tr>
<tr>
<td>N-BK10</td>
<td>1.11</td>
<td>1.32</td>
<td>1.46</td>
<td>551</td>
<td>2.28</td>
</tr>
<tr>
<td>N-BK7</td>
<td>1.40</td>
<td>1.11</td>
<td>1.56</td>
<td>557</td>
<td>2.14</td>
</tr>
<tr>
<td>N-BK7HT</td>
<td>1.11</td>
<td>1.11</td>
<td>1.24</td>
<td>557</td>
<td>2.69</td>
</tr>
<tr>
<td>N-FK5</td>
<td>1.21</td>
<td>0.93</td>
<td>1.12</td>
<td>466</td>
<td>2.99</td>
</tr>
<tr>
<td>N-FK51A</td>
<td>1.18</td>
<td>0.76</td>
<td>0.90</td>
<td>464</td>
<td>3.71</td>
</tr>
<tr>
<td>N-K5</td>
<td>1.44</td>
<td>0.95</td>
<td>1.37</td>
<td>546</td>
<td>2.43</td>
</tr>
<tr>
<td>N-KZFS11</td>
<td>1.80</td>
<td>0.81</td>
<td>1.46</td>
<td>551</td>
<td>2.29</td>
</tr>
<tr>
<td>N-KZFS2</td>
<td>2.24</td>
<td>0.81</td>
<td>1.81</td>
<td>472</td>
<td>1.84</td>
</tr>
<tr>
<td>N-KZFS4</td>
<td>2.17</td>
<td>0.84</td>
<td>1.82</td>
<td>536</td>
<td>1.83</td>
</tr>
<tr>
<td>N-KZFS5</td>
<td>2.20</td>
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<td>2.09</td>
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CHAPTER SIX

6 CONCLUSIONS AND RECOMMENDATIONS

The development of solar energy technologies is on a fast track. Today, more than any other time in history, the potential for the use of solar energy in everyday applications has gained a lot of attention. A large number of energy companies, even fossil fuel companies, are putting a lot of effort in developing renewable energy technologies. The BP oil company has one of the most advanced solar panel. The GE Company is also known to develop solar energy collection and storage technologies. More solar power plants are being built in California, Spain and around the world. Irrefutably, there is no turning back from the promise and pursuit of renewable energies, particularly solar energy.

This work presented a system that would help increase the performance of existing solar energy collecting technologies. The Volumetric Absorption Solar Collector is based on the same phenomenon that exists in solar ponds and is governed by the physics of a flat plate collector. However, the VASC system is thermodynamically superior to both the solar pond and the flat plate collector, since it has the ability to provide more heat.

A model of the VASC was developed and used to predict the performance of the collector under different conditions. This model was validated through experimental analysis using a small semitransparent material, the borosilicate glass. This glass material had a material number, A, of 0.58. It was shown that the performance of a VASC heavily depends on the value of A. The higher the value of A is, the greater the collector. Increasing the value of A has constraints, however, given by the physical properties of the material. Some materials with a high A value may not be able to handle the temperatures that can be reached during the application. An ideal medium would be the one with a high transparency, low conductivity and a high temperature allowance.

One of the potential applications of the volumetric absorption solar collector was presented and analyzed mathematically. It involved the combination of a VASC with a flat plate collector. The theoretical analysis showed that the combined system would slightly increase fixed losses but strongly decrease variable losses, therefore have a greater overall performance.
The increase in fixed losses had a negative impact on the combined system for the very low temperature applications but as the temperature gets higher, this impact was nullified. The application of a VASC to flat plate collectors is not to be confused with FPC with multiple covers. When this is done, a significant amount of radiation, 8% per glazing, is lost through reflection and reradiation. With one thick semitransparent material, the reflective losses are minimized and the overall performance is improved.

Finally, different materials available on the market deemed to have a good performance for this application were presented, along with their relative cost. It was found that the best of the chosen materials are not necessarily the most expensive for this particular application, which puts the VASC system at a competitive advantage in terms of economics.

In the future, it is suggested that an experimental analysis be done on the VASC-FPC system that was proposed and analyzed in this work. From the theoretical analysis, it was shown that for temperatures of approximately 100°C, the combined system can perform at efficiencies as high as 4 times the efficiency of a normal flat plate collector alone. It would be useful to prove this assertion through experimental analysis.

The next suggestion for future work is to locate other potential applications for the volumetric absorption solar collector. Examples of such include the use of the VASC as a volumetric solar energy receiver for compound parabolic collectors. A theoretical analysis of the performance of the combined system as well as an experimental analysis would be beneficial.

Even though a wide range of materials were presented, it is suggested that future work on this topic tries to determine the best material for this application. This would be the material with a high thermodynamic stability (high transformation temperature), high transmissivity in order to allow more solar radiation to pass through, and a low thermal conductivity in order to keep much of the energy received and reduce conduction heat losses.

Finally, it is suggested that a comprehensive economical analysis be done for a VASC system or a VASC-FPC system or any other application that uses the VASC. This would help make an informed conclusion about the economic viability of the collector and whether the added manufacturing costs of this collector are offset by its thermodynamic superiority.
## APPENDIX A

### OPTICAL GLASSES FROM SCHOTT

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### OPTICAL GLASSES: HOYA OPTICS

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#### APPENDIX 11 Price Level for Hoya Optics Glass.
REFERENCES


BIOGRAPHICAL SKETCH

Philibert Girurugwiro, a native of Rwanda, was born on 12/12/1985 and grew up during the most violent and tumultuous period of his country’s history. As a refugee in Tanzania, he had to suspend his education. When he returned home, he completed high school and received a national award for outstanding performance in science. In 2006, Phil received a Rwandan Presidential Scholarship to study in the United States. He enrolled at Oklahoma Christian University, majoring in mechanical engineering. In 2008, he returned home to work in the energy sector of the Rwandan Ministry of Infrastructure. There he quickly discerned the potential value of renewable energy to his country’s development. After receiving his BS in engineering from Oklahoma Christian University in 2010, Phil entered FSU’s Masters Program in Mechanical Engineering with an emphasis on sustainable energy. At FSU, he also became a fellow of William Kerr Institute of Intercultural Education and Dialogue. He hopes to acquire the necessary skills with which to contribute to the advancement of his country’s economy by reducing its high level of energy dependence.