2011

Investigation into the Potential Use of Windbreaks to Improve Solar Collector Performance

Michael Watts
Minnesota State University - Mankato

Investigation into the Potential Use of Windbreaks to Improve Solar Collector Performance

By
Michael Watts

A Thesis Submitted in Partial Fulfillment of the Requirements for
Master of Science
In
Engineering

Minnesota State University, Mankato
Mankato, Minnesota

May 2011

Thesis Endorsement Page

Date: 1/6/2011

This thesis paper has been examined and approved.
Examining Committee:

Saeed Moaveni PT
Dr. Moaveni, Chairperson

Patrick Tebbe
Dr. Tebbe

Louis Schwartzkopf
Dr. Schwartzkopf

Abstract

This thesis “Investigation into the Potential of Windbreaks to Improve Solar Collector Performance was written by Mike Watts as part of a Master of Science degree in Mechanical Engineering from Minnesota State University – Mankato in 2011.

The global demand for energy is ever increasing; however, the world has a limited number of fossil fuels available. Therefore, alternative renewable energy sources must be utilized. For this reason, solar thermal collectors have become an increasingly popular method for providing hot water or space heating. However, solar thermal collectors are most commonly used in areas that experience warm climates throughout the year. In areas that experience seasonal climates, the cold temperatures and harsh climate conditions significantly reduce the performance of solar thermal collectors during the winter months. This thesis examined the potential that the implementation of a windbreak could have on improving the performance of a solar collector, by reducing the wind induced convection losses, during winter climate conditions.

In order to determine the effect of the windbreak, two collectors were operated simultaneously and side by side, one of which had a windbreak. The expected wind direction was from the northwest, so the windbreak was positioned on the westward side of the eastward collector. In this position, a northwest wind would pass over the first collector unhindered and the windbreak would provide shelter to the second collector. The performance of two collectors was measured by calculating and comparing the instantaneous efficiencies.

Data was collected during February 2010 and October and November 2010. The results indicated that both wind speed and wind direction will impact the effect that the windbreak has. As one would expect, during non-windy days there was no significant difference observed between the two collectors. On Windy days in which the wind came from the expected wind direction, the windbreak appeared improve the collector’s performance. However, due to the uncertainty in the measurements, and the limited number of data points, a definitive declaration cannot be made.

Table of Contents

Chapter 1 6
Introduction 6
Chapter 2 10
Literature Review 10
Chapter 3 23
Theoretical Background 23
3.1 Solar Thermal Collectors 23
3.2 Windbreaks 27
Chapter 4 30
Experimental Methodology 30
4.1 System Description 30
4.2 Data Collection 35
4.3 The Windbreak 37
4.4 Data Analysis 38
Chapter 5 40
Data Analysis 40
5.1 February 2010 40
5.2 Fall 2010 43
Chapter 6 49
Conclusions and Recommendations 49
6.1 Conclusions 49
6.2 Recommendations for Further Study 51

List of Tables and Figures

Figure 1: A Flat Plate Solar Collector (Image from U.S. Department of Energy Website).10
Figure 2: Collector Heat Gain and Heat Loss 25
Figure 3: Windbreak Diagram 29
Figure 4: Transfer and Heating Loops 31
Figure 5: Heating Loop 32
Figure 6: Transfer Loop 33
Figure 7: The Collector Loop 34
Figure 8: Omega Weather Station 36
Figure 9: The Collectors with windbreak 38
Figure 10: Daily Collector Efficiency for February 2010. 41
Figure 11: Collector Heat Gain Comparison 42
Figure 12: Daily Collector Efficiencies for fall 2010. 44
Figure 13: Collector Performance versus Wind Speed for Windy Days Fall 2010.......... 45
Figure 14: Average daily collector surface temperature 47
Figure 15: Difference in Average Collector Surface Temperature versus Wind Speed... 48

Table 1: Summary Table for January and February 2010 Testing Period 42
Table 2: Summary of Collector Efficiency on Windy and Non Windy Days 46

Chapter 1

Introduction

As the world's population grows, so does its demand for energy. The world population grew from 3 billion in 1959, to 6 billion in 1999, and this growth is expected to continue into the 21st century. The U.S. Census Bureau projects that the population growth will continue and the world's population will reach 9 billion by 2044 [1]. This growth in population is accompanied by an increase in energy consumption. As a developed country, demand for energy in the United States is relatively stable. However, even in the United States the demand for energy is steadily increasing [2]. Furthermore, the rising demand cannot keep up with the limited amount of natural resources. Of the 94.72 quadrillion Btu that the United States consumed in 2009, only 7.18 quadrillion Btu were provided by renewable resources. The U.S. Government has recognized that it must be vigilant in its promotion of renewable energy resources. As a result, the federal government and many state and local governments have begun offering incentives to promote solar, wind and other renewable energy systems [3].

One source of renewable energy that is included in the incentive programs is solar thermal energy. Flat plate solar collectors are the simplest type of solar collector, and consist of only three main components: an absorber, a top cover glazing, and an insulated backing. Solar radiation is absorbed by the absorber plate of a solar collector. The radiation causes a temperature rise in the absorber plate, and the fluid that flows through the tubes that are in direct contact with the absorber plate. The fluid is then pumped to another location where thermal energy is transfer to another fluid. Common applications of solar systems include domestic water, space, or pool heating. Despite the modern applications, solar thermal energy is not a new development. In fact, Horace de Saussure was credited with the world's first solar collector in 1767 [4]. However, despite roots dating back over 200 years, the solar thermal industry is still developing. Market research has shown that many home owners view saving money to be the deciding factor in whether they will purchase a solar thermal system, or use a conventional system [5]. A solar thermal system requires an initial investment cost to purchase and install the system. The benefit is seen because the solar energy which is free, replaces the owners dependence on non-renewable resources, typically natural gas. However, in a survey conducted by the National Renewable Energy Laboratory (NREL), many respondents cited the initial installation costs of the system to be too high. Furthermore, NREL found that that for solar systems to be economically feasible to a significant market, the installed cost should be in the range of $1000-$1500 [6]. For this reason, the National Renewable Energy Laboratory has devoted research into developing cheaper solar thermal systems. Additionally, the government incentives have helped reduce the investment cost for the owner, and the solar thermal industry has experienced growth in recent years. However, the areas in which solar collectors are most popular experience warm climates throughout the year [7]

Many of these financial concerns are compounded in the northern latitudes because of the cold conditions that they experience during winter. The reduction in solar radiation results in a reduced heat gain through the collector and the low ambient temperatures can result in an increase in collector heat loss to the surroundings. Combined, these factors will case a reduction in the collector's performance. Additionally, these areas experience fewer sunlit hours; therefore, solar thermal systems will provide less energy during this periods resulting in reduced savings for the owner. This reduction in savings makes solar thermal systems less attractive financially in cold climate areas than in warm climates. Therefore, steps must be taken to enhance the performance of solar thermal systems in the northern colder climates to make them more desirable in these areas.

Improved collector design can improve the collector's efficiency during all climate conditions and can help compensate the loss experienced during the winter months, and this area is the source of a significant amount of research. A variety of methods have been attempted to improve the performance of flat plate solar collectors. Honeycomb collectors have been shown to have higher efficiencies than traditional collectors [8].
Thin films have also proven to be very useful in creating selective absorbers and anti-reflective coatings [9-10]. While these methods have been proven to increase collector performance, they would also increase the cost of the collector, and don't directly address the issues solar collectors face in cold climates.

The previously mentioned research areas have either focused on reducing the natural convection heat transfer between the absorber and the glazing, or on reducing the reflectance or re-emitted losses. However, according to Turgot and Onur, "wind induced heat losses have an important effect on the efficiency of solar collectors. This is especially true in cold climates where temperature differences between the collector surface and the ambient are relatively large" [11]. These conditions are similar to the winter conditions that the Midwestern United States experiences because in addition to the cold temperatures the highest wind potential also occurs during the winter months. Therefore, this potential heat loss was investigated further in this thesis.

Windbreaks and shelterbelts have a long history of being used to direct wind and provide sheltered areas. Windbreaks are most commonly seen around farms to protect the crops and top soil, and they have also been used effectively to direct snow drifts and sand dunes [12]. However, properly positioned windbreaks have also been shown to reduce heating costs in rural homes [13-14]. The successful usage of windbreaks in these large scale applications shows promise that scaled down windbreaks could be beneficial in providing protection for small scale applications.

This thesis examined the potential of using a windbreak on a small scale to provide a flat plate solar thermal collector protection from the wind in order to improve its performance. Specifically, this thesis investigated whether the performance of a flat plate solar collector could be improved by implementing a windbreak, and if a threshold of wind speed and ambient temperature for which the windbreak became beneficial existed.

Chapter 2

Literature Review

Solar collectors have a wide variety of applications, ranging from moderate to high temperatures. Flat plate collectors provide moderate temperature rises of the working fluid and are commonly used for space and water heating. Additionally, flat plate collectors are mechanically simpler than and cheaper than either evacuated tube or concentrating collectors. For this reason, they are commonly used in domestic applications. Additionally, due to their relative simplicity and wide range of use, flat plate collectors and their performance is the subject of much ongoing research.

Figure 1 depicts a typical flat plate solar collector design. The collector consist of four primary components: an absorber, a glazing material, flow tubes and insulation. Solar radiation hits the absorber and causes it to increase in temperature. Fluid flows through the flow tubes, which transfers heat from the absorber to the fluid.

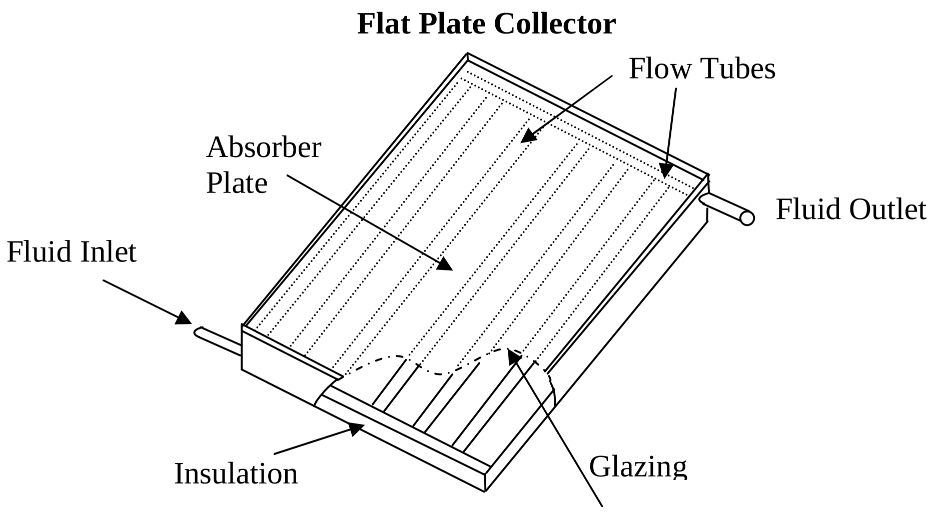


Figure 1: A Flat Plate Solar Collector

The insulation is located on the back side of the absorber and reduces the heat loss from the absorber through the back of the collector. The purpose of the glazing is to reduce the heat loss from the top of the collector.

Collector performance is determined by its efficiency, which is the ratio of the energy transferred to the fluid to incident radiation [15]. Due to the simplicity of the design, there are only a few ways to improve collector performance. If either the rate of heat loss to the surroundings is reduced, or the amount of absorbed is increased, the collector efficiency will be improved.

The primary modes of heat transfer from the absorber to the surroundings are convection and radiation, and both of these have been sources of research. Furthermore, the focus on the convection losses has primarily been focused on the natural convection losses between absorber and the glazing. The primary purpose of the glazing cover is to reduce the convective losses from the collector. Additionally, a second glazing can reduce the heat loss even further. More advanced methods have also been attempted. One method that researchers have investigated is to implement another barrier between the cover and the absorber plate. The barrier obstructs natural convection between the two surfaces and reduces the overall heat loss.

A. A. Ghonheim investigated the effect different arrangements of honeycomb patterns had on collector performance [16]. Early honeycomb studies completely filled the air gap between the top cover and the absorber plate. However, the presence of a small air gap between the absorber and the honeycomb material and between the honeycomb and the glazing will reduce the conduction and radiation losses. Ghonheim investigated the effect that the length of the gap between these layers had on collector performance. In the study, a square cell honey comb pattern of polycarbonate was used, and the gap distance between the layers was varied between 0 and 12 mm. The performance of the collectors with the honeycomb suppressant was compared with the performance of the collector without the honeycomb suppressant.

The results showed that the bottom gap thickness was more important than the top gap thickness, and an optimal bottom gap thickness of 3 mm was found. This can be explained by the method of heat transfer in a honeycomb collector. As the gap approaches zero, conduction to the honeycomb from the absorber increases, which results in an increase in radiation from the honeycomb walls. However, if the gap thickness is increased beyond the optimal value, convection from the absorber increases the heat transfer to the honeycomb material, which results in increased radiation losses from the honeycomb. The collector with a gap thickness of 3 mm showed a reduction of 48% in the collector heat loss coefficient. However, the honeycomb structure also reduced the optical efficiency of the collector by 14%. This is important to note because the effect of optical efficiency is dominant at low temperatures, and the heat loss is dominant at high temperatures. Therefore, the efficiency of the honeycomb collector will be better for medium and high temperature differences, but a collector without honeycomb will have a higher efficiency for low temperatures

In another similar study [17], the performance of single and double honeycombed collectors was compared to a collector without honeycomb suppression. In each case, the total gap between the absorber and the glazing was 60 mm. The honeycomb structures used in each case were 16 mm thick, and for both cases the top and bottom air gaps were adjusted in order to determine the optimal values. In the double honeycombed case, the gap between the honeycombs was also adjusted to in order to determine if an optimal value could be found.

As the previous study indicated, a bottom gap of 3 mm was found for both the single honeycomb and double honeycomb collectors. Since this value was found to be common for both cases, it was kept constant for additional testing of the double honeycombed collector, and the top and middle air gaps were changed. While the double honeycombed collector showed an improvement in the reduction of the heat loss over the single honeycomb case, it also suffered the penalty of a greater reduction in the optical efficiency. Therefore, the single case had a higher efficiency over the entire range of operating conditions than the other two cases. Since the effect of the honeycomb suppressant is a balance between the reduction of the heat loss and the reduction of the optical efficiency, if a material with better optical properties is used, the double honeycomb collector may perform better.

Varol and Oztop also investigated a method of reducing the convective losses between the absorber and the glazing [18]. They numerically simulated the natural convection that occurs between the glazing and two absorber shapes: the typical flat absorber, and a wavy-sinusoidal absorber. Their results showed that the shape of the absorber had a significant effect on the amount of natural convection heat transfer. In addition, the wavy collector resulted in greater heat transfer than the flat plate collector. Therefore, the results of this study indicated that the wavy absorber had a negative impact on the collector's performance, but the researchers suggested that further studies should be conducted.

The gap between the two surfaces is typically filled with air, which is the fluid that is the means for convection between the two surfaces. This is practical because it would increase manufacturing costs to create a vacuum between the surfaces, or to use another fluid. Furthermore, only a small number of products with a gas filling other than air have been marketed and they have had limited success. However, Vestlund, Rönnelid, and Dalenbäck numerically modeled natural convection between the two surfaces, and compared an air filled collector with a collector filled with an inert gas [19]. The gases that they modeled were: Argon, Krypton, Xenon and Carbon Dioxide. Their simulation showed that Carbon Dioxide did not improve collector performance. However in the cases of Argon, Krypton, and Xenon, the performance of the collector was improved, and in some cases by as much as 20%. Additionally, the researchers suggest that construction of thinner collectors could offset the cost of the gas.

Another method researchers have investigated to improve collector performance is by reducing the amount of radiation that is re-emitted by the collector. This is typically done by applying coatings to traditional absorber materials. However, if the coating is to improve the collector efficiency it must reduce the emissivity of the absorber, without reducing its absorbtance. Finding materials with low emissivity and high absorbtance has proven difficult, but researchers have had luck with metal oxides.

Garba, Sambo and Mosugu investigated the effect of chemical coatings on solar collector plates and in turn on thermal performance of the collector [20]. In their study, two types of coatings, Copper Oxide, and carbon black, were used on three substrate materials, aluminum, copper and iron. The copper oxide coating was applied to the plates using spray pyrolysis and the carbon black coating was applied using a painting technique. The performance of the coatings was tested by first measuring the absorbance and reflectance of the uncoated plates at various angles of incidence. The plates were then tested again with the coatings applied. The results showed that both coatings increased the plate's absorbance and decreased the plate's reflectance. Additionally, the plates coated with copper oxide had a higher absorbance than the plates coated with carbon black for all angles of incidence.

More recently, Katumba, Olumekor, Forbes, Makiwa, Mwakikunga, Lu and Wäckelgaurd compared the absorptivity and emissivity of carbon nano-particles embedded in ZnO and NiO [21]. The study measured the reflectance of each material and used the reflectance to determine the absorbtance and emissivity of each material. The performance of the coatings was determined by finding the ratio of the normal absorbtance to the normal emissivity. The coating with the higher ratio has the better optical properties for an absorber

The results showed that while the paint had the highest normal absorption at 93%, it also had the highest normal emissivity at 33%. The ZnO had an absorptivity of 71% and an emissivity of 6%, and the NiO had an absorptivity of 84% and an emissivity of 4%. The NiO coating clearly has the highest absorption-emissivity ratio at 20.91, and the ZnO coating has a ratio of 12.70 which is still much higher than the paint which has a ratio of only 2.85. This data clearly indicates that the NiO absorber has more desirable characteristics than the other two materials.

Research in coatings has not been limited to coatings for absorbers. Most flat plate solar collectors utilize a cover material to reduce the amount of heat loss to the surroundings, and low iron, tempered glass is typically used for its wide temperature range and high transmittance. However, even high transmittance glasses typically have transmittances of around 90%. This results in a significant loss even before the solar radiation strikes the absorber plate. For this reason, anti-reflective coatings have become another popular area of research.

A single glass cover reflects approximately 8-10% of the incident radiation, and a double glazed collector may reflect up to 17%. By reducing the reflectance of the glazing material, more solar radiation will hit absorbing material and collector performance will improve. For this reason, the glazing materials are often coated with an anti-reflection layer. According to, Khoukhi, Maruyama, and Komiya, the ideal refractive index for the coating should be equal to the square root of the refractive index for the glass [22]. However, it is difficult to find coating materials that meet this requirement. A few commonly used coating materials are magnesium fluoride, lithium fluoride and aluminum fluoride.

Khoukhi *et al* discovered a new material that has a lower refractive index than that of the materials that have been used previously. Using a dip-coating process a thin layer of SiO_2 is deposited on the glass surface. The results showed that this coating had a significantly higher solar transmittance than other coatings and uncoated glass.

Kesmez, Camurlu, Burunkaya and Arpac coated glass substrates with thin layers of $Si0_2$ and then $Ti0_2$ [23], the purpose of which was to create a surface that was self cleaning and anti-reflective. The Silicon layer increased the transmittance of the glass by 6%, which offset the loss in transmittance caused by the self-cleaning titanium layer. The end result was a self-cleaning, anti-reflective surface.

While utilizing one of these methods could improve collector performance, applying several would have a greater effect. Hellstrom, Adsten, Nostell, Karlsson and Wackelgard simulated the effect that improving absorbtance and emittance characteristics of the absorber as well as the improving the optical characteristics of the glazing and the reduction of natural convection between the two surfaces would have on investigated the effect that the optical and thermal properties of the collector have on its performance [24]. These properties were investigated individually and collectively at an operating temperature of 50 °C in order to determine which improvement would be the most effective.

The results showed that an increase in absorbtance from .95 to .97 only had a moderate effect on the collector's performance, and resulted in an increase in the collector's annual energy output of less than 5%. In addition, reducing the emittance of the absorber from .1 to .05 showed a similarly moderate improvement. However, when both improvements were applied to the model, the combined effect was nearly equal to the sum of the individual effects, and amounted to an increase in the energy output of approximately 7%. Additionally, the effect of lowering the emittance increases as the operating temperature of the collector increases. Reducing the reflectance of the glazing by 4% showed an increase in the annual energy output of 6.5%. Furthermore, it is feasible that this could be further improved upon, but not with the currently industrially produced coatings. Lastly, two methods for reducing natural convection losses were investigated a Teflon film and a Teflon honeycomb. An increase in the energy output of 6% and 12% was found for the Teflon film and honeycomb, respectively. Lastly, for a collector equipped with each of these improvements, a total increase of 25% was seen.

Furthermore, Hellstrom *et al*, speculate that improving the absorbers characteristics, and using current anti-reflection coatings on the glazing can be cost effective. However, the Teflon honeycomb had a relatively high material cost and was about 12.5 times higher than just a single film and is less cost effective. Yet, including a single Teflon film could be beneficial and cost efficient.

The improvements suggested so far have all been applied to traditional flat plate solar collectors and haven't directly addressed the issues (such as reduced incident solar radiation, fewer sunlit hours and increased heat loss due to cold ambient temperatures) that solar thermal collectors endure in cold climates.

Groenhout, Behnia and Morrison attempted to develop an advanced solar collector that would be more effective during winter months [25]. Their design incorporated a double-sided flat plate absorber mounted on stationary concentrators. Groenhout *et al* assessed the performance of the collector by conducting indoor and outdoor tests in order to determine the heat loss characteristics and the optical and thermal properties. Furthermore, the characteristics of the new design were compared with traditional flat plate designs.

The collector was modeled by simulating an absorber plate by placing three electric heaters between two aluminum sheets. The absorber was located above the concentrators, and the underside of the absorber was partially insulated. The uninsulated part of the absorber was exposed to the concentrators, and the entire area of the absorber and concentrators was covered with low iron glass that is traditionally used in flat plate collectors. The ambient temperature as well as the surface temperature of the absorber, glazing and the collectors was measured and recorded with type-T thermocouples. The effect of wind over the top cover was simulated by installing a ducted air flow above glazing.

The heat loss characteristics of the collector were determined through numerous experiments at various operating temperatures for several hours of steady state operation. The total heat loss through the glass cover and insulated walls was estimated as equal to the power input during steady state operation. A reduction in the conduction losses through the insulated area of the absorber were reduced because the absorber area that was in contact with the insulation was significantly reduced. Additionally, the incorporation of a low emittance coating on the double sided absorber, coupled with the concentrators reduced the radiation losses through the back of the collector. This resulted in an increase in the ratio of convective losses to conduction and radiation losses over traditional flat plated collectors. However, the total heat loss appeared to be between 30-70% lower than in traditional systems.

While these methods have potential in improving the collector's efficiency, they focus primarily on limiting the natural convection that occurs between the surfaces or on improving the optical properties of the absorber and glazing. None of these studies have addressed the problem of heat loss due to forced convection in any detail. Yet, research has shown that forced convection will contribute significantly to the heat loss from the collector. Kumar, Sharma, Kandpal and Mullick simulated the effect that wind has on the convective heat transfer coefficient in a laboratory setting [26]. The collectors were simulated using flat plate electric heaters and industrial fans simulated the wind. With this setup, the researchers were able to test different surface temperatures and wind speeds. The researchers allowed the experiment to reach steady state and used measured the surface temperature and the ambient temperature to calculate the convective heat transfer coefficient. Once plotted with respect to wind speed, the data showed good agreement with a linear regression line.

A similar study was conducted by Sharples and Charlesworth [27]. This study also simulated the conditions of a solar collector with a heated plate; however, the plate had similar dimensions to typical flat plate collectors and the study was conducted outside in actual weather conditions, and the "collector" was mounted on a pitched roof. The surface temperature of the plate was measured with thermocouples in nine locations. Similarly to Kumar *et al*, the average plate and ambient temperatures were used to calculate the convective heat transfer coefficient. The experimental results showed that either a power or a linear regression could be used to model the data. Furthermore, the experimental results also showed good agreement with models previously proposed by other researchers.

In another study by Kumar and Mullick they revisit their earlier work, and model the wind induced convection coefficient experimentally [28]. An unglazed test plate with an area of approximately 0.9 m^2 was mounted on a roof outside. The top of the test plate was exposed to solar radiation and the bottom was insulated. The temperatures on the surface of the test plate and in the insulation assembly, and the ambient temperatures and wind speed were recorded. The wind induced heat loss coefficient was determined by applying a heat loss balance on the test plate. Likewise in their earlier study, they modeled the heat transfer coefficient with linear and power regression models, and their data showed good agreement with both models.

While the exact results from individual studies have been slightly different, they have generally estimated the convective heat loss coefficient with either a linear or a power regression model. Satori conducted a study more recently in an attempt to determine the accuracy of several models and attempted to find a consensus on which model is the most exact in predicting the forced heat loss coefficient over flat plates and solar collectors [29]. Satori determined that the type of flow will affect which model is the most accurate. Therefore, he suggested that for three different types of flow, laminar, fully turbulent and mixed flows, three different power regression models should be applied. However, each of the three models has the same general form, and only differ in their coefficients or exponents.

These studies are significant because convective heat transfer also increases linearly with the convective heat transfer coefficient. Therefore, it can be expected that more heat transfer will occur as wind speed increases, and at considerably high wind speeds, this could be significant. Despite this fact, there is relatively little research focused on reducing the amount of forced convection losses from flat plate solar collectors.

Windbreaks have traditionally been used to direct wind to protect farmland, and to direct wind drifts and sand dunes. In these cases, the windbreaks are typically constructed from trees and shrubs and reduced wind speeds in the sheltered areas [30]. However, windbreaks have been also shown to provide protection from winter winds which result in reduced heating costs for homes and buildings. Heat loss through walls, floors and roofs can be reduced because calm air is a better insulator than moving air. This can be thought of in a similar fashion to the wind chill index.

Chilling winds can induce building heat loss through infiltration and surface heat transfer. This is most apparent in poorly insulated buildings, buildings in highly exposed environments such as coastal buildings, and high-rises. Prior and Keeble described applied a wind chill index to buildings in order to assess the benefit of using windbreaks and shelterbelts for wind protection [31]. They estimated the benefit of utilizing windbreaks by calculating the reduction in the buildings wind chill.   The average number of hours per heating season for which the building's wind chill index exceeded 900 W/m^2 was calculated for five locations of a two story building. The calculation was done for three conditions. Under the first condition no windbreak was implemented. The second condition implemented the windbreak at a distance of 150 meters from the building and the third condition implemented the windbreak 15 meters from the building. Even with a windbreak 150 meters away, the number of wind chill hours exceeding 900 W/m^2 was reduced by approximately 50-75% for the five locations. With a windbreak positioned at 15 meters the number of wind chill hours was reduced by nearly 90% for each of the five locations.

However, it should be noted that the estimation assumed that the wind reduction would be the same for all directions, which may not be the case for all scenarios.

While windbreaks have been traditionally been applied to large scale applications, there is reason to believe that similar benefits can be expected for scaled down applications. This thesis tested this belief by constructing a windbreak to shelter a flat plate collector. The principles that are used in large scale applications were examined and applied to the construction of a small scale windbreak.

Chapter 3

Theoretical Background

3.1 Solar Thermal Collectors

The principles under which flat plate solar collectors operate are relatively simple. The collector consists of three main components, the absorber, the glazing, and insulation. The absorber faces the sun, and receives incident solar radiation, and as it absorbs the solar radiation its temperature rises. The absorber is usually black or another dark color in order to maximize the amount of solar radiation it absorbs. The absorber contains a series of tubes through which a fluid flows. The fluid removes heat from the collector, and the heat removed from the collector can be used to heat a buildings hot water, or used for space heating.

Any heat loss from the collector to the surroundings results in less heat transfer to the fluid. Therefore, the purpose of the glazing and the insulation is to minimize the amount of heat transfer to the surroundings. The back of the absorber is typically insulated to reduce the amount of conduction and convective losses. The top of the absorber cannot be insulated, the absorber must face a transparent surface in order to receive the solar radiation. Therefore, a glazing material is often used to reduce the amount of heat loss due to convection. Glass is commonly used because of its high transmittance and its ability to withstand large temperature ranges. Additionally, a flat plate collector can work without a glazing material, but its performance will be significantly reduced.

Solar radiation consists of three components, direct radiation, diffuse radiation, and reflected radiation. Direct radiation, or beam radiation, is the radiation that is received directly from the sun. The amount of direct radiation a surface receives is dependent on the angle and orientation of the surface relative to the sun. For example, in the northern hemisphere solar collectors are mounted facing south in order to maximize the amount of direct radiation they receive. As radiation from the sun enters the Earth's atmosphere, some of it is scattered and it no longer follows along the path of the direct radiation. The scattering affect is universal, and diffuse radiation travels in all directions in equal amounts. Therefore, the amount of diffuse radiation that hits a surface is independent of the surface's angle or orientation. A good example of diffuse radiation can be seen on cloudy days. On cloudy days much of the direct radiation is blocked by the clouds, yet there is still plenty of daylight during the day. Reflected radiation is the last form of radiation. Radiation can be reflected from the ground or other surfaces back onto another surface. Reflected radiation is similar to direct radiation in that it is dependent on the orientations of the two surfaces involved. Since solar thermal collectors are oriented facing the sky, the amount of reflected radiation that they receive is usually minimal[32].

The combined source of direct, diffuse and reflected radiation that the collectors receive is the total amount of energy gain that the collector can provide. However, only a portion of the incident radiation that is received will be transferred to the fluid and be useable. Figure 2 depicts the solar radiation received by the collector, and the heat transfer from the absorber. The first loss occurs at the glazing material. As radiation hits the glazing, most of it passes through the material, but some of it will be reflected back to the surroundings. High transmittance glasses typically have transmittance values of about 90%. This results in a significant loss even before the radiation has hit the absorber. Secondly, the absorber will also reflect some of the radiation back through the glazing material. The radiation that is absorbed by the absorber will cause a temperature rise, which results in heat transfer to the fluid and heat loss to the surroundings. The heat

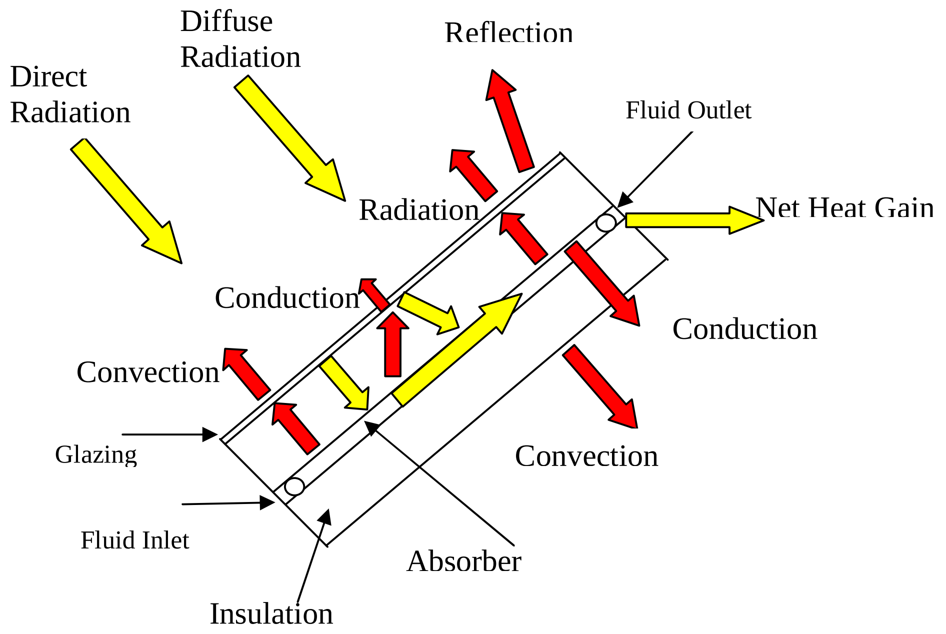


Figure 2: Collector Energy Balance

loss to the surroundings is due to conduction, convection and radiation. The insulation on the back of the collector reduces the heat loss due to conduction. The greatest losses occur from the top surface because it is not insulated. First, the absorber will re-emit some radiation back to the surroundings. Secondly, the air gap between the absorber and the glazing will permit convection and conduction, with convection being the primary mode of heat transfer. All of these heat losses amount to a significant reduction in the heat gain of the collector.

The performance of the collector is determined by how much of the original incident solar radiation is actually transferred to the fluid, and how much is lost (thermal and optical losses) to the surroundings. For steady state operation, the useful energy gain of a collector is defined by:

$$Q_u = A_c[S - U_L(T_{pm} - T_a)]. \quad (1)$$

The incident solar radiation is denoted as S, and the output of the collector is determined by the Area of the collector, A_c, the collector heat transfer coefficient, U_L, and the mean absorber and ambient temperatures, T_{pm} and T_a. The overall heat transfer coefficient for a collector is a combination of the convection, conduction and radiation losses from the surfaces of the collector. Again, the top of the collector is the largest factor in the heat loss coefficient with the primary modes of heat transfer being convection between the absorber and the glazing, and from the glazing to the surroundings and radiation from the absorber.

In this form, Equation (1) is not particularly useful because the mean temperature of the absorber is not easily obtained. However, by using the fluid temperatures and the flow rate the useful energy gain, Q_u, of the collector can be calculated from:

$$Q_u = \dot{m}C_p(T_o - T_i) \quad (2)$$

Equation (2) is preferable to Equation (1) because it uses easily measurable quantities. The temperature difference term, is the rise in temperature of fluid from the inlet to the outlet of the collector. The mass flow rate of the fluid is denoted by $\dot{m}$. This term is typically found by measuring the volumetric flow rate of the fluid and calculating the mass flow rate using the fluid density. In Equation (2), the heat capacity of fluid is represented by C_p

The instantaneous efficiency is commonly used to gauge a collector's performance and is defined as the ratio of the useful energy gain of the collector to the total incident radiation.

$$\eta_i = \frac{Q_u}{A_c G_t} = \frac{\dot{m}C_p(T_o - T_i)}{A_c G_t} \quad (3)$$

The denominator in this equation is the instantaneous incident solar energy, and is the product of the collector area, A_c, and the incident solar radiation flux, G_t, which is typically measured with a pyrometer.

3.2 Windbreak

Windbreaks have a long history of being used to reduce wind speeds, and to control local climate and environments. One of the most common uses of a windbreak is to prevent erosion, and increase crop yields on farms. These large scale windbreaks often use natural barriers, such as trees and bushes, but artificial windbreaks have also been used.

The primary purpose of a windbreak is to reduce wind speed. The amount of reduction and the range of the sheltered area is dependent on the shape, porosity, and thickness of the windbreak. The length of the sheltered area is typically measured with respect to the windbreak height. Wind tunnel and numerical simulations have indicated that the area that receives the most benefit from the windbreak is within a distance of 8-10 times the windbreak height. Furthermore, the reduction in wind speed is greatest near the windbreak, and the wind speed gradually increases as it moves further away from the break.

The porosity of the windbreak has a significant effect on the amount of wind speed reduction, and the size of the sheltered area. Dense windbreaks, typically defined as having porosities less than 0.3, have the potential to produce recirculation bubbles on their leeward side. Initially the recirculation is small, but increases with increasing break density. Cornellis and Gabriels conducted an experimental investigation in an attempt to find the optimal porosity for a wind break. They determined a range of porosities from 0.2 to 0.35 provided the maximum reduction in wind velocities [33]. Santiago, Martin, Cuerva, Bezdenejnykh and Sanz-Andres numerically and through wind tunnel experiments investigated the effect porosity has on the windbreaks sheltering ability [34]. They determined that a porosity of 0.35 provided the maximum benefit. The two investigations give slightly different values for the optimal porosity of the windbreak, but both indicate a similar range.

The thickness of the windbreak also has a significant impact on the flow down stream from the break. Thick windbreaks, with widths ten times the height or greater, will cause the location of the greatest wind speed reduction to be on the windward side the windbreak. In these cases, the wind speed has already begun to pickup before it has passed the windbreak. In contrast, thin windbreaks show the location of the greatest wind reduction downstream with a typical distance of 3-4 unit heights [34]. As a result, thin windbreaks shelter a significantly larger area than thick windbreaks.

The shape of the windbreak also has an effect on the sheltered area. Most studies indicate that smooth-shaped and streamlined windbreaks result in less wind-reduction than vertical sided breaks. This is due to the reduced resistance of the streamlined breaks. The rectangular shape is generally believed to provide the greatest protection. However, Wang *et al* tested a wide range of shapes and only found slight differences in the wind-speed reduction [35].

A windbreak was constructed for this thesis from a sheet of clear polycarbonate. A diagram of the windbreak that was constructed is shown in Figure 3. The windbreak was 96 inches long and extended 8 inches above the collector’s surface. The windbreak was given a porosity of 0.2, which is the lower value of the range that was found to provide the maximum wind protection. The porosity was created by drilling a series of 1 inch diameter holes.

Additionally, the holes are located on the top half of the windbreak, leaving the bottom half of the windbreak solid.

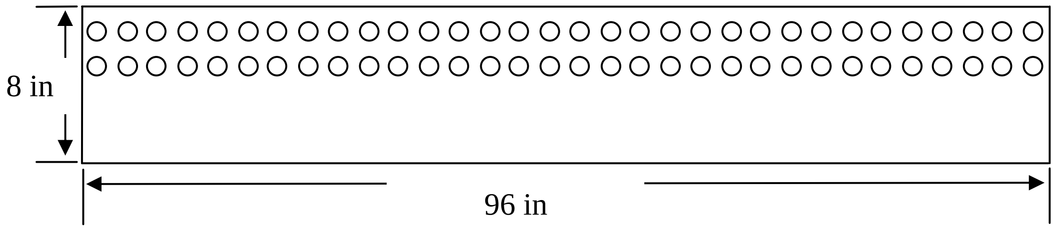


Figure 3: Windbreak Diagram

Chapter 4

Experimental Methodology

4.1 System Description

A series of experiments were conducted to study the effect of a windbreak on reducing heat loss from a flat plate collector. The experimental set up was located on the campus of Minnesota State University on the fourth floor and roof top of Trafton Science Building. The MSU system consisted of all of the main components of a system that could be found in a residential application for either space or water heating. The primary components include: the collectors, a storage tank, and expansion tank, a heat exchanger and the pumps to circulate the fluid.

The solar system consisted of three independent loops, a collector loop, a transfer loop and a heating loop. Each loop has its own pump which circulated the fluid through the loop. The collector and transfer loop pumps were controlled by the same switch and the heating loop pump was controlled by a separate switch. A photograph the heating and transfer loops is shown in Figure 4.

Figure 4: A Photograph of Transfer and Heating Loops

The heating loop (Figure 5) pumps water from the storage tank through a register. As the water passes through the register, heat transfers from the water to the register and ultimately to the room. This is one method that could be used in a residential application for space heating. In a residential application that uses the solar collectors to provide water heating only, the space heating loop could be omitted from the system.

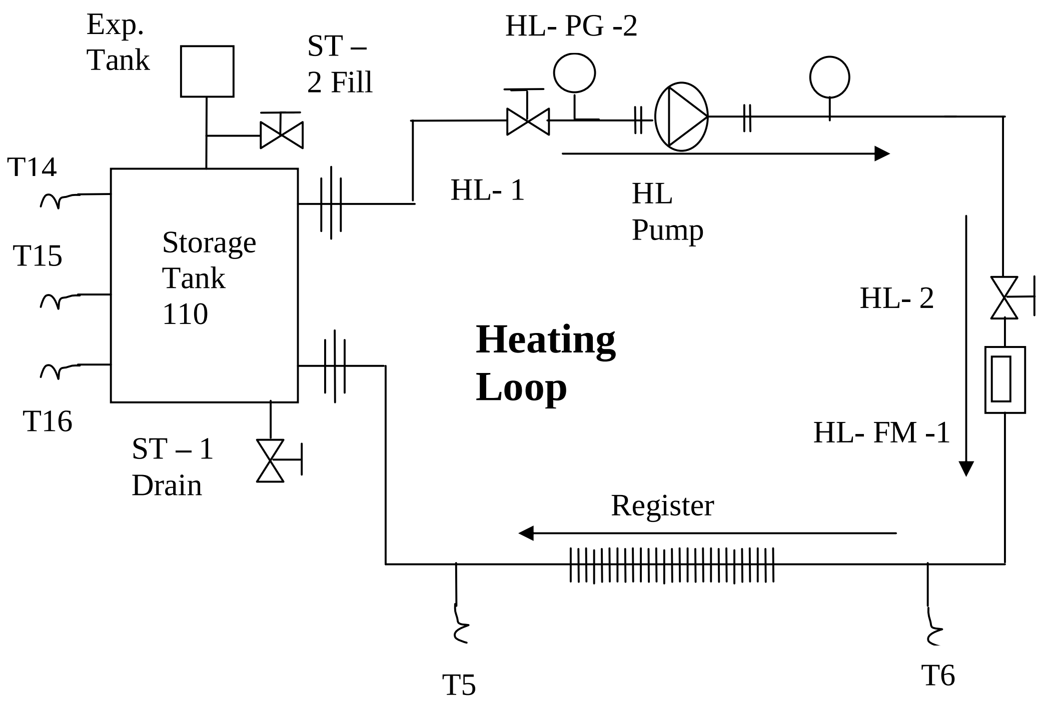


Figure 5: Heating Loop

As shown in Figure 6, the transfer loop was connected to the storage tank and includes a pump and a heat exchanger which transfers heat from the collector loop to the transfer loop. Fluid from the storage tank and fluid from the collector loops are both circulated through the heat exchanger. As the fluids pass through the heat exchanger, heat is transferred from the collector loop fluid to the transfer loop fluid. If water is used as the transfer fluid for both loops, it is possible to remove the heat exchanger and circulate the water from the collectors to the storage tank directly. However, due to the cold temperatures that are experienced during Minnesota winters, it is necessary to use an anti-freeze-water mixture to prevent pipe freezing. Therefore, in order to keep the anti-freeze from mixing with the potable water, the loops must be separated and a heat exchanger is required.

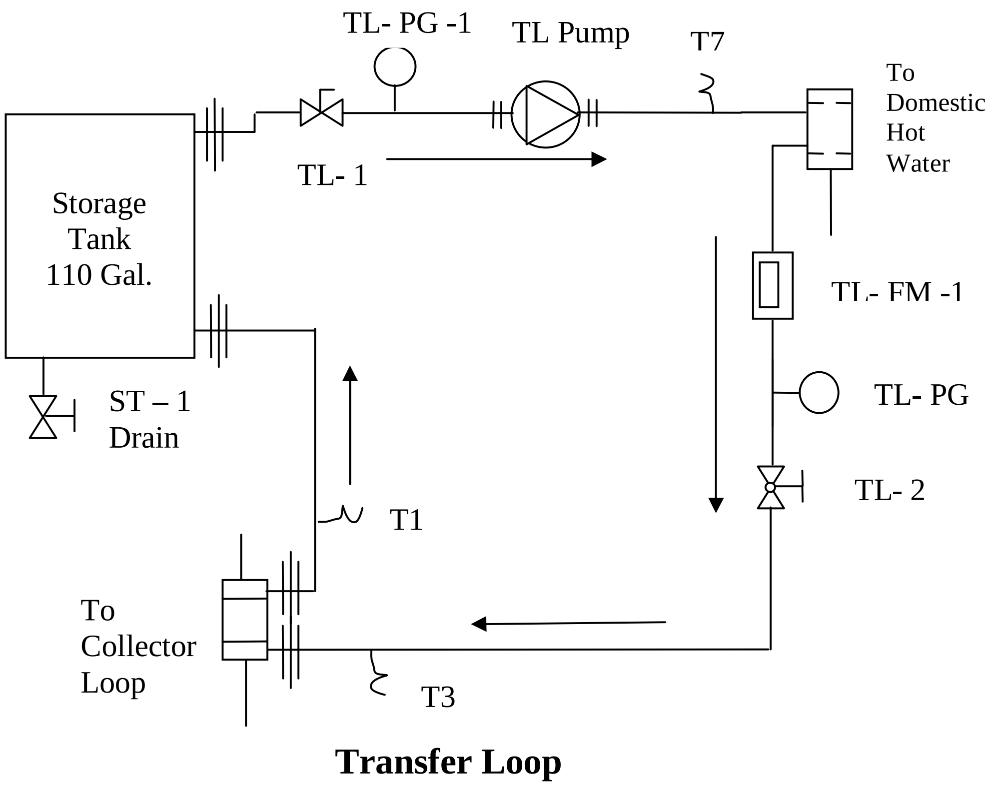


Figure 6: Transfer Loop

The collector is the loop that is responsible for removing the heat that the collectors gain from the sun so that it can be used for either space or water heating. In addition to the collectors and the pump, the collector loop includes an expansion tank. As the fluid flows through the collectors, it will heat up and expand. The purpose of the expansion tank is to allow space for the fluid to expand and relieve pressure.

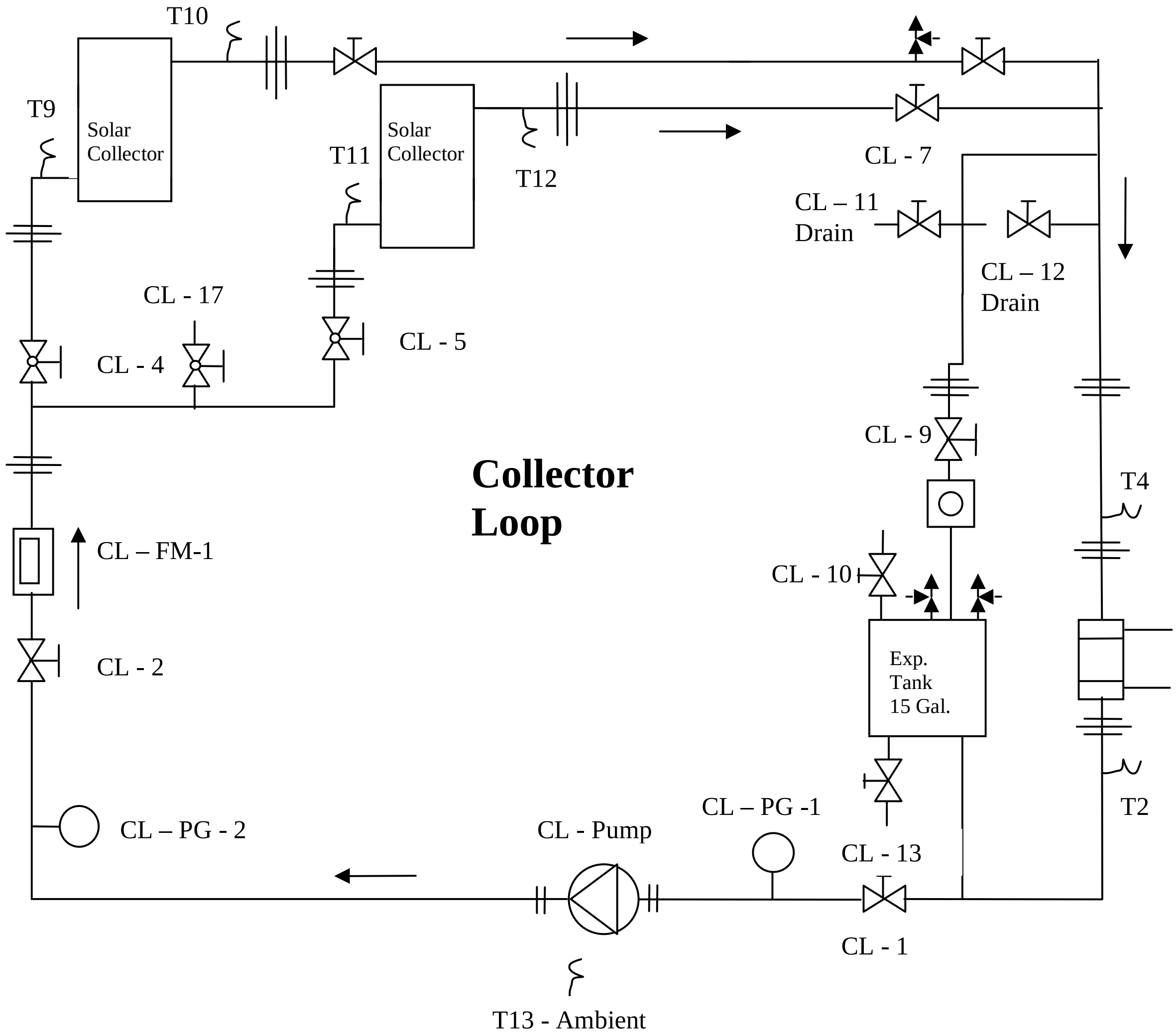


Figure 7: The Collector Loop

The collector loop is the loop that is of primary concern in this study because it encompasses the two flat plate solar collectors and they are the focus of this study. The two solar collectors are located side by side and each is 48 x 96 inches and are tilted an angle of latitude + 15 degrees which amounts to 60 degrees. Figure 7, depicts the collector loops components and their locations. As shown in Figure 7, fluid is pumped from expansion tank to the collectors and back again. Pressure gages are located before and after the pump, and a flow meter is located after the pump. Thermocouple wells are located at the entrance and exit of the solar collectors and at the inlet and outlet to the heat exchanger. Since the system will be operated during times when the temperature could drop below 0˚C, a 50% ethelyne glycol, 50% water mixture will be used in the collector loop.

The thermocouples were calibrated by measuring the temperature of water at a known reference point and comparing the measured temperatures with the reference value. The reference temperature was measured with a mercury thermometer. This was done for two points, with boiling water and an ice water bath, and the reference points and the corresponding thermocouple measurements can be found in Appendix 1.

4.2 Data Collection

The performance of the two collectors were measured by calculating their instantaneous efficiencies as given by Duffie and Beckman[15] from:

$$\eta = \frac{\dot{m}C_p(T_{out} - T_{in})}{A_c G_t} \quad (4).$$

The numerator in Equation (4) is the useful heat gain from the collector and consists of the fluid mass flow rate, the specific heat of the fluid and the inlet and outlet temperatures of the fluid as it passes through the collector. The denominator is total incident solar radiation on the collector. It consists of two terms, the incident solar radiation and the area of the collector.

The heat gain through the two collectors can be determined from the flow meter and the inlet and outlet thermocouples. The thermocouples (type T) were connected to a data acquisition system, and a LabView program will record the temperatures at five minute intervals. Since the collector loop only includes one flow meter, it was used to measure the total flow through the loop, and it will be assumed that the flow is split evenly through both collectors.

In order to determine the instantaneous collector efficiency, the total amount of solar radiation is required. Therefore, an Omega weather station was set up next to the collectors, and it recorded the ambient temperature, solar radiation, wind speed and wind direction at five minute intervals. Ordinarily pyrometers are mounted parallel to the ground, and the recorded horizontal radiation must be corrected to determine the solar radiation on an inclined surface. However, in this study, the pyrometer was mounted the same angle as the solar collectors tilt, 60 degrees, eliminating the need to correct the recorded radiation. The pyrometer measures the incident radiation flux. In order to determine the total instantaneous amount of radiation incident on the collectors, the flux must be multiplied by the collector area.

Figure 8: Omega Weather Station

4.3 The Windbreak

The windbreak was constructed from a clear polycarbonate sheet of 1/8 inch thick. The sheet was chosen to be thin in order allow for the maximum transmittance and reduce the risk of the obstruction of sunlight and shading. As shown in Figure 8, the windbreak is positioned along the full length of the collector (8 feet and extends 8 inches above the collector's surface. As stated previously, the estimated sheltered area is approximately 8-10 unit lengths of the windbreaks height, giving the sheltered area a range of 64 to 80 inches. Additionally, the collector is 48 inches wide; therefore, the outside edge of the sheltered area is beyond far edge of the collector. Therefore, the entire collector should be within the maximum sheltered area of the windbreak. Lastly, the windbreak was given a porosity of 0.2. This corresponds to the lower limit on porosity that was previously stated to give maximum shelter. In order to generate this porosity, 96 one inch diameter holes were drilled into the surface of the windbreak. In addition, the holes were drilled in the top half of the windbreak, so that they would be further from the collector's surface.

Figure 9: The Collectors with windbreak

4.4 Data Analysis

A baseline for the collector efficiencies was calculated with no wind break present. This ensures that there is no significant difference between the two under normal operation. A significant difference was determined by calculating the uncertainty of the heat gain of the collectors. The total uncertainty in the heat gain is given by:

$$\delta_q = \sqrt{\delta_{q\Delta t}^{\ 2} + \delta_{qQ}^{\ 2}} \qquad (5)$$

Equation (5) was derived by taking the partial derivative of the heat gain equation with respect to both the temperature rise and the heat gain. Since the heat gain through the collectors is a product of the flow rate and temperature rise, the uncertainty equation is a function of both of these components. The first term represents the uncertainty in the temperature measurements and the second term represents the uncertainty in the flow rate measurements.

It is assumed that the performance of the two collectors is the same, and therefore, the heat gain from the collectors should not be greater than the uncertainty in the measurements.

The windbreak was then implemented on the westward side of the eastward collector because the expected wind direction is from the northwest. In this position, a westward wind passes over the first collector unhindered, but the wind break obstructs the flow before it passes over the second collector. This allows for the efficiencies of the two collectors with the windbreak present to be compared to the efficiencies that were calculated with no windbreak, and if there is a significant change between them, it can be concluded that the difference is due to the windbreak. Furthermore, if a windbreak effect can be determined, the wind speed and ambient temperatures will be examined and it will be attempted to identify the minimum wind speed and temperature for which the windbreak effect occurs.

Chapter 5

Data Analysis

As mentioned previously, data was collected during February 2010 and October and November 2010.

5.1 February 2010

Data collection began in late January 2010, and continued through February. Data was collected for the first seven days without the windbreak present. The windbreak was implemented on the eighth day and was present for the remainder of the testing period. An average daily efficiency was calculated by calculating the instantaneous efficiency for each five minute interval for each day, and averaging them over the entire day. Additionally, efficiencies were only calculated for days that received enough sunlight to cause a heat gain for the collector. For example, days that were particularly cloudy or snowy were omitted because there was either no heat gain through either collector or both collectors showed a net heat loss.

Figure 10 shows the average daily efficiencies for both collectors for January 28, 2010 through February 28. The graph shows that collector two (the sheltered collector), on average, has a slightly higher efficiency than collector one. The amount that the efficiencies differ, typically vary between 0 and 5%. Table 1 summarizes the daily collector efficiencies and average wind speeds for the pre-windbreak and post-windbreak testing period.

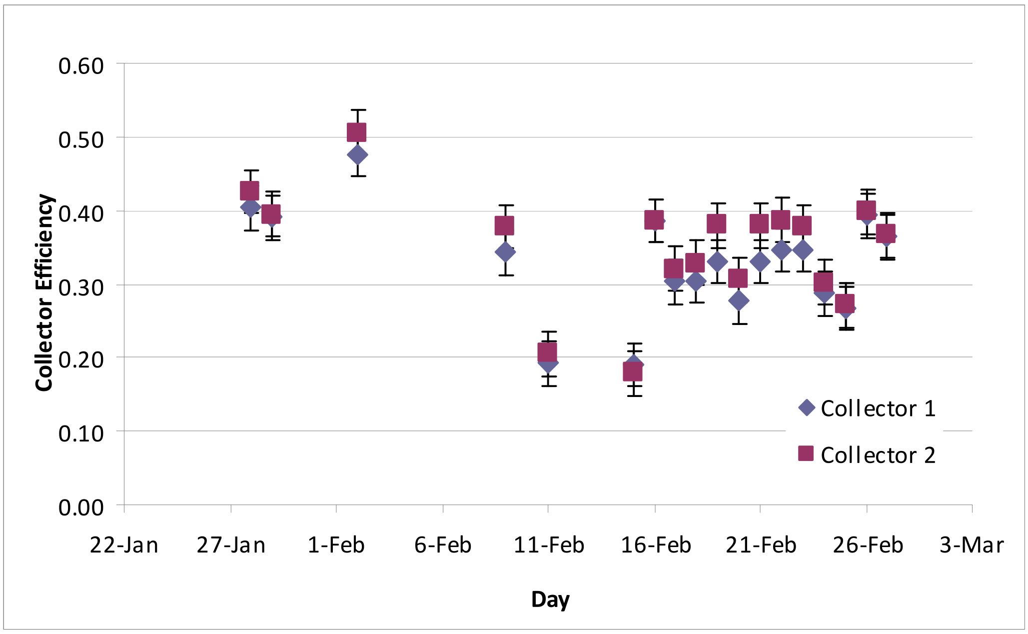


Figure 10: Daily Collector Efficiency for February 2010.

Table 1 shows the average of the daily efficiencies and the average wind speed for the pre and post windbreak testing periods. The table shows that there is not much of a difference in the efficiencies between the pre and post windbreak test periods. In fact, collector two had the same efficiency with the windbreak present as it did without. While the difference between the collectors efficiencies increased by 1% when the windbreak was present, it cannot be definitively concluded that this was due to the windbreak. An uncertainty analysis was performed using Equation (5), and a sample calculation is shown in appendix 3. The accuracy of the thermocouples is given to be accurate to plus or minus one degree. Therefore, on a typical day, this can cause an uncertainty in the heat gain of 100 to 200 Watts.

	Daily Efficiency		Wind Speed
	Collector 1	Collector 2	mph
Pre windbreak average	0.34	0.35	3.6
post windbreak average	0.32	0.35	2.8
total average	0.34	0.35	3.1

Table 1: Summary Table for January and February 2010 testing period

Figure 11 shows the instantaneous difference in the heat gain between the two collectors for February 23. This date was chosen because it had the highest daily wind speed during this testing period. The graph shows that collector two, has on average a higher heat gain. However, the difference between the two collectors is typically less than 200 Watts which is within the range of uncertainty.

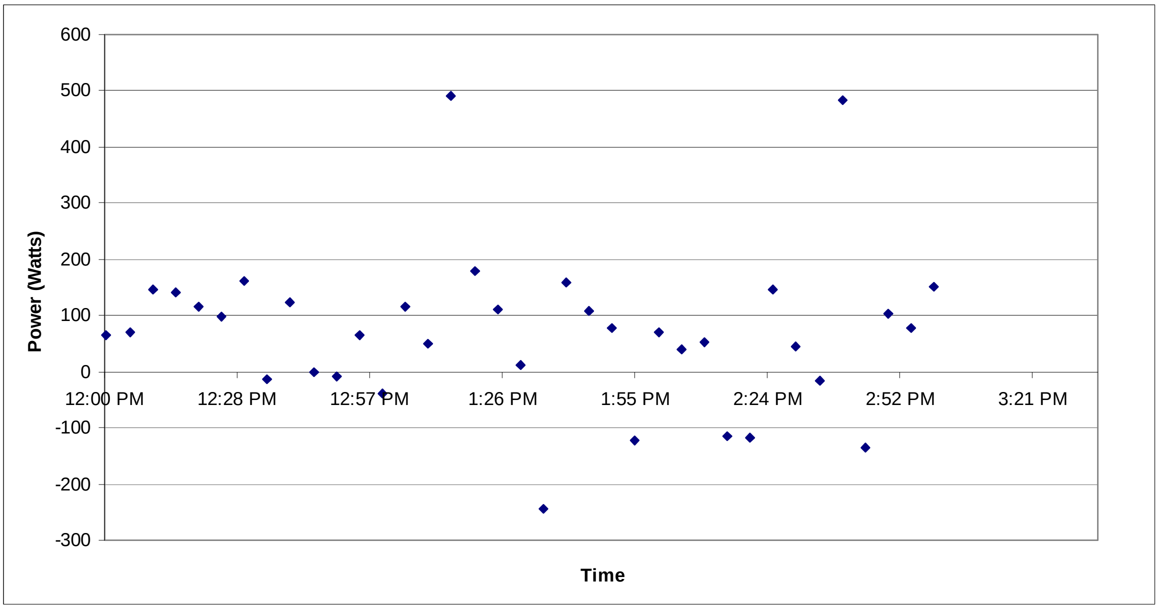


Figure 11: Collector Heat Gain Comparison

While there didn't seem to be any significant benefit from the windbreak on collector performance during this test period, it was also relatively calm during this testing period.

Only two days with an average daily wind speed above 5 mph occurred during this period, and both occurred before the windbreak was present. The highest daily wind speed that occurred while the windbreak was present was only 4 mph. Therefore, this test period was not sufficient to conclude as to whether the windbreak was beneficial or not. Therefore, further testing was conducted in the fall.

5.2 Fall 2010

Data collection began in the fall in October and continued through November and was conducted in the same fashion that it was at the beginning of the year. The same windbreak was used and it was positioned in the same place on collector two.

Figure 12 shows the average daily efficiency for the two collectors for the months of October and November. During this collection period collector one showed slightly higher efficiencies on average than collector two which is opposite of the trend that was seen in the February data. Additionally, the data shows a slightly higher difference in the efficiencies between the two collectors. However, the efficiencies on most of the days are within 5% of each other, which is reasonable given the uncertainty in the measurements.

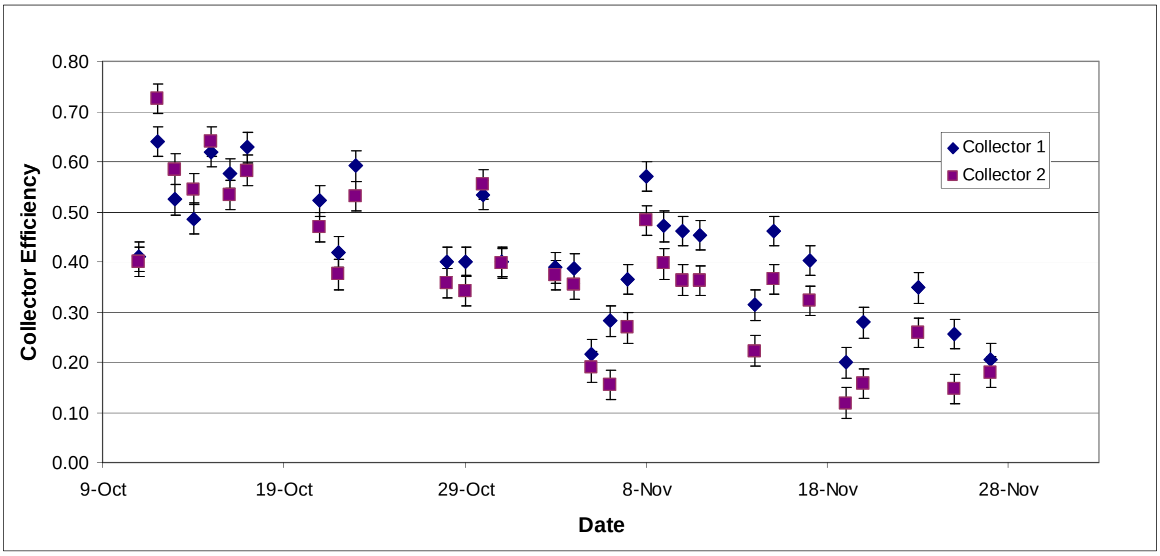


Figure 12: Daily Collector Efficiencies for fall 2010.

Over the entire collection period, collector one showed an average efficiency of 44%, and collector two showed an efficiency of 39%. In order to determine if the windbreak had an effect on collector performance, the data was divided into wind days and non-windy days.

Figure 13 plots the collector efficiency versus the average daily wind speed for the days with wind speed greater than five mile per hour. Five miles per hour was chosen as the cutoff point because the highest average daily wind speed that was experienced during the February testing was four miles per hour. Therefore, the days with wind speeds less than five miles per hour should be comparable between the two test periods.

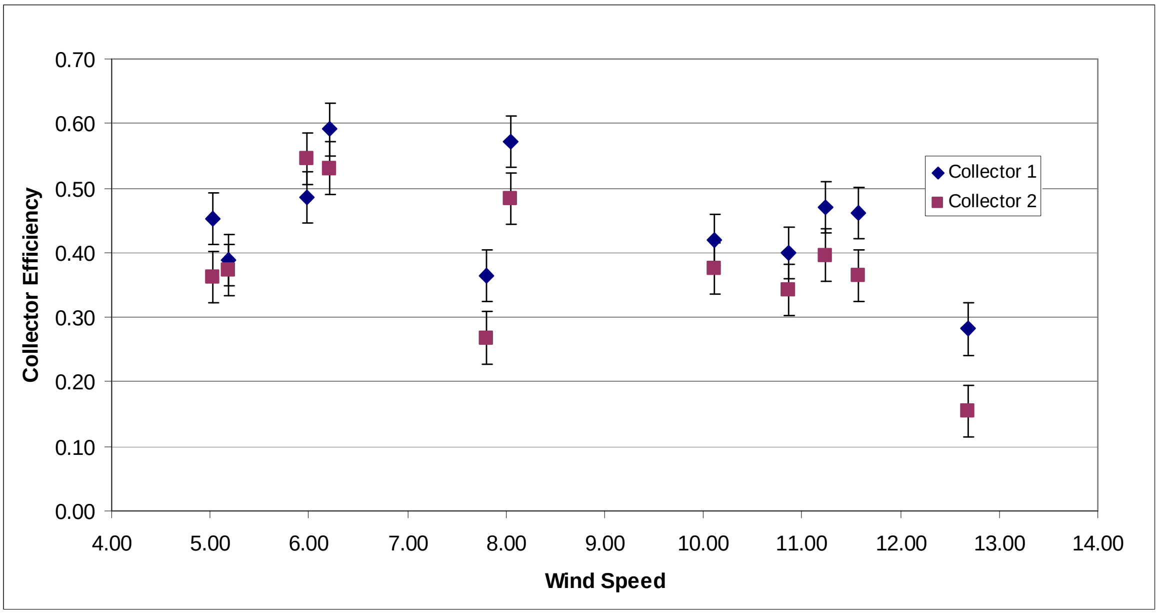


Figure 13: Collector Performance versus Wind Speed for Windy Days Fall 2010

At first glance it is obvious that collector one consistently has a higher efficiency than collector two. In fact, the difference in efficiencies is greater for windy days than it is for the entire data as a whole. For all the days with wind speeds greater than 5 mph, collector one has an average efficiency of 48% and collector two has an efficiency of 41%. This is a difference of 7% compared to 5% when all of the days were considered. However, many of the windy days had eastern or south eastern prevailing winds, and the windbreak was designed with the intention that it would encounter westward winds. The wind direction is important because with westward winds, the wind will pass over the first collector unhindered and then hit the windbreak before it passes over collector two. However, with eastward winds, the wind will pass over collector and then hit the windbreak on the far side of the collector. Therefore, the windy days were analyzed further by taking the wind direction into consideration.

Table 2 summarizes the average collector efficiencies for windy and non windy days and the efficiencies for windy days for both westward and eastward wind directions.

	February 2010	Fall 2010				
	All Days	All Days	Non-Windy	All Windy Days	Westward Windy Days	Eastward Windy Days
Collector 1	0.34	0.43	0.42	0.44	0.44	0.45
Collector 2	0.36	0.38	0.38	0.38	0.43	0.36

Table 2: Summary of Collector Efficiency on Windy and Non Windy Days

On windy days with eastward prevailing winds, collector one had an average daily efficiency of 49%, and collector two had an efficiency of 40%. This shows an even greater divergence than was seen initially when all of the windy days were analyzed together. In contrast on windy days with westward prevailing winds, the efficiencies were 46% and 44% for collector's one and two respectively. This would seem to indicate that the windbreak has a positive impact when the wind direction is from the west and a negative impact when the wind is from the east. However, of all the windy days that were experienced during this time period, only three of them were from the west. In contrast, eight days had prevailing winds from the east or south east. This sample size is not large enough to make a definitive conclusion about the effectiveness of the windbreak. Furthermore, the current data is not enough to make a definitive conclusion on whether the windbreak had a negative impact on collector two's performance when eastward winds were experienced or if the windbreak had a positive impact on collector one's performance. Additionally, it should be noted that the average efficiency for non windy days was 42% for collector one, and 37% for collector two. This is a difference of 5%, whereas the data that was collected in February showed only an average difference of 2%. However, if the individual days are examined, both time periods showed variations of up to 5%, and therefore the periods are comparable.

Thermocouples were also mounted, using a clear adhesive, on the glass cover of the collector in order to determine the surface temperatures. Four thermocouples were placed on each collector in a grid like pattern.

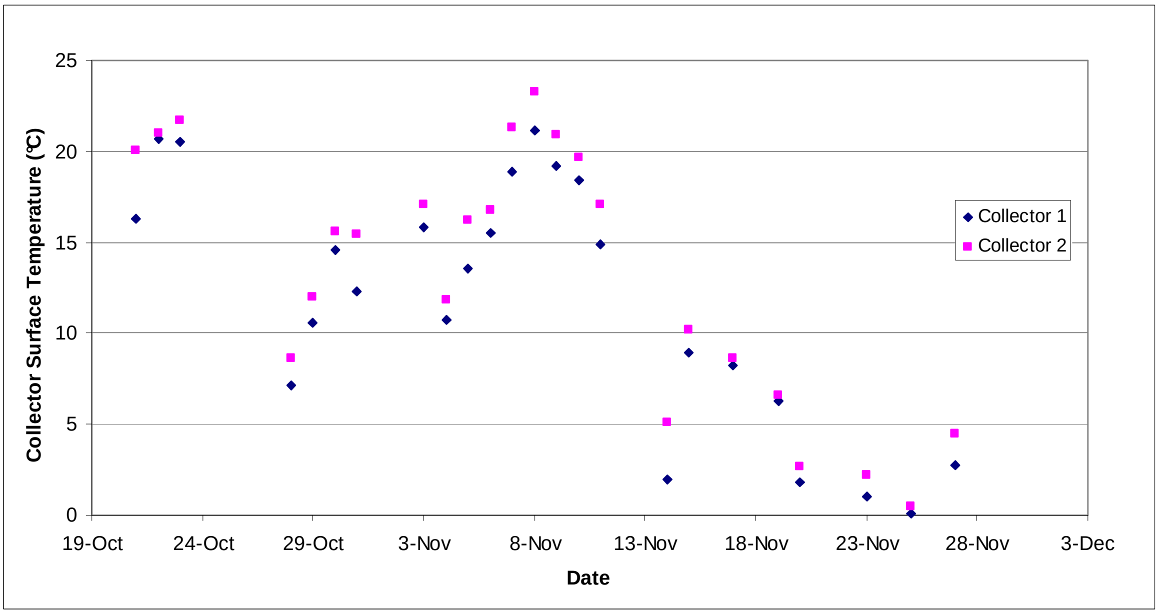


Figure 14: Average daily collector surface temperature

These four measurements were averaged as an estimate of the average surface temperature. Figure 14 shows the average daily surface temperatures for the two collectors. No clear trends are readily identified except that collector two has a consistently slightly higher surface temperature. Over the entire period, collector two has an average surface temperature of 1.5 ºC higher than collector one.

As the average daily surface temperature graph didn't show any clear trends, the difference between the collector's average surface temperatures was plotted versus wind speed. This is shown in Figure 15.

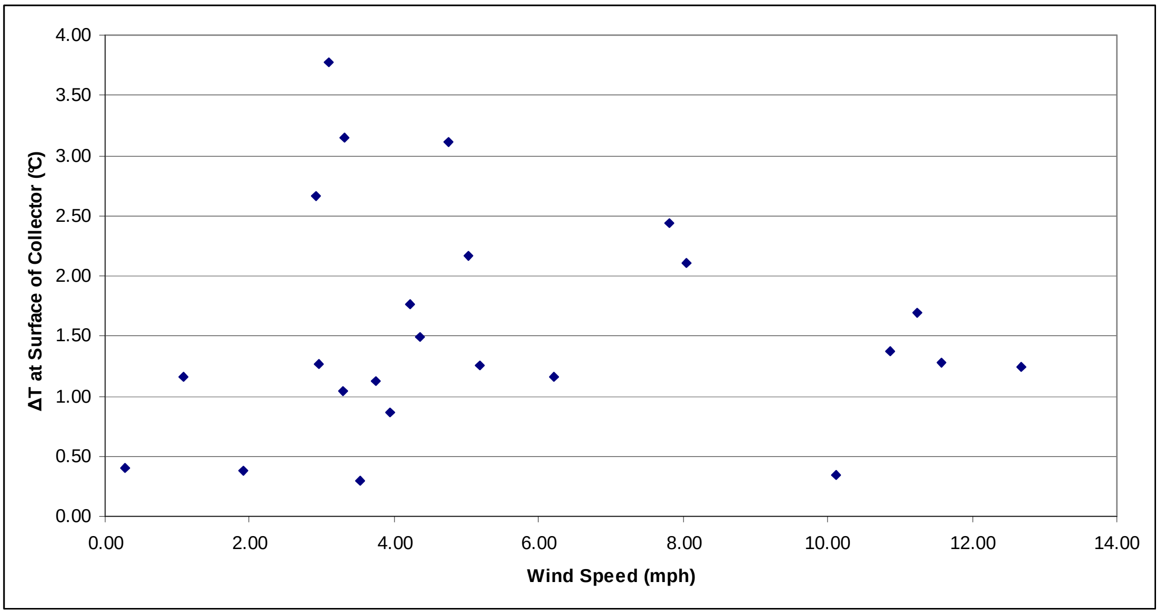


Figure 15: Difference in Average Collector Surface Temperature versus Wind Speed

Again, no clear trends are apparent in this plot. In fact, the greatest differences occurred with wind speeds less than 5 mph. However, it should also be noted that the incidents of greatest difference also occurred on days with warmer ambient temperatures. Additionally, the surface temperature of collector 2 is always higher than the surface temperature of collector 1, and this indicates that there is greater heat loss from collector two. Since both collectors are of the same type and age, it is unlikely that the construction of the collectors is the source of the discrepancy. However, since only one flow meter was present on the collector loop, it was necessary to assume that the flow rates through the two collectors were the same. However, if the flow rates were slightly different, it would effect the heat gain through the collector, and could cause the difference in the surface temperatures.

Chapter 6

Conclusions and Recommendations

6.1 Conclusions

The purpose of this thesis was to examine the potential of utilizing a windbreak to improve the performance of a flat plate solar collector. More specifically, this thesis examined whether a windbreak could be implemented to improve the performance of a solar collector during the winter months. The thesis focused on the performance during the winter months because the cold temperatures and harsh climates pose an obstacle for solar thermal technology in the northern United States. Furthermore, the Midwestern United States experiences high wind potential during the winter months in addition to its cold temperatures, and it was believed that the high wind speeds, when combined with the cold temperatures could result in significant heat loss from the solar collector due to forced convection. A windbreak was implemented in hopes of directing the wind flow away from the surface of the collector, and thus resulting in lowered forced convection losses and an increase in collector performance.

The effectiveness of the windbreak was assessed by comparing the efficiencies of two solar collectors, one which was sheltered by a windbreak and one which was not sheltered. Data collection was conducted during two different time periods. Data collection for the first time period began in January and February 2010. An average daily efficiency was calculated for the two collectors for the first seven days without a windbreak present, and with the windbreak implemented for the remaining days. For this time period, only a slight difference between the two collectors was observed. For the period without a windbreak, the efficiencies were 34% and 36% for collector one and two respectively. With the windbreak implemented, the efficiencies were 33% and 36%. This difference was too small to make a definitive claim as to the windbreaks effectiveness. Additionally, the data collection occurred during a time period of relatively little wind. Therefore, it was decided that further experimentation was required.

Data collection resumed in October 2010, and continued through November 2010. The efficiencies that were calculated during this time period showed an opposite trend, in that collector one showed a slightly higher efficiency, 44% than collector two 39%, than was seen during the February collection. However, in general the discrepancy between the two periods on non-windy days showed similar ranges, and therefore the two time periods are comparable.

The efficiencies of the two collectors showed a greater divergence when only windy days were analyzed. The average collector efficiencies for days with 5 mph winds or higher were 48% for collector one, and 41% for collector two. However, this did not take wind direction into account, and many of the windy days experienced eastward or south-eastward wind directions. This was opposite of what was expected, which was westward winds. When wind direction was taken into account, the efficiencies of the collectors on eastward windy days was 49 % and 40% for collector one and two respectively. On westward windy days, the efficiencies were 46% and 44%. However, these results indicated that wind direction makes a difference on the whether or not the windbreak is beneficial. However, only three of the windy days had westward prevailing winds. This sample size is not large enough to make a strong claim about the potential of the windbreak. Additionally, the efficiencies on the eastward windy days could either indicate that the windbreak partially sheltered collector one, and thus caused an increase in the collector's performance; or it could indicate that it caused a reduction in the performance of collator two. The current data is insufficient to make a claim for either.

The last item that was analyzed was the surface temperatures of the solar collectors. The surface temperatures compared by measuring the surface temperature with a grid of four thermocouples on each collector. An average surface temperature was then computed for each collector. Overall, the surface temperature of collector two was slightly higher, about 1.5 ºC, than that for collector one. An attempt to correlate the surface temperatures with wind speed was made, but no obvious pattern was present.

6.2 Recommendations for Further Study

The data collected up to this point has been inconclusive. This is partially due to the uncertainty in the calculation of the collector's performance. The uncertainty in the performance of the collectors is due to the uncertainty in the measurements of the flow rate and the temperatures. Because the collector loop only had one flow meter, it was necessary to assume that the flow through each collector was the same, and half of the total flow that was measured. However, it would be better if each collector had its own flow meter so that the flow through each could be measured directly. Additionally, the accuracy of the results could possible be improved by using more accurate thermocouple wire.

While, uncertainty in the measurements is partially to blame caused some ambiguity in the results, the most of the ambiguity was due to unforeseen confounding variables in the methodology. The most obvious uncontrollable variable was the wind speed and wind direction. In a real world experimental setup as this one, one can only test in the conditions for which the environment provides. This caused an obvious problem during the fall period when most of the windy days came from the opposite direction that was anticipated. An obvious solution to this problem would be to conduct tests in a laboratory setting where these conditions can be controlled. A wind tunnel could be used to simulate a natural wind and a scaled down windbreak could be constructed. The solar collector could be simulated by using a hot plate as was done in some of the previously mentioned literature and an idea of the potential of the windbreak could be gained by measuring the surface temperature of the hot plate at difference wind speeds and with and with out a windbreak. This would be a method to both gain an idea of the windbreaks potential and a way to test various windbreak designs in order to maximize the wind reduction over the collector.

Additionally, the system could be modeled numerically. Modeling the system numerically would allow for more variables to be examined, and if a numeric model was done in conjunction with a laboratory study, the results between the two could be compared in order to determine an optimal solution.

However, even if a laboratory and numeric study were conducted, it would still be beneficial to assess the performance of the windbreak on a real world solar collector. With this in mind, windbreak which can be easily removed and adjusted could be design. This would allow for the position of the windbreak to be adjusted depending on the wind direction. Moreover, the amount of shelter a windbreak provides is very dependant on the angle at which the wind is incident. And, as was seen during the entire experimentation period, wind directions are hard to predict and often vary during the day. Therefore, different configurations of windbreaks could be examined. For example, for this thesis, a windbreak was only positioned on the westward side of the collector. However, it may be beneficial to place a windbreak on multiple sides. For example, if the placing a windbreak on the south and west sides may be more beneficial during south-southwest winds than just a single windbreak. Therefore, it would be beneficial to examine these variables more closely.

Lastly, at this point in time, there is not sufficient data to conclude that there is a benefit to implementing a windbreak on a solar thermal collector. While some of the data collected this fall did appear indicate that there may be a windbreak effect, there is insufficient evidence to make that claim at this time. Therefore, further experimentation is with the previously mentioned recommendations in mind is suggested.

References

[1] U.S. Census Bureau (2010). *World Population: 1950-2050.* Retrieved October 2010 from http://www.census.gov/ipc/www/idb/worldpopgraph.php

[2] U.S. Energy Information Administration (2008). *Solar Thermal.* Retrieved September 2010, from ttp://www.eia.doe.gov/cneaf/solar.renewables/page/solarthermal/solarthermal.html

[3] Database of State Incentives for Renewables and Efficiencies (2010). Retrieved October, 2010 from, http://www.dsireusa.org/

[4] U.S. Department of Energy (2010). *History of Solar*. Retrieved October 2010 from http://www1.eere.energy.gov/solar/pdfs/solar_timeline.pdf

[5] National Renewable Energy Laboratory. (199). Report on Solar Water Heating Quantitative Survey Retreived October 2010 from, ftp://ftp.nrel.gov/pub/solar_waterheat-out/market_studies/26484.pdf

[6] Burch, J., Salasovich, J., Hillman, T. *Cold-Climate Solar Domestic Water Heating Systems Analyses and Opportunities for Cost Reduction.* Paper presented at the ISES Solar World Congress, Orlando, Florida August 6-12, 2005. Retrieved online October 2010, from http://www.nrel.gov/docs/fy06osti/37748.pdf

[7] U.S. Energy Information Administration (2010). *Forecasts & Analysis.* Retreived 2010 from http://www.eia.doe.gov/oiaf/forecasting.html

[8] Kaushika, N. D., Ray, R. A., & Priya, P. (1990). A honeycomb solar collector and storage system. *Energy Conversion and Management*, 30, 127-134.

[9] Koltun, M., Gukhman, G., Gavrilina, A. (1992). Stable selective coating "black nickel" for solar collector surfaces. SPIE 1727.

[10] Schüler, A., Dutta, D., de Chambrier, E., Roeker, C., De Temmeran, G., Oelhafen, P., Scartezzini, J. (2006). Sol-Gel deposition and optical characterization of multilayered $Si0_2/Ti_{1-x}Si_x0_2$ coatings on solar collector glasses. *Solar Energy Materials & Solar Cells*, 90, 2894-2907.

[11] Turgut, O., Onur, N., (2008). Three dimensional numerical and experimental study of forced convection heat transfer on solar collector surface. *International Communications in Heat and Mass Transfer*, 36, 274-279.

[12] Brandle, J. R., and Nickerson, H. D. (2010). Windbreaks for Snow Management. University of Nebraska. Retrieved October 2010 from, http://www.nrcs.usda.gov/technical/ECS/forest/wind/snow.pdf

[13] United States Department of Agriculture – Natural Recources Conservation Service. (2010). *Conservation Practices that Save: Windbreaks/Shelterbelts.* Retrieved October 2010 from, http://www.nrcs.usda.gov/technical/energy/windbreak_11_06.pdf

[14] Agriculture and Agri-Food Canada. (2010). *Shelterbelts help cut heating costs.* Retrieved October 2010 from, http://www.4.agr.gc.ca/AAFC-AAC/display-afficher.do?d=1202403359345&lang=eng

[15] Duffie, J. A., & Beckman, W. A. (2006). Solar engineering of thermal processes (3rd ed.) Hoboken, New Jersey: John Wiley & Sons Inc.

[16] Ghoneim, A. A. (2004). Performance optimization of solar collector equipped with different arrangements of square-celled honeycomb. *International Journal of Thermal Sciences*, *44*, 95-105.

[17] Abdullah, A. H., Abou-Ziyan, H.Z., Ghoneim, A.A. (2003). Thermal performance of flat plate solar collectors using various arrangements of compound honeycomb. *Energy conversion and management*, 44, 3093-3112.

[18] Varol, Yasin & Oztop, H. F. (2007). A comparative numerical study on natural convection in inclined wavy and flat-plate solar collectors. *Building and Environment, 43,* 1535-1544.

[19] Vestlund, J., Rönnelid, M., and Dalenbäck, J. (2009). Thermal Performance of Gas Filled Solar Collectors. *Solar Energy* 83, 896–904

[20] Garba, B., Sambo, A. S. & Mosugu, M. M. (1991). The effect of chemical coatings on the performance of solar collector plates. *Renewable Energy,* 1, 661-665

[21] Katumba, G., Olumekor, L,. Forbes, A., Makiwa, G., Mwakikunga, B., Luf, J. Wäckelgard, E. (2008). Optical, thermal and structural characteristics of carbon nanoparticles embedded in ZnO and NiO as selective solar absorbers. *Solar energy materials and solar cells, 92,* 1285-1292.

[22] Khoukhi, M., Maruyama, S., Komiya, A., and Behnia, M., Flat Plate Solar Collector Performance with Coated and Uncoated Glass Cover, *Heat Transfer Engineering*, vol 27, no 1, pp. 46 – 53, 2006.

[23] Kesmez, Ö., Carmurlu, H. E., Burunkaya, E., Arpac, E., (2009). Sol-Gel preparation and characterization of antireflective and self cleaning double layer nanometric films. *Solar Energy Materials & Solar Cells,* 93, 1833-1839.

[24] Hellstrom, B., Adsten, M., Nostell, P., Karlsson, B., Wackelgard, E. (2003). The impact of optical and thermal properties on the performance of flat plate solar collectors. *Renewable Energy*, 28, 331-344.

[25] Groenhout, N. K., Behnia, M., Morrison, G. L. (2002). Experimental measurement of heat loss in an advanced solar collector. *Experimental Thermal and Fluid Science.* 26, 131-137.

[26] Kumar, S., Sharma, V. B., Kandpal, T. C., & Mullick, S. C. (1997). Wind induced heat losses from outer cover of solar collectors. *Renewable Energy,* 10, 613-616.

[27] Sharples, S. & Chalesworth, P. S. (1998). Full-scale measurements of wind-induced convective heat transfer from a roof mounted flat plate solar collector. *Solar Energy,* 62, 69-77.

[28] Kumar, S., & Mullick, S. C. (2010). Wind heat transfer coefficient in solar collectors in outdoor conditions. *Solar Energy,* 84, 956-963.

[29] Satori, E. (2006). Convection coefficient equations for forced air flow over flat surfaces. *Solar Energy,* 80, 1063-1071.

[30] Kansas State University (2004). Windbreaks for Kansas. Kansas Forest Service. Retreived October 2010 from http://www.ksre.ksu.edu/library/forst2/mf2120.pdf

[31] Prior, M. J. & Keeble, E. J. (1990). Directional Wind-chill data for planning sheltered microclimates around buildings. *Energy and Buildings*, 15-16, 887-893.

[32] American Society of Heating, Refrigeration and Air-Conditioning. (2005). Ashrae Handbook Fundamentals I-P Edition. ASHRAE Inc. Atlanta, Georgia.

[33] Cornelis, W. M., & Gabriels, D. (2005). Optimal windbreak design for wind-erosion control. *Journal of Arid Environments, 61,* 315-332

[34]Santiago, J, L., Martin, F, Cuerva, A, Bezdenejnykh, A, Sanz-Andres (2007). Experimental and numerical study of wind flow behind windbreaks. *Atmospheric Environment,* 41, 6406-6420.

[35]Wang, Hao, Takle, E. S., & Shen, Jinmei (2001). Shelterbelts and Windbreaks: Mathematical Modeling and computer simulations of turbulent flows. Annual Review of Fluid Mechanics, 33, 549-586.

Appendix 1

Thermocouple Calibration

The thermocouples were calibrated by measuring the temperature of boiling water and ice water with the thermocouple and comparing it to a value obtained with a thermometer.

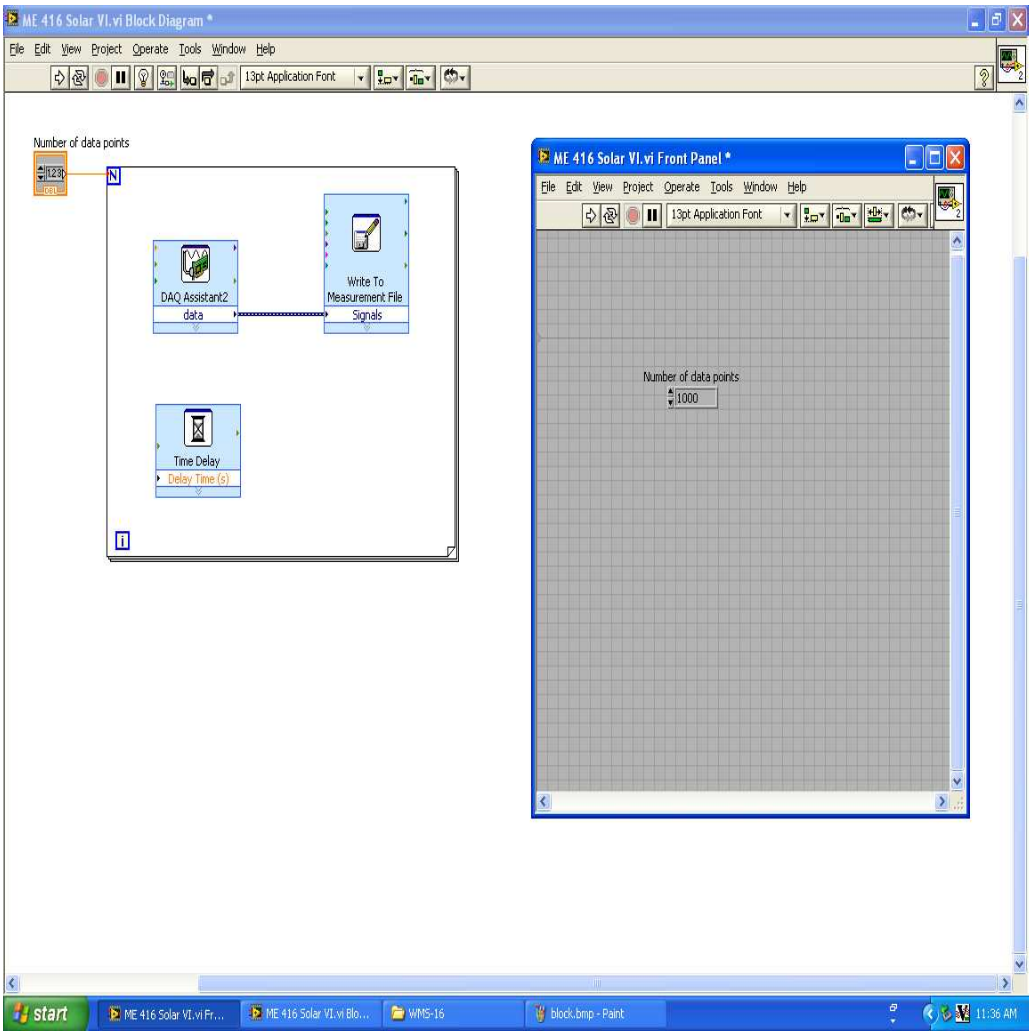
The measured values are recorded below:

Thermocouple	Ice Water (℃)	Boiling Water (℃)	Thermometer			ΔT Ice (℃)	ΔT Boiling (℃)
			Ice (℃)	Boiling (℃)			
1	1	99.5	0.5	98.5		-0.5	-1
2	1	98.5	0.5	98.5		-0.5	0
3	1.5	99.5	0.5	98.5		-1	-1
4	1	99	0.5	98.5		-0.5	-0.5
5	0.7	99	0.5	98.5		-0.2	-0.5
6	1	99	0.5	98.5		-0.5	-0.5
7	0.9	98	0.5	98.5		-0.4	0.5
8	1	97	0.5	96		-0.5	-1
9	1	94	0.5	94		-0.5	0
10	1.3	93.5	0.5	92		-0.8	-1.5
11	1.3	95	0.5	94.5		-0.8	-0.5
12	1.3	93	0.5	92		-0.8	-1
13	1.4	94	0.5	93.5		-0.9	-0.5
				Average Error		0.607692	0.576923

Appendix 2

LabView Program

Below is a screen shot of the LabView program that was used to record the temperature data. Both the front panel and the block diagram are shown.



Each thermocouple was connected to a separate channel of the Data Acquisition unit, and the DAQ was connected to a computer. The DAQ had an onboard thermister and took temperature measurments with reference to 0 °C. The time delay was set and controlled in the block diagram. The LabView program recorded the temperature of each thermocouple and wrote the data to a LabView Measurement file.

Appendix 3

Uncertainty Analysis

Power gained by the collectors is calculated from:

$$q = \Delta T * C_p * \rho * Q$$

Where:
ΔT is the temperature rise through the collector
Cp is the specific heat of the fluid
ρ is the density of the fluid
Q is the volumetric flow rate.

Total uncertainty is given by the partial derivatives of the power gain:

$$\delta_q = \sqrt{\delta_{q\Delta t}{}^2 + \delta_{qQ}{}^2}$$

Where:

$$\delta_{q\Delta T} = \tfrac{dq}{d\Delta T}\delta_{\Delta T}$$

And

$$\delta_{qQ} = \tfrac{dq}{dQ}\delta_{Q}$$

Therefore,

$$\delta_q = \sqrt{(C_p * \rho * Q * \delta_{\Delta T})^2 + (\Delta T * C_p * \rho * \delta_{qQ})}$$

Below, shows a sample calculation with data taken from February 23, 2010 at 12:00 PM.

$$\delta_q = \sqrt{\begin{array}{l}(3412[J/kg-k]*1077[kg/m^3]*0.022[L/s]*1[k]*\tfrac{1m^3}{1000L})^2 \\ +(3412[J/kg-k]*1077[kg/m^3]*5.0[k]*0.003[L/s]*\tfrac{1m^3}{1000L})^2\end{array}}$$

$$\delta_q = \sqrt{80.8^2 + 55.12^2} = 97.8[J/s]$$

A factor of two is missing from the final uncertainty equation, but this only accounts for bias terms, and is not a factor in measurement precision.