5-2015

Characterizing Water as Gap Fill for Double Glazing Units

Bright Adu
Western Kentucky University, bright.adu792@topper.wku.edu

CHARACTERIZING WATER AS GAP FILL FOR DOUBLE GLAZING UNITS

A Thesis
Presented to
The Faculty of the Department of Architectural and Manufacturing Sciences
Western Kentucky University
Bowling Green, Kentucky

In Partial Fulfillment
Of the Requirements for the Degree
Master of Science

By
Bright Adu

April 2015

CHARACTERIZING WATER AS GAP FILL FOR DOUBLE GLAZING UNITS

Date Recommended 4-1-2015

Bryan Reaka

Dr. Bryan Reaka, Director of Thesis

Stacy Wilson

Dr. Stacy Wilson

Shahnaz Aly

Shahnaz Aly

Carl A Fox 4-23-15

Dean, Graduate School Date

I dedicate this thesis to my parents (Mr and Mrs. Adu Sackey) and two of my very dear friends Lorian Morgan and Albert Osei who motivated and supported me throughout my stay in school.

ACKNOWLEDGMENTS

I am grateful to God for granting me the grace to pull through my academic work and thesis research. I would like to express profound gratitude to my graduate thesis committee members (Dr. Bryan Reaka, Dr. Stacy Wilson, and Ms. Shahnaz Aly) for their help and input for this thesis. I cannot fail to thank the EMCC staff, especially Ron Rizzo, for their support and help in building the prototype for testing. I would also like to thank the professors and staff at the AMS department, especially Dr. Mark Doggett and John Pace, for making my academic exploits a success. Some of my friends who have been a great source of inspiration to me include Kwasi Boateng, Pegah Kakavand, Zachary Jones, and Mr. Tay Williams.

Finally, I would like to show my appreciation to the Environmental Protection Agency for funding this project as well as thank Dr. Keith Sylvester for including me in EPA-P3 research.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHARACTERIZING WATER AS GAP FILL FOR DOUBLE GLAZING UNITS

Bright Adu April 2015 69 Pages

Directed by: Bryan Reaka, Stacy Wilson, and Shahnaz Aly

Department of Architectural and Manufacturing Sciences Western Kentucky University

The use of sunlight has always been a major goal in the design and operation of commercial buildings to minimize electrical consumption of artificial lighting systems. Glazing systems designed to allow optimal visible light transmission also allow significant unwanted direct solar heat gain caused by infrared light. Conversely, glazing systems that are designed to reflect unwanted direct solar heat gain significantly reduce the transmittance of visible light through windows. The goal of this research was to characterize the performance of water as gap-fill for double-glazing units in eliminating the compromises that exist in current glazing systems with respect to light and heat transmittance. An in situ test approach and computer simulations were conducted to measure the performance of water-filled glazing units against air-filled glazing units. The thermal transmittance and solar heat gain coefficient values obtained from both the field experiments and computer simulations, glazing units with air-fill proved better than the glazing units with non-flowing water-fill. However, the high convective coefficient and the high thermal mass of the water can be used to its advantage when it is allowed to flow at peak temperatures, thus, maintaining lower temperature swings indoor. This can lead to a reduction of about 50-70% direct solar heat and still maintain high visibility.

Introduction

The rapid growing energy consumption in the world has raised concerns about meeting future demands without having adverse effect on the environment. A number of agencies including the International Energy Agency have advocated the efficient use of energy by the various sectors of the economy (Pe´rez-Lombard, 2008). The use of energy by the building sector accounts for a significant part of the world's energy use and emissions (Jelle, 2011). In buildings, energy consumption emanates from many sources including air-conditioning, heating, lighting, and household electrical appliances. Heating and air conditioning alone accounts for about 80% of the energy needs of residential buildings (Fulvio, Beccali, Cellura, & Mistretta, 2008). From Figure 1, windows and lighting needs contribute a higher percentage to energy losses and end uses in buildings. In the United States, windows account for about 3% (that is approximately 2 quads of annual energy) in energy consumption regarding heat gain and heat loss in buildings (Arasteh, Goudey, & Kohler, 2008). Due to these hikes in electricity consumption, it is imperative to find window systems that take advantage of natural daylighting and yet prevents direct heat gain into the indoor space. Making such decisions usually result in compromises between thermal transmittance and light transmittance. The nature of these compromises are dependent on the geographic location of the building, orientation of the building and the purpose of the building.

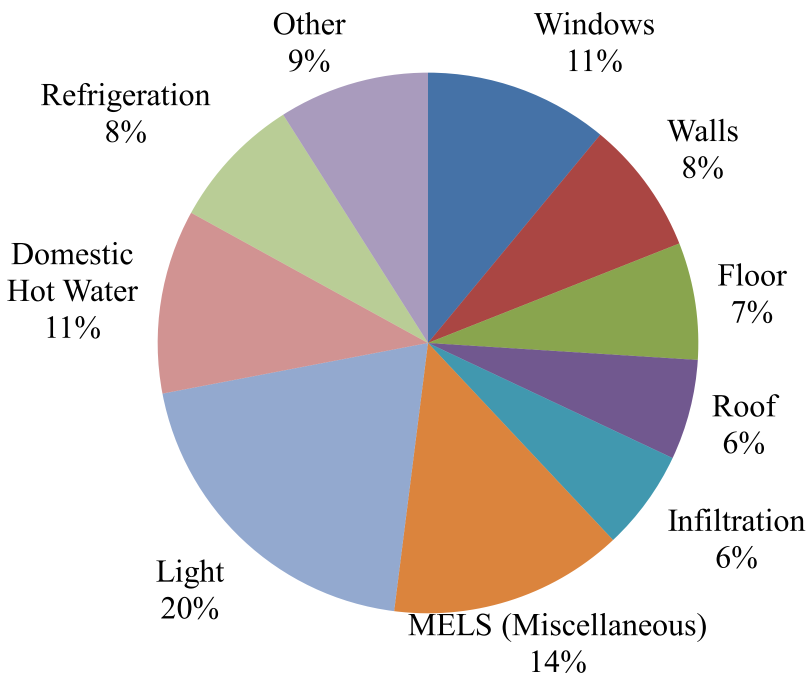

Figure 1. Relative average disaggregated end uses and losses of energy in buildings. Note: MELS, miscellaneous electric loads or plug loads; infiltration, leakage of air into and out of conditioned space (Judkoff, 2008, p. 449).

Research into highly insulating glazing systems is fulfilling an important role in reducing energy consumption in the 21st century. In the last 25 years, there have been major technological advancements in glazing systems that is solving some of the significant challenges relating to its heat loss control, and transmittance of daylight with minimal solar heat gain (Selkowitz, 1999). Since heat transfer takes place through conduction, convection, and radiation, glazing systems with high thermal performance should be able to regulate heat loss and heat gain through all the three heat transfer mediums. The suppression of convective and conductive heat transfer can be done by filling multiglazed window gaps with fluids or gases with low thermal conductance such as argon, krypton, or sulphur hexafluoride. Larger gap widths to a certain limit increase the thermal performance of glazing units (Menzies & Wherrett, 2005). Some of the glazing systems on the market include low-E glass and multi-pane glasses with various combinations of clear and low-E glasses. The low-E glass is effective in reducing radiative heat transfer, but also affects the amount of visible light transmission entering through it. This introduces trade-offs in thermal and visible light transmission of glazing units. The goal of this research was to investigate systems that can eliminate such compromises, thereby, reducing electricity consumption associated with lighting, cooling, and heating loads in buildings.

Problem Statement

The research problem of this study is the energy consumption of glazed buildings and sustainability of the environment. Glazing units permit natural lighting in a building, which offsets cost associated with artificial lighting. The light from the sun comes with infrared radiations that increase solar heat gain across glazing units. Consequently, compromises are usually made between daylight transmittance and the thermal performance of traditional glazing systems (Selkowitz, 1999). One of the solutions proposed in this research is to use liquid fills (water) in double glazing units instead of air or inert gases to control the transmittance of infrared radiation while allowing visible light to transmit through the unit. The proposed product is environmentally friendly since the liquid (water) that will be used is benign and has no negative impact on the environment.

Significance of the Research

Understanding the causal effect of glazing systems on the energy consumption of buildings will allow a greater accountability for electric energy use. While traditional glazing systems allow for compromises between daylight transmittance and thermal performance, this study seeks to eliminate such compromises by optimizing thermal performance with improved light transmittance. This development in glazing systems has the potential to reduce energy consumption significantly. A reduction in electrical energy consumption will consequently lead to reduced carbon emissions into the atmosphere.

Purpose of the Research

The objective of this research is to investigate the effects of fluids (water) on the thermal and optical properties of glazed window systems. Traditional multiglazed window systems have their gaps filled with air or inert gases to limit heat transfer across the window, but these systems have failed to produce the desired effects, which is high thermal performance with optimal visible light transmittance. This research seeks to characterize the performance of water as gap fill for double glazing window systems. The dependent variables of this study are the thermal transmittance, solar heat gain, and visible light transmittance of glazing units. The independent variables of the study are the type of gap fill, gap width, the heat loads from the sun, and the area of the test specimen.

Hypothesis

1. Glazing units with water fill in its cavity have a higher thermal transmittance, low solar heat gain coefficient, and high visible light transmittance as compared to double glazing units with air-filled gaps.
2. Glazing units with moving water-fills reduce heat transfer rate in and out of room space by more than 50%.
3. The parameters that affect the reduction of solar load gain are related to the optical and thermal properties of the glass and the glazing fluids.

Assumptions

The assumptions for this study are

1. The difference between the surface heat transfer coefficient of the glass unit and the window frame (PVC board was used in this research) is small enough and will therefore not affect the results.
2. In situ testing of the specimen simulates heat transfer expected in field installations.
3. The surround panel used has a thermal resistance value close to that of an actual wall.
4. The heat loss exchanges between the surround panel and fenestration is insignificant.

Limitations and Delimitations

The intensity of solar radiations is not constant throughout the year and not the same for every geographic location. This study is more suitable for hot climates and climates with diurnal weather conditions. Other critical performance properties such as the structural, acoustic and blast properties of glazing units were not considered in this study.

Definition of Terms

Conduction: It is the transfer of heat through solids or a fluid medium without movement of the hot material except on a molecular scale (Butterworth, 1977).

Convection: It is the transfer of heat through fluids, either by random motion of the molecules or by the bulk fluid (Incropera, DeWitt, Bergman, & Lavine, 2011).

Diurnal weather conditions: This refers to the variations in meteorological parameters such as temperature and relative humidity during the day (National Oceanic and Atmospheric Administration, 2015).

Heat flux: It is the quantity of heat transferred per unit area (Butterworth, 1977).

Quads of energy: It is equivalent to one quadrillion British thermal units, i.e. 10^{15} BTU (American Physical Society, 2015).

Radiation: It is the exchange of heat between bodies that are not in direct contact and does not require any intermediary heat carrier (Butterworth, 1977).

Solar heat gain coefficient (SHGC): It is the ratio of solar gain entering through the window to the amount of incident solar radiation (National Fenestration Rating Council Incorporated, 2004).

Thermal Transmittance (U-Value): It is the amount of heat transferred through a unit area of an object when there is a temperature difference across both sides of the object (American Society for Testing and Materials, ASTM C1199-12, 2012).

Visible Light Transmittance: It is the ratio of the visible light entering a glazing unit to the incident visible light (National Fenestration Rating Council Incorporated, 2004).

Review of Literature

Buildings are designed to shelter occupants from the bare effects of changing weather conditions. The quality of comfort occupants of a building enjoy is a function of many variables including climatic conditions, building assembly, building thermal envelope and the availability of sustainable building materials. Achieving indoor comfort comes at a cost. It is incumbent on the owner and the builder to make economically viable choices of materials in order to enhance the efficiency of the building. Moreover, a significant amount of energy can be saved by the proper selection of materials as well as design of the building. Notable among the criteria for good thermal comfort is the choice and components of the building thermal envelope. The thermal envelope of the building acts as a separator between the outdoor climatic conditions and the indoor conditions. It comprises of all the structural elements, insulation materials for the roof and walls, windows, doors, and floor slabs of the building. The type of insulation materials used in the envelope contributes largely to the energy savings in a building space. Other room conditioners such as space air-conditioning and heating can be greatly reduced and savings on energy achieved by knowing the right insulation material to use (Al-Homoud, 2005).

A greater consumption of energy takes place during the operational phase of buildings for heating, cooling, ventilation, lighting, and other electrical appliances usage. This can be reduced by focusing on the factors that affect energy consumption in a building. Builders can take advantage of building façade concepts and building envelopes to limit energy use resulting from changing outdoor and weather conditions. Some of the alternatives available include envelope alternatives; types of fenestrations and glazing systems; thermal mass and insulating properties of building materials; lighting requirements and daylight controls; and HVAC systems and controls. In moving towards a zero building energy performance goal, a holistic approach involving a thorough assessment of all indoor environment quality has to be used. Developing systems that can resolve some of the issues regarding heat gain, heat loss, and daylight requires an understanding of the spectral properties of sunlight and transparent materials. One of the building façade elements that have been studied over the years for regulating the amount of solar radiation entering into a building space is window and glazing systems (Kim & Todorovic, 2013).

Energy Conservation Potential of Glazing Systems

The sun's energy is vital to life on earth. The sun emits its energy in a range of wavelengths and energy capacities. Most of this energy that is transmitted through a glazing unit is in the visible light spectrum with red light at the low-energy end of the visible spectrum and violet light, at the high-energy end. Infrared is part of the sun's radiation that produces thermal effects when absorbed. For highly glazed commercial buildings, solar heat gain from infrared radiation contributes to the heat loads of the building, and this translates into high-energy use from the operation and maintenance of air conditioning systems (Gueymard & duPont, 2009). Moreover, energy consumption for lighting in commercial buildings is on the high side and further increases the heat supplied to a roomspace. From Figure 2, lighting from commercial buildings consumed 20% of energy use, which was the highest, followed by space heating that accounted for 16%, then 14% of energy use for space cooling. Over all, lighting, space-heating, and space-cooling accounts for about 50% of energy use in the buildings sector (Sawyer, 2014).

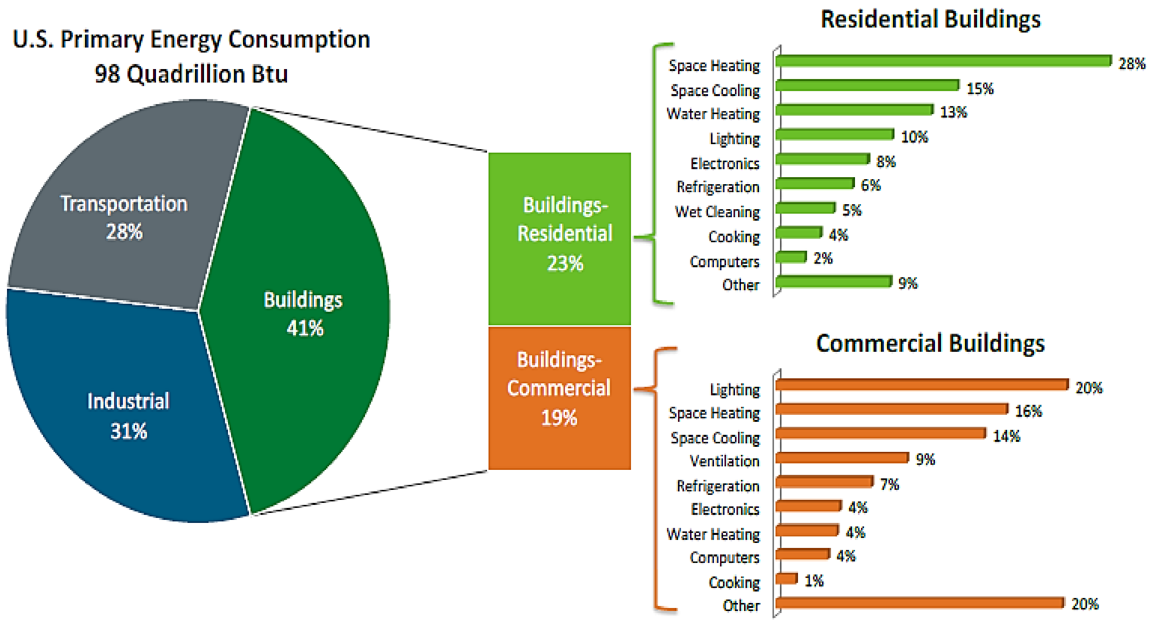

Figure 2. U.S. 2010 primary energy end-use (Sawyer, 2014, p. 1).

The selection of a glazing system plays an important role in determining a building's energy performance. The two major energy related functions glazings play in energy efficiency is the thermal performance and lighting of buildings. The thermal performance, which is normally expressed as the U-value or the R-value, shows the insulation potential of the building element or envelope. A material with low thermal transmittance (U-value) reduces the amount of heat gain and losses to the indoor environment. The walls, roofs, and slabs of buildings are normally insulated with materials of very low thermal conductance and as such; do not pose a significant source of energy loss in a building. Therefore, to minimize heat loss or gain in a building façade, windows or glazing units with a low thermal transmittance value, and a high visible transmittance have to be selected to reduce consumption associated with heating, cooling, and lighting in a building (Selkowitz, 1999).

Some of the products under research that are able to adapt to the changing weather and climatic conditions include smart glass (electrically switchable glass), micro blinds, gasochromic glass, and liquid crystal devices. Most dynamic windows under development use spectrally selective (chromogenic) materials to control solar radiation transmittance, thereby, transforming the static properties of the window to have a dynamic ability in solar transmittance control. Though dynamic windows perform satisfactorily during summer and winter in reducing energy consumption, the cost of mass production is prohibitively high and the time for payback is often too long to be economically viable (Gil-Lopez & Gimenez-Molina, 2013).

Window and Glazing Systems

Windows, as essential elements of building facades have been used in buildings for daylight and ventilation purposes. It improves the aesthetics and defines the nature of space indoors. Studies have shown that, access to natural light and a well-ventilated space improves the health, comfort, and productivity of people. Notwithstanding, windows represent a major dent in the thermal insulation of buildings, contributing significantly to the heating and air conditioning loads of facilities. Since the use of the sun’s energy is a major goal in the design of energy efficient buildings, glazing systems can be designed to allow optimal visible light transmission with less unwanted heat gain (Selkowitz, 1999).

Glazing units and window systems are made up of glass pane(s), frames, spacers, gap fills, and sealants as shown in Figure 3. The number of glass panes can be one, two, three or four, depending on the level of insulation desired. The primary components of glass are usually a blend of metallic oxides, predominantly silica, which do not crystallize when cooling from solid to liquid state. Glasses have transparent features because of its non-crystalline or amorphous structure. Clear glass is obtained by adding antimony or manganese to the melt to decolorize the green colorization from iron impurities in the sand. Metallic compounds are normally added to the mix to get different glass colors (Lyons, 2007). Due to the high amount of energy required to melt silica for glass, it is very expensive to manufacture pure silica glass. To reduce the temperature for heating and the embodied energy, sodium oxide from soda and calcium oxide from limestone can be added to the mix (Josey, 1997).

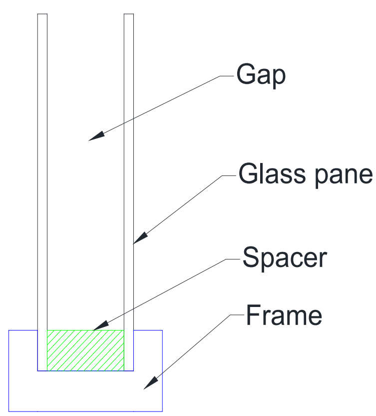

Figure 3. Parts of a window system.

The principal composition of modern glass for construction is 70-74% silica, 12–16% sodium oxide, 5–12% calcium oxide, 2–5% magnesium oxide with small quantities of aluminum, iron, and potassium oxides. The production of glass is relatively energy intensive with 15000 kWh/m^3 as compared to concrete with 625 kWh/m^3 energy consumption. The appropriate use of glass in design of buildings gives it a better pay back in terms of its energy efficiency (Lyons, 2007). Based on the method of production, there are four types of glass used for construction. They are ordinary annealed glass, toughened glass, laminated glass, and insulating glass units. Annealed glass is the most frequently used architectural glass. It has good surface flatness and not subject to distortion. When broken, it breaks into sharp dangerous shards. It is therefore not safe to use annealed glass at locations where it can easily break. Annealed glass can be strengthened or tempered with heat or chemicals. The resultant strength and resistance to thermal stresses of a tempered glass is at least four times the strength of an ordinary annealed glass. Due to the toughened nature, it is difficult to cut the glass pieces after production. The glass therefore has to be cut in the required sizes prior to processing. When tempered annealed glass breaks, it shatters into many small fragments. This type of glass is suitable for safety glazing under certain conditions (Josey, 1997). Laminated glass, another type of glass, comprises of two or more layers of glass adhered together with a plastic interlayer. It is normally used for safety glazing because it remains intact even if one layer cracks. When it cracks, it does so without disintegrating. The plastic interlayer can provide varying optical and thermal properties by incorporating photochromic or thermo-chromic material in the interlayer. The last and most used glass unit for insulation is the insulating glass. It consists of two or more layers of glass with a spacer that encloses an air space. The air space usually contains inert gases or gels that reduce heat gain and loss through the glazing unit (Lyons, 2007).

Glass must be supported securely in a frame to make it structural and maximize its useful life span by preventing wind loads from shattering it. The type of frame used affects the overall thermal performance of the window system. Several researchers are examining the manufacture of highly insulating frames to reduce heat loss through frames. The type of frame used is dependent on the operating system of the window. The structure of the frame has to fit the way the window is opened. Window frames are normally made of wood, Aluminum, glass façade, or PVC with Aluminum cladding. The choice of spacers also affects the overall thermal transmittance of the window system. Spacers keep glass panes apart at a uniform dimension. Some of the other functions of spacers include, accommodating stresses imposed on the glass panes due to thermal expansion and pressure; provide gas tight seals to prevent leakage; and provide moisture barriers by putting desiccants in the spacers. Using insulating spacers have the potential of reducing U-value by about 12% for highly insulating glazing systems. It is important to choose frames and spacers with high insulating values in order to improve the thermal performance of the window system (Gustavsen, Jelle, Arasteh, & Kohler, 2007).

Solar Properties of Glazing Units

As solar radiation passes through a medium, three things are bound to happen. Some of it is reflected, a portion is absorbed, and the rest is transmitted. Each of these properties can be optimized depending on its application to get the desired results. For a glass window wherein it is required to admit daylight and either prevent solar heat gain or allow solar heat gain, the optical properties can be altered to get the desired results (LBNL, 2013). Figure 4 below shows the percentages of solar radiation reflected, absorbed, or transmitted by a quarter-inch clear glass.

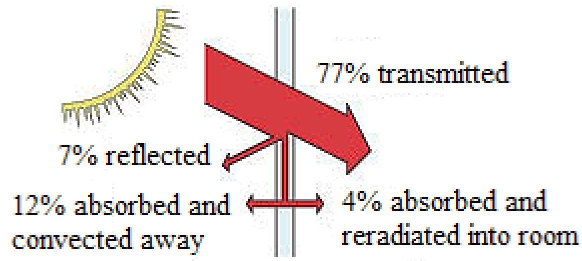

Figure 4. ¼-inch clear glass showing proportions of solar radiation reflected, absorbed, and transmitted (Efficient Windows Collaborative, 2014).

Physical properties of glazing units.

The physical properties of glazing units include transmittance, reflectance, and absorptance. Transmittance refers to the proportion of the solar radiation that can pass through the glazing. Since the sun emits its energy in different wavelengths, glazing units' transmittance can be defined by the kind of wavelength it is allowing to pass through. When the transmittance is in the visible light spectrum, it is called visible light transmittance, if it is in the UV light spectrum; it is referred to as UV-transmittance. Putting together all the transmittance gives the total solar energy transmittance of the glazing unit. The visible light transmittance of a glazing unit gives an indication of how effective it is in providing daylight and a clear view of the outdoor environment (LBNL, 2013).

When solar energy is incident on a surface, a portion of it is reflected back into the atmosphere. The reflectivity of glass is dependent on the quality of the glass surface, the presence of surface coating, and the angle of incidence of the solar radiation. The sharper the angle of incidence, the more the light is reflected rather than transmitted or absorbed. For clear glass, it reflects about 50% and above for angle of incidence greater than 70 degrees. The reflectivity of a glass surface can be increased by applying metallic coatings. This produces mirror-like surfaces, reflecting most of the incident light. Most of the coatings on the market reflect all the spectrum of the solar radiation. It is however undesirable to apply such coatings on glazing units. Coatings that are spectrally selective are more appropriate due to its ability to allow transmission of visible light and reflect radiation in the infrared spectrum for hotter climates, or admit infrared transmission in colder climates (Efficient Windows Collaborative, 2014; LBNL, 2013).

Glass absorbs radiant energy that is neither reflected nor transmitted. The absorbed energy increases the temperature of the glass. The absorptance of glass can be increased by adding chemicals that trap radiant energy. If it absorbs energy in the visible light spectrum, the glass appears dark, but if it absorbs in the UV or infrared spectrum, there is no significant change in color or appearance of the glass. Absorptive glasses are normally used in solar hot water heating applications. They are also used to reduce direct solar heat gain of indoor space environment (Efficient Windows Collaborative, 2014).

When glass absorbs heat or light, it is either reradiated or convected away by the air current on the surface of the glass. The ability of a material to reradiate absorbed heat is its emissivity. When the emissivity of the glass facing indoor environment is high, it radiates more heat to the room space, causing unwanted heat gain in summer conditions or hotter climates. Therefore, reducing the emissivity of glass improves its thermal resistance. A typical glass has emissivity of 0.84; meaning it emits 84% of absorbed radiant energy (Efficient Windows Collaborative, 2014; LBNL, 2013).

Thermal Performance of Glazing

The thermal performance of a glazing unit is a function of the solar energy transmittance, the reflectance of the glass, emissivity of the glass panes, the width of interspace, type of cavity fill, and the material and configuration of the spacer around the perimeter of the glazing cavity. The thermal performance of glazing units is rated based on their thermal transmittance and the solar heat gain coefficient. To reduce direct solar heat gain, glass manufacturers apply low-emissivity coating to the surface of glass panes to reflect long-wave radiant energy (infrared). Though low-e glass reduces solar heat gain, it reduces the transmittance of visible light through windows significantly. Numerous combinations of glass panes and gas fills have been developed to remediate such conditions but have seen little success. The primary deficiency, which is either low visible light transmission or high solar heat gain, persists (Apte, Arasteh, & Huang, 2003).

Single-pane clear glazing has low thermal performance and high visible light transmittance. It is suitable for applications where thermal performance is not required. Replacing the single glazing with double-pane glazing containing air-filled gaps will increase the thermal performance. Further adding low emissivity coating will make the product perform better in its thermal performance but will reduce visible light transmission. The coating acts as a filter with spectrally varying optical properties to reflect the infrared component of the sun's radiation (Apte, Arasteh, & Huang, 2003). The spectral properties of the coating can however be treated to include parts of the visible light and infrared spectrum in order to allow for daylighting, solar heat gain and cooling (LBNL, 2013).

The gap in a double glazing unit has an optimum width for every gas, beyond which convection increases, resulting in an increase in thermal transmittance. When the air gap is too small (that is lower than the optimum), conduction takes place in the interspace and increases the U-value. It is therefore imperative to find the optimum gap width required for the lowest thermal transmittance possible for the glazing unit. The optimum gap width for air and Argon fills is 12 mm, and Krypton is 6 mm (Lawrence Berkeley National Laboratory (LBNL), 2013).

However, as interest in the concept of zero-energy buildings increase, other high performance glazing alternatives units are still being researched. One of such high performance glazing technologies, dynamic glazing systems, that can change their solar heat gain properties with seasonal variations, are still being developed.

Thermal Mass Effect

Buildings made of concrete insulation, earth, and solid wood are known to reduce heating and cooling loads. These building materials are used mostly in hot climates and they provide a fairly comfortable thermal atmosphere for the occupants even without air conditioners. The thermal mass of the building absorbs heat gain from the sun, and excess heat from the light and other appliances in the building. The absorbed heat energy is delayed and released with time. This helps to flatten out thermal waves caused by atmospheric temperature swings. Studies conducted by Kosny et al. (2001) revealed that cooling and heating loads for buildings with massive walls could be far lower than buildings with lightweight wood.

Using the thermal mass of a building is an effective way of controlling the heating and cooling loads of a building. Usually, the thermal performance of a building is measured by the steady state R-value, which does not account for the dynamic thermal performance of envelope systems. Even though most homeowners use lightweight wood in building, massive structures built of materials with a high thermal mass can help to regulate the heating and cooling loads, thereby reducing the energy consumption of those buildings. The measurement systems and analysis for steady state thermal transmittance can however not be used to analyze dynamic thermal performance of buildings. In order for the measurement systems to reflect the dynamic response to weather conditions, thermal mass effect has to be incorporated in the analysis. In a research conducted by Kosny, Kossecka, Desjarlais, and Christian (2001), they suggested a method called dynamic benefit for massive systems (DBMS) to evaluate the effective R-value. The DBMS evaluation is done by comparing the thermal performance of a massive wall to a lightweight wood frame wall. The resulting DBMS is multiplied by the steady state R-value to get the R-value equivalent for massive systems. In addition, thermal structure factors (heat capacity, R-value, and response factors) can be used to assess the thermal mass heat storage capacity of the wall.

Glazing Systems with Fluid Fills

Glazing systems with fluid fill gaps have been poorly marketed, so its influence in reducing energy consumption has not been realized. Water is the most common fluid with low cost, and a significant impact on heat exchange. Due to water’s high opacity to infrared, it can be used to trap the infrared thermal radiation from the sun, store it for some time, and gradually dissipate the heat. Moreover, water is highly transparent, allowing the visible part of light to pass through, while blocking infrared (Gil-Lopez & Gimenez-Molina, 2013). Water molecules exchange energy at a rapid rate in the form of vibrations on the surface of the water mass. When energy from infrared light pulse is incident on the surface of water, the hydrogen bond between the water molecules vibrate. The outermost molecules with single OH groups pointing into the air are highly efficient at capturing the energy and conducting it into the water. The energy transfer on the surface is slower as compared to the downward transfer of energy. Water therefore, can act as a good absorber and distributor of energy (Zhang, Piatkowski, Bakker, & Bonn, 2011). The transparency of water provides the opportunity to use transparent facades, such as glass, to maximize the use of sunlight energy.

Chow, Li, & Lin (2011) conducted research on using flowing water in a double glazing unit as a pre-water heater in buildings where hot water is required. The performance of the combinations of clear-and-clear, absorptive-and-clear, and reflective-and-clear glass panes were studied and evaluated. Considering all working and weather conditions, the absorptive-and-clear glass combinations were found to have the highest efficiency as a water-preheating device. The disadvantage of using this combination is its low visible light transmission as compared to the clear-and-clear glass combination. For heat gain reduction (U-factor and solar heat gain coefficient), a double glazing system with flowing water was found to be better than an air sealed double glazing unit. Increasing the water flow velocity to 0.01 m/s in summer increases the rate of heat exchange between the water column and the outer ambient air temperatures. To fulfill pre-water heating functions of the glazing unit, the velocity of flow should be kept low; that is in the laminar flow regime. The advantage of using a moving fluid (water) medium over air is that the convective heat transfer between the glass surfaces and the water stream is higher than that of air and as such, it acts as a solar heat collector. Due to the higher specific heat capacity of water as compared to other fluids, it can store more heat and removed later, than for the same volume of air. In addition, the removed heat component can be reused for other purposes (Chow, Li, & Clarke, 2011).

Heat Transfer across Glazing Units

Glass has been an essential part of building envelopes for admitting daylight, visual interaction with the outdoors, and for ventilation purposes when it is operable, for a long time. All of these benefits come with unwanted heat gain and loss. With proper orientation, though not always practicable, a building with glass windows can take advantage of the benefits and reduce the heating and cooling loads of the building. A window is normally recognized as an energy loser in a building envelope due to its low thermal resistance, and these losses have to be compensated using HVAC. The boundary air film layers on glazing units provide most of the thermal resistance of windows. Some of the other factors that influence the thermal resistance of glasses include the glass emissivity, air temperature, and wind velocity. Multiglazed windows are filled with air or gases to increase the insulating properties of windows. The transfer of heat across the gap in a multiglazed window is a function of the height and width of the gap, the thermal conductivity of the fill, viscosity, and the thermal expansion coefficient of the gap fill. Convective heat transfer is insignificant for a sufficiently small gap width and height. As the gap widens, heat transfer takes place by conduction on the boundary air film layer, and convection in the air gap. As the gap is widened further, conductive, and convective heat transfer, remain fairly constant. In this situation, increasing the gap width increases the heat flow rather than reduce it. Radiative heat transfer contributes significantly (about two-thirds) to heat flow in ordinary clear double-glazing, and therefore, it is imperative to use radiative transfer barriers such as low emittance coating to reduce the heat flow. The conductive and convective heat transfer can then be reduced by replacing the air fill with gas fills of high viscosity and lower thermal conductivity such as inert gases (Menzies & Wherrett, 2005; Wasley & Utzinger, 1996; Department of Energy, 1997). The solar thermal and optical properties of a window system are described below.

Thermal transmittance: It is affected by the apparent thermal conductance of the test specimen and the total heat supplied to the specimen. According to ASTM standard C1199-12 (2012), the thermal transmittance of a fenestration can be calculated from the equation:

$$Us = Q_s/[A_s\ (t_h - t_c)] \qquad (1)$$

Where U_s is the thermal transmittance, Q_s is the heatflow through the test specimen, A_s is the projected area of the test specimen, t_h is the average roomside temperature, and t_c is the weather side average temperature in Equation 1.

Table 1 shows different configurations of glazing units with their corresponding thermal transmittance values. As the number of glass panes increase, the U-value decreases. Moreover, the kind of inert gas filling the cavity has an influence on the U-value of the fenestration system.

Table 1

The U-value of Glazing Units with Different Configurations and Cavity Fills

Glazing U-Value (W/m^2 K)			
Glazing Configuration	Cavity fill		
	Air	Argon	Krypton
Single pane, 4mm	5.8		
Double glazing (4-12-4)mm	2.9	2.7	2.6
Triple glazing (4-12-4-12-4)mm	2.0	1.9	1.7
Double glazing with single coating(4-12-E4)mm	1.6	1.3	1.1
Triple glazing with single coating(4-12-4-12-E4)mm	1.3	1	0.8
Triple glazing with double coating (4E-12-4-12-E4)mm	1	0.7	0.5

Note: 4mm is the thickness of the glass and 12mm is the spacing of the cavity. Adapted from Selkowitz (1999, p.15).

Solar Heat Gain Coefficient: For locations where solar heating is required, it is desirable to have a higher SHGC, whereas a lower SHGC is well suited for cooling dominant conditions. SHGC is the single most significant determiner of the cooling loads of a building. The intensity of heat supplied through this means surpasses heat transfer due to temperature differential developed on both sides of the glazing unit. Solar heat gain comes from the direct and diffuse radiation from the sun and those reflected from the ground and other objects around (LBNL, 2013; Stein & Reynolds, 2000).

Visible Light Transmittance: This determines the amount of daylight that a building receives through a glazing material. In commercial buildings where lighting contributes significantly to energy consumption, a glazing material with high visible transmittance will reduce energy use significantly. VT is influenced by the type of glass, number of glass panes, and the presence of emissivity coatings on the glass. VT could be as high as above 90 percent for water white clear glass to about only 10 percent for highly reflective glass surfaces. Glare for glazing units with high visible light transmittance can be mitigated by using shades and blinds to get the required amount of light to the indoor space (LBNL, 2013).

Methodology

Experimental Design

Traditional multiglazed windows have their gaps filled with air or inert gases to reduce convective and conductive heat transfer. This research sought to characterize the performance of fluid filled glazing systems. The experimental setup measured the heat transfer rate of solar radiation across a double glazing unit with fluid fill. The optical and thermal properties of the glazing system were investigated and compared to the performance of an air filled double glazing unit. A heat transfer computational fluid dynamics model was developed to simulate the performance of both setup under the same environmental conditions and to establish operational parameters for the fluid-filled glazing unit.

Variables

Infrared is the part of the sun's spectrum that causes direct heat gain across glazing units. A glazing unit, therefore, should either reflect the infrared radiation or redirect it to prevent unwanted heat gains in the room space. The amount of heat associated with infrared radiation transmitting through a glazing unit has to be regulated to maintain good thermal comfort. In this research, the independent variables that affect the heat transfer properties of the test specimen (double glazing unit) are the area of glass, the net rate of heat transfer through the glazing unit, and the temperature differential across the glazing unit. The net rate of heat transfer depends on the width of the gap interspace, the type of gap fill, the apparent thermal conductance of the individual components of the glazing assembly, and the solar irradiance for the setting of the apparatus. The physical and mechanical properties of the glass and the gap width of the glazing assembly remained constant for the experimental setups. The solar irradiance was recorded at every 15 minutes interval. The gap was filled with air, and later with water to evaluate the performance of water-filled glazing relative to air-filled glazing unit.

Instrumentation and Materials

The instruments that were used in experimental measurements included:

Pyranometer (Middleton Solar EQ08): This instrument was used to measure total solar radiation. It measures solar irradiance within the visible light and near infrared spectrum (i.e. 380-3000 nm). The range of solar irradiance is from 0 to 4000 W/m^2 with a sensitivity of $18\mu V/Wm^{-2}$.

Thermocouples: Type T and K thermocouples were used to measure the surface, air and water temperatures of the test specimen.

Data logger and acquisition software: A data logger (OMB-DAQ 55) with an expansion module (OMB-PDQ2) was used to collect the temperature data from the thermocouples. Millivolt signals from the thermocouples were converted to temperature data directly using the data logger's software. The software allows for portability of data from the software's native file format to Matlab, LabView, and Excel platforms.

Computational fluid dynamics Model and Window Simulation Software: These were used to develop a model to characterize the thermal properties of the liquid in the glazing system. It also provided similar conditions to enable comparison of the air-filled and fluid-filled glazing units.

Construction of the Test Bench

A glazing unit with liquid fill (water) of size 1.2 m by 1.2 m was chosen as the test specimen. The test box for the glazing unit was built of steel channel (as shown in the working drawing in Figure 5) and Expanded Polystyrene insulation (EPS) board with an R-Value of 20 (the R-20 was obtained by adhering two R-10 EPS boards with 2-inch thickness each) to prevent heat losses. An adhesive caulk was used to seal the joints of the insulation board to prevent air leakage, thereby, focusing attention on the thermal performance of the glazing unit. The steel channels and the polystyrene boards were coated with a black Jack elastomeric coating (white in color) to act as a radiant barrier to further reduce the interaction of the steel with the thermal properties of the glazing unit as shown in Figure 6. The double glazing unit was built with a quarter inch tempered glass of dimensions 46 inch by 46 inch. A PVC board was used as a spacer to maintain a one and half inch consistent space between the two glasses. The glass and the PVC board were adhered together with a fish aquarium silicone caulk to prevent water leakage. The frame around the glass was made of PVC board in order to reduce heat transfer interactions of the frame and the glass. The picture of the glazing unit is as seen in Figure 7.

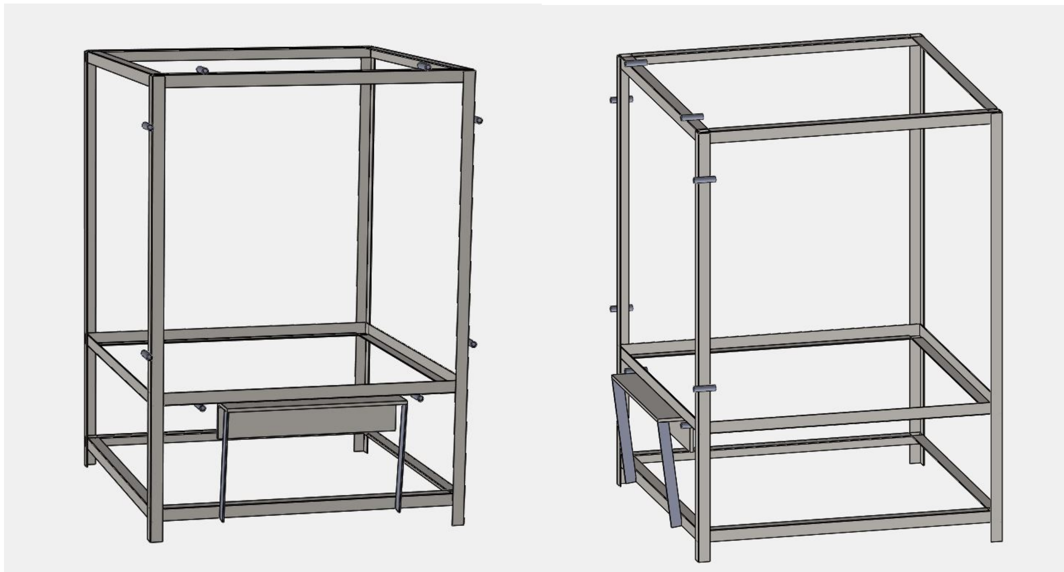

Figure 5. Working drawing for test bench construction.

Figure 6. Fabricated test bench with an open aperture.

Figure 7. Glazing unit under fabrication.

Experimental Procedures

Design considerations.

ASTM C119-12 was used as a guide in designing the experimental procedure. Thid standard provides the procedures for measuring the steady-state thermal transmittance of fenestration systems using the hot box method. Section 4.3 of the manual however, states that the test procedure can be used to test products at other conditions other than the conditions described in the document for research purposes or product development. Since this experiment does not use the hotbox method the procedure was modified to suit the field testing. *ASTM C1363-11* was used together with *ASTM E1423-14* to define the locations and density of the temperature sensors on the glazing unit to get accurate surface temperature measurements. Moreover, since the research was conducted in situ, *ISO 15099* was used to calculate the various heat transfer coefficients in order to obtain the U-values presented in appendix A1. The thermal transmittance values that were determined were true experimental values but not standardized thermal transmittance due to the modifications made to the experimental set up. The values obtained from both the air-filled and fluid-filled were compared to study the trend of heat transfer variations over the testing period.

Procedures.

Three different experimental setups were used in this research, and they are described as follows:

Experiment 1: A homogenous continuous surround panel (expanded polystyrene board) was installed in the aperture of the test bench and temperature sensors were attached to both sides of the panel. The density of the temperature sensors attached were nine sensors, equally and symmetrically spaced on each side of the expanded polystyrene as seen in Figure 8 (American Society for Testing and Materials, ASTM C1199-12, 2012; ASTM C1363-11, 2011). The surface temperature on both sides of the surround panel were measured and averaged. The net heat flow through the panel was determined and compared to the amount of heat that was supplied to the surround panel by the sun's radiation.

Experiment 2: The extruded polystyrene board in the aperture was removed and replaced with the test specimen with closed air fill, and temperature data were recorded. The sensor density was also nine sensors on each side of the test specimen as shown in Figure 8. Figure 9 shows a picture taken from the field-testing.

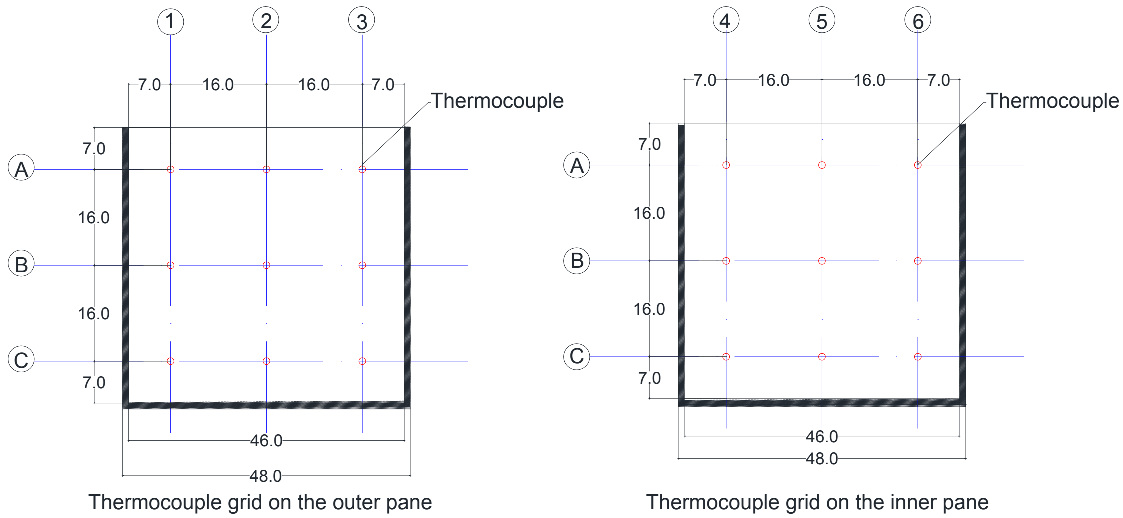

Figure 8. Schematic of thermocouple grid for experiments 1 and 2.

Figure 9. Picture of experimental setup 2 simulating air-filled glazing unit.

Experiment 3: The gap between the glass panes was then filled with water and temperature probes were inserted as seen in the configuration in Figure 10. Temperature sensors were attached to the surface of the glass on each side as seen in Figures 11 and 12.

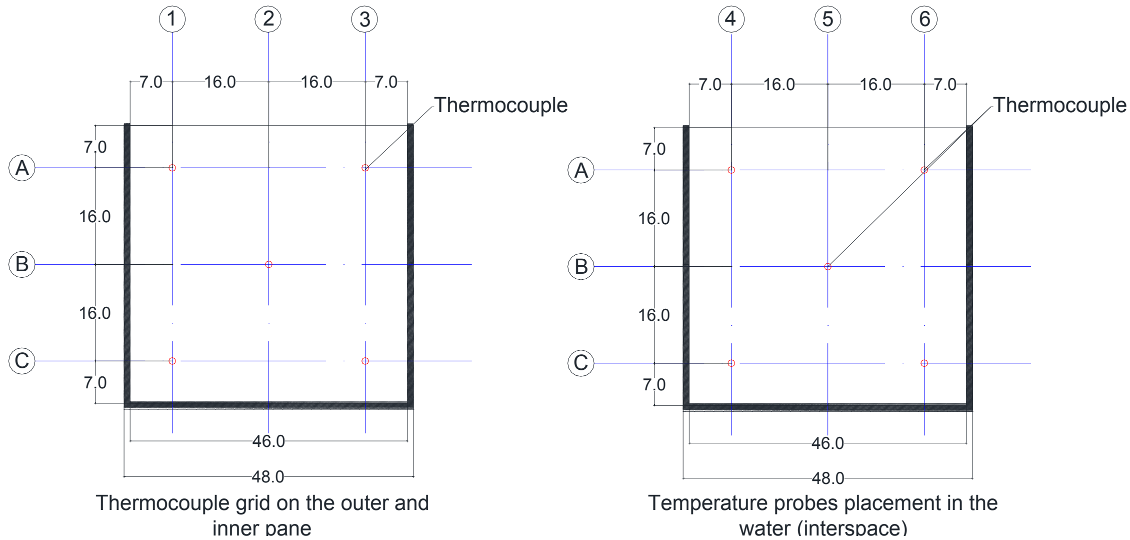

Figure 10. Thermocouple grid and temperature probes placement for experiment 3.

Figure 11. Picture of water-filled glazing unit with thermocouples attached.

Threats to Validity

Below are some of the factors that posed a threat to the validity of the study:

1. History – Developments in the manufacturing process of glazing systems with better thermal and optical performance can affect this study. This study was based on the assumption that there is always a trade-off between the optical and thermal properties of traditional glazing units.
2. Selection of glazing material – A double glazing unit with known physical properties was selected for this study. The study can be generalized for other glazing units with different physical properties by developing a mathematical model as seen in Appendix A that permits other researchers to manipulate in order to adapt to other glazing units with fluid-fill cavities.
3. Setting- The experiment was conducted in-situ to get an approximate representation of the effects of infrared radiation on fenestration units. Weather conditions affect the amount of insolation supplied to fenestration units. In order to get a consistent set of data, the experiment was conducted on days with similar weather conditions. Moreover, computer simulation with similar environmental conditions was run on the model developed to compare both the air-filled and fluid-filled glazing units.

Results and Discussions

For each of the experiments, a day with low to no cloud cover was chosen to avoid a higher percentage scattering of the sun's radiation. The first set of data, which was for the characterization panel (expanded polystyrene walls), was gathered on August 15, 2014 to estimate the quantity of heat that was lost or gained from the surroundings of the test box. This formed the baseline for calculating the amount of heat lost or gained through the walls. The results showed that an insignificant amount of heat was lost or gained through the expanded polystyrene walls as compared to the glazing test specimen. The maximum quantity of heat entering or leaving through the walls was 2.94 W as shown in Table A2 of appendix A. A summary of the data gathered for this setup and the properties of the EPS are in Table A1 of the appendix.

The second and third set of data were gathered to analyze the effect of air and water fill on the trend of variation for the room side glass surface and room side air temperatures during the day. Only the trend in variation could be analyzed because the data were taken on different days with slightly varying environmental conditions. Other dependent variables such as solar heat gain coefficient and thermal transmittance could not be compared in the experimental phase due to the slightly varying environmental conditions.

The second set of data was gathered on the 24 and 25 of September 2014, for periods of the day with no cloud cover, and on October 27, 2014 to compare with the data from the 24 and 25 of September 2014. This experiment simulated the performance of a double glazing window with sealed air-fill in the gap as expected in field installations. The parameters of interest were the surface temperatures of the double glazing window on the outside and inside, the outside ambient air temperature variation, and the room side air temperature.

The third set of data was gathered on September 26, 27, and the 8 October 2014. This experiment was conducted to simulate the performance of water-filled glazing windows in reducing solar heat loads supplied into indoor building space. The variables of interest for this setup were the surface temperatures of the double glazing window on the outside and inside, the outside ambient air temperature variation, water temperature, and the room side air temperature. These set of data helped to study the trend in the variation of the rate of heat transfer into the room for both the air-fill and water-fill glazing units. The data also provided insight into the behavior of the water in heat transfer.

The room air temperatures recorded for the window glazing with sealed-air fill showed a steep continuous rise in temperature from the time of recording to sunset as seen in Figures 12 through 14. It can also be seen that the recorded temperatures of the room for all the three days (24 September, 25 September, and 27 October) were almost always higher than the glass surface temperatures. This is because the air-gap provides no means of heat storage to delay transmission of direct solar heat gain. The only heat storage possible is absorption of heat by the glass, which is negligible.

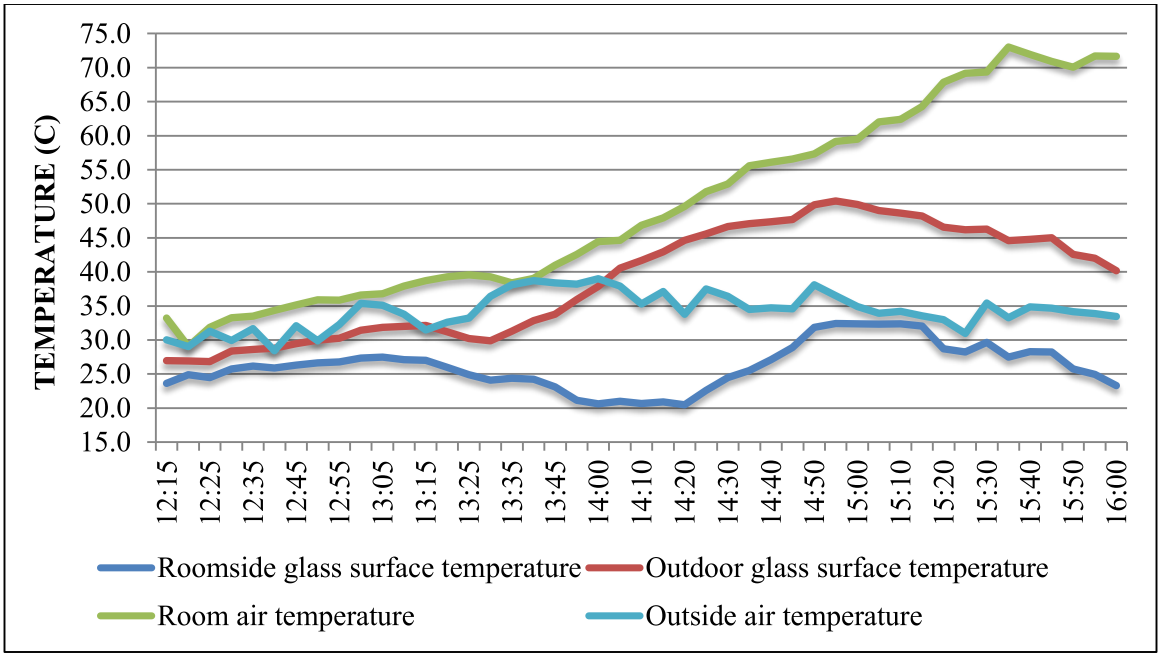

Figure 12. Graphs showing air-filled glazing unit. Temperatures were recorded on

September 24, 2014.

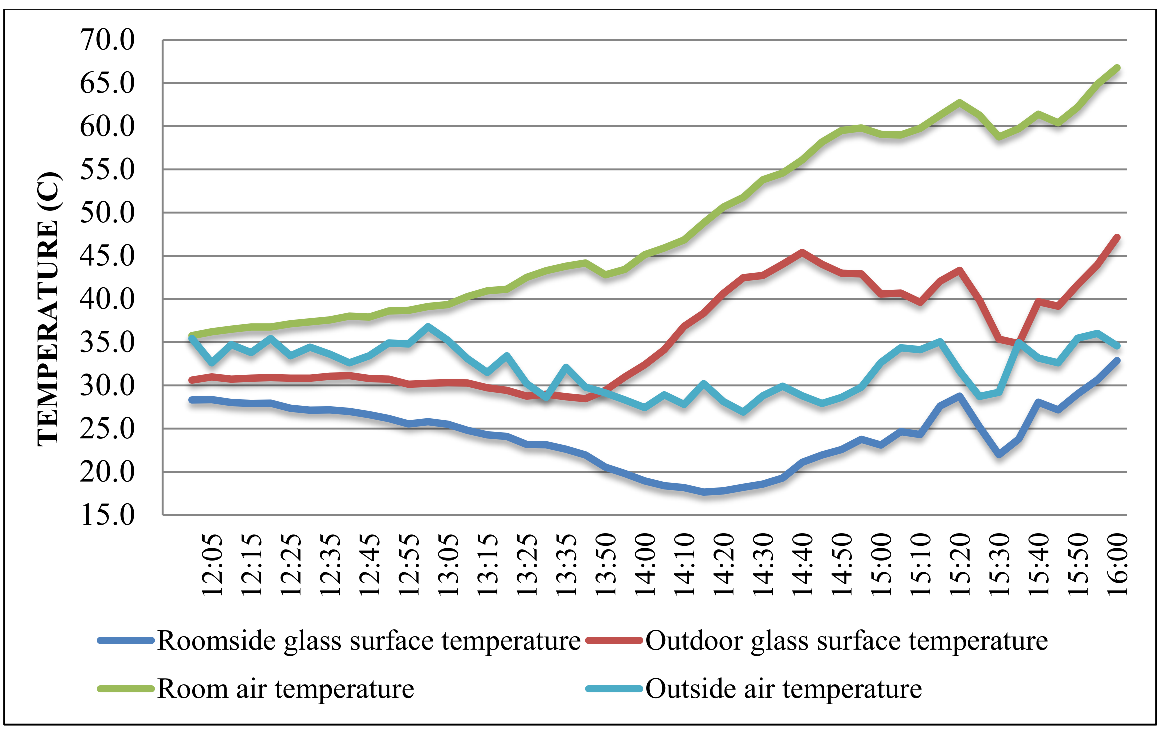

Figure 13. Graphs showing glazing unit with air fill. Temperatures were recorded on

September 25, 2014.

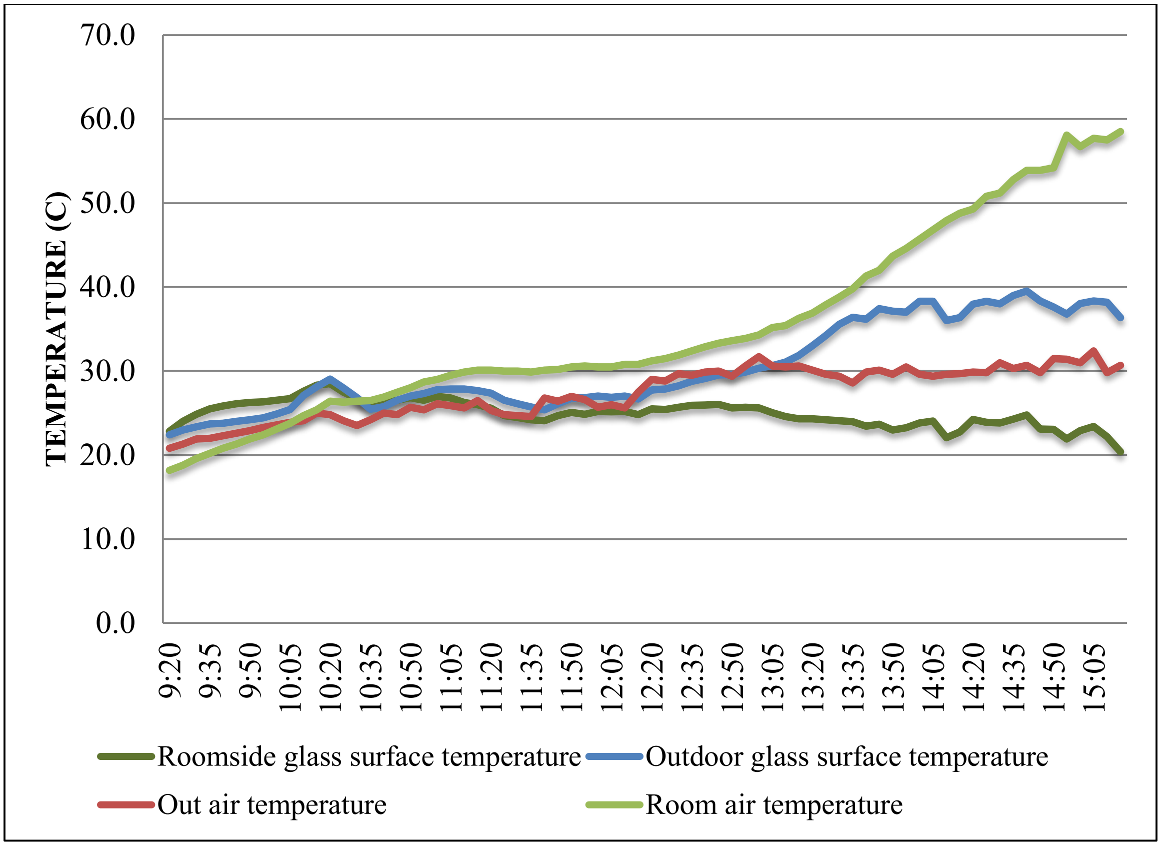

Figure 14. Graphs showing glazing with air fill. Temperatures were recorded on October 27, 2014.

The room air temperature of the window glazing with water on the other hand rose gradually from morning to late afternoon as shown in Figures 15 through 17. The glass surface temperatures were lower than the room temperature almost the entire time. As the temperature of the water got relatively higher, it began to reradiate heat into the room and the atmosphere. This could show that the water is able to collect and retain heat from the sun and allows some amount to be transmitted when there is a temperature difference between the water and the room air temperature or outside air.

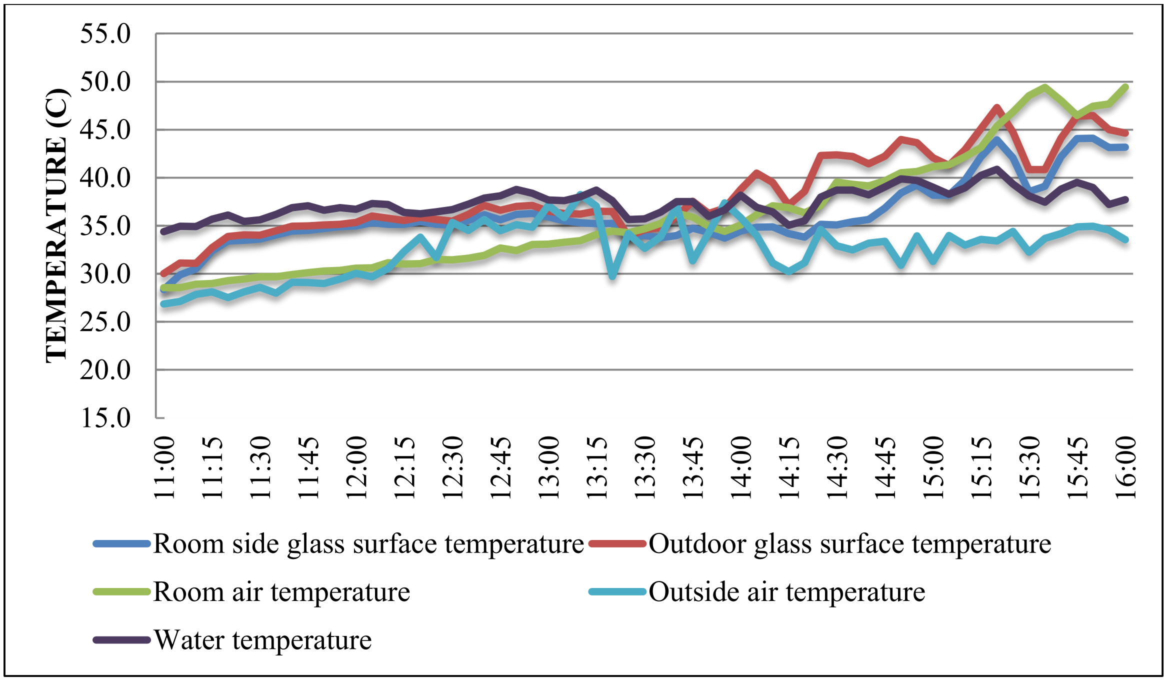

Figure 15. Graphs showing a water-filled glazing unit. Experimental temperatures recorded on September 26, 2014.

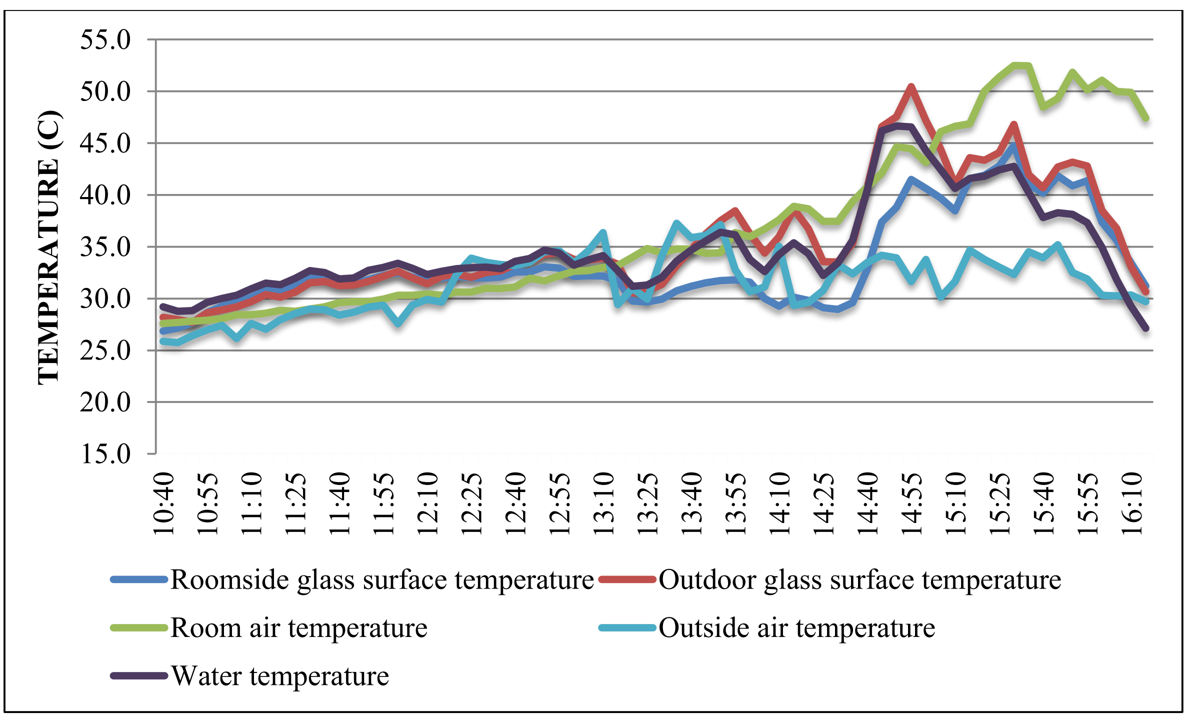

Figure 16. Graphs showing a water-filled glazing unit. Experimental temperatures were recorded on September 27, 2014

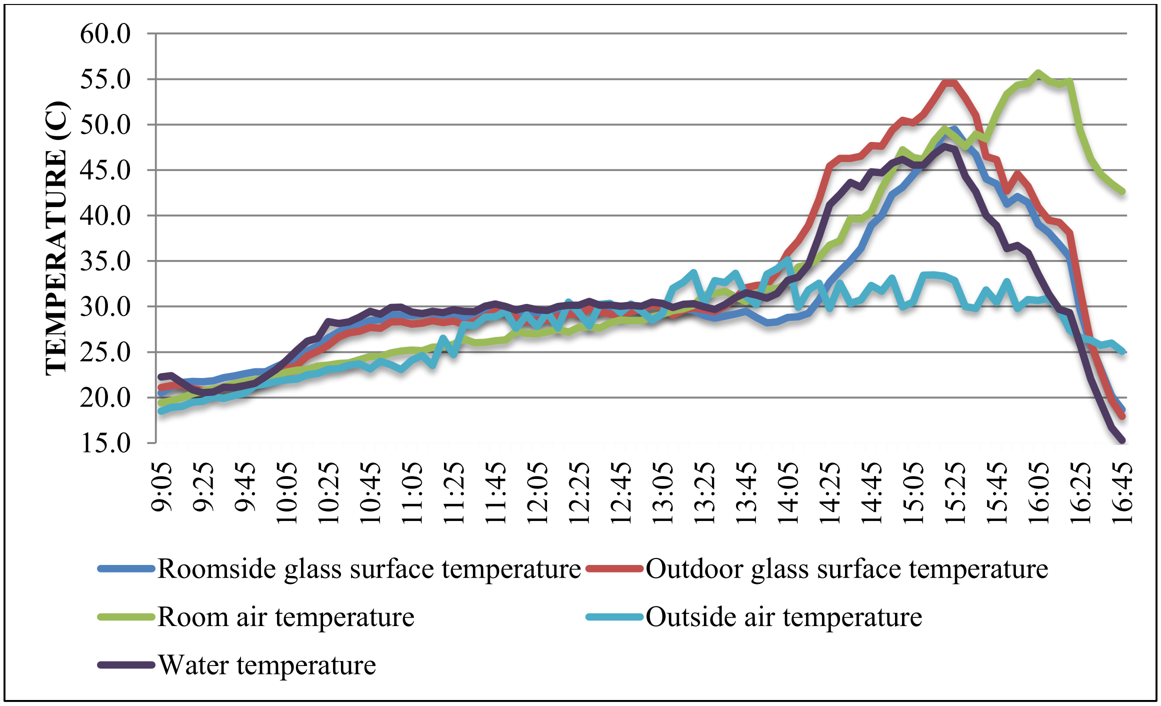

Figure 17. Graphs showing a water-filled glazing unit. Experimental temperatures were recorded on October 8, 2014.

Analysis

Analysis of the data gathered was done by using Window 7.3 simulation software designed by the Lawrence Berkeley National Laboratory (LBNL W7.3), which is an open source software. A computational fluids dynamic (CFD) model was designed with MatLab for this research in order to analyze the properties of the fluids. The algorithm developed for the CFD analysis and heat transfer rate is found in Appendix B of this paper. It was developed using ISO 15099.

Assumptions for Data Analysis

1. The glass was assumed straight with a smooth surface.
2. The thermophysical properties of the fluids used for calculations were considered constant for the range of temperatures in this data analysis.
3. The temperature distribution on each surface of the glass was assumed uniform. This reason for doing so was that the temperature of the surface was area weighted and an average calculated.

Heat Transfer Properties of the Fluids in Glazing Cavity

The heat transfer in the glazing cavity is influenced by the thermophysical properties of the fluid. The thermophysical properties of the fluids (water and air) are shown in Table 2. The heat transfer properties of both water and air can be simulated using computational fluid dynamics and the LBNL W7.3 software. The algorithm that was used is found in Appendix B of this paper.

Table 2

Thermophysical Properties of Air and Water

Property	Water	Air
Conductivity (W/mK)	0.60	0.0241
Viscosity (Kg/ms)	0.0089	1.722E-5
Specific heat (J/KgK)	4184	1006.103
Density (Kg/m^3)	1000	1.292
Prandtl	6.206	0.7197
Heat transfer coeff (W/m^{2}K)	97.73	2.807

Simulations

Computation simulations were run with Lawrence Berkeley's Window 7.3 at the same environmental conditions to determine the thermal transmittance, solar heat gain coefficient, and visible light transmittance for both glazing units. The NFRC 100-2010 summer environmental conditions were used as shown in Table 3.

Table 3

Environmental Conditions Based on NFRC 100-2010

Parameter	Value
Inside air temperature	24.0 °C
Effective room temperature (Radiation)	24.0 °C
Effective room emissivity (Radiation)	1.00
Outside air temperature	32.0 °C
Convection Coefficient	15 W/m^2K
Outside wind speed	2.75 m/s
Effective sky temperature (Radiation)	24 °C
Effective sky emissivity (Radiation)	1.00
Direct solar radiation	783 W/m^2

The ouput parameters of the glazing units were calculated based on the glazing configuration 6mm-38.1mm-6mm (i.e., 6mm glass, 38mm gap width, and 6mm glass). The optical properties of the 6mm glass are presented in table 4 below.

Table 4

Optical Properties of 6 mm Clear Glass

Parameter	Value
Solar transmittance	0.771
Solar reflectance	0.070
Visible transmittance	0.884
Visible reflectance	0.080
Infrared transmittance	0
Infrared emissivity	0.84
Conductivity	1

Hypothesis 1:

The thermal transmittance, solar heat gained coefficient, and visible light transmittance for both glazing systems were evaluated using the LBNL W7.3 software as shown in Table 5. The results obtained from the LBNL W7.3 simulations are consistent with the results obtained from the field experiments as shown in Tables A3 and A4 of the appendix A. Both results show that glazing units with air-sealed gaps have better thermal properties as compared to glazing units with water fill gap. This is due to the high convective heat transfer coefficient of water as compared to the air as shown in Table 2 above. The solar heat gain coefficient of the glazing containing water is however lower than the air-filled glazing as stated in hypothesis 1. The visible light transmittance for both systems were the same and therefore, hypothesis 1 can be supported based on the evidence presented.

Table 5

Center of Glass Results from LBNL Window 7.3 Simulation

Variable	Water	Air
U-Factor (W/m^2-K)	4.856	2.585
SHGC	0.696	0.706
Relative heat gain (W/m^2)	543	532
Visible light transmittance	0.786	0.786

The calculation procedure of the U-value for the glazing unit considers the conductivity, convective heat transfer coefficient, and the radiative heat coefficient of the individual components of the unit, but does not account for heat stored by the components as shown in Equation 2.

$$U = \left(\frac{1}{h_e} + \frac{1}{h_t} + \frac{1}{h_i}\right)^{-1} \dots\dots\dots\dots\dots\dots\dots\dots(2)$$

Where;

h_e is the outdoor heat transfer coefficient, which depends on the windspeed around the glazing system, outdoor climatic factors and the surface emissivity of the outdoor glass.

h_i is the indoor heat transfer coefficient, which is based on the radiative heat conductivity and convective heat transfer coefficient of the indoor environment as well as the glazing surface emissivity.

h_t is the overall thermal conductance of the glazing system, which is dependent on the radiative and convective heat transfer coefficient of the glazing cavity fill.

Figures 18 and 19 show the impact heat storage by the glazing cavity fluid has on the amount of heat transmitted into indoor space. The graph shown in Figure 18 shows that air does not store heat and therefore allows direct solar heat to be transmitted into indoor space. As long as the water stores heat as shown in Figure 19, it reduces the amount of heat transmitted into indoor space. Therefore, calculating only the thermal transmittance of the glazing system to assess its thermal performance is inadequate to characterize the nature of the fluid in the glazing cavity.

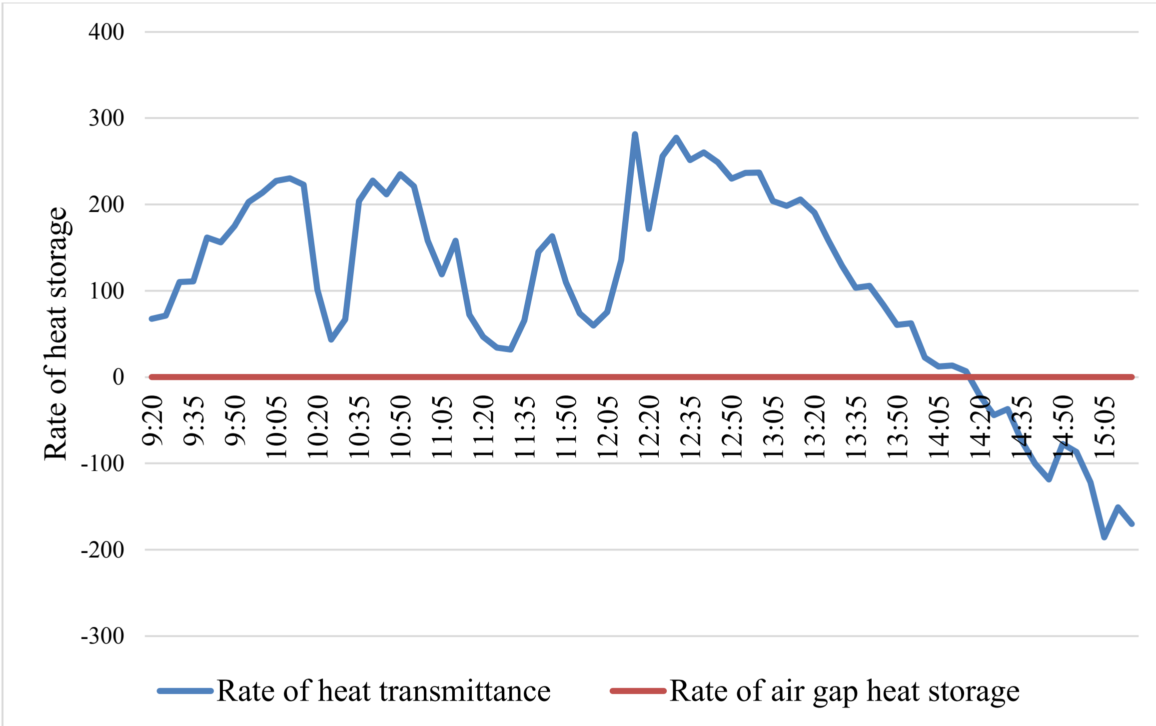

Figure 18. Graphs showing the rate of heat storage and rate of heat transfer by an air-filled glazing unit.

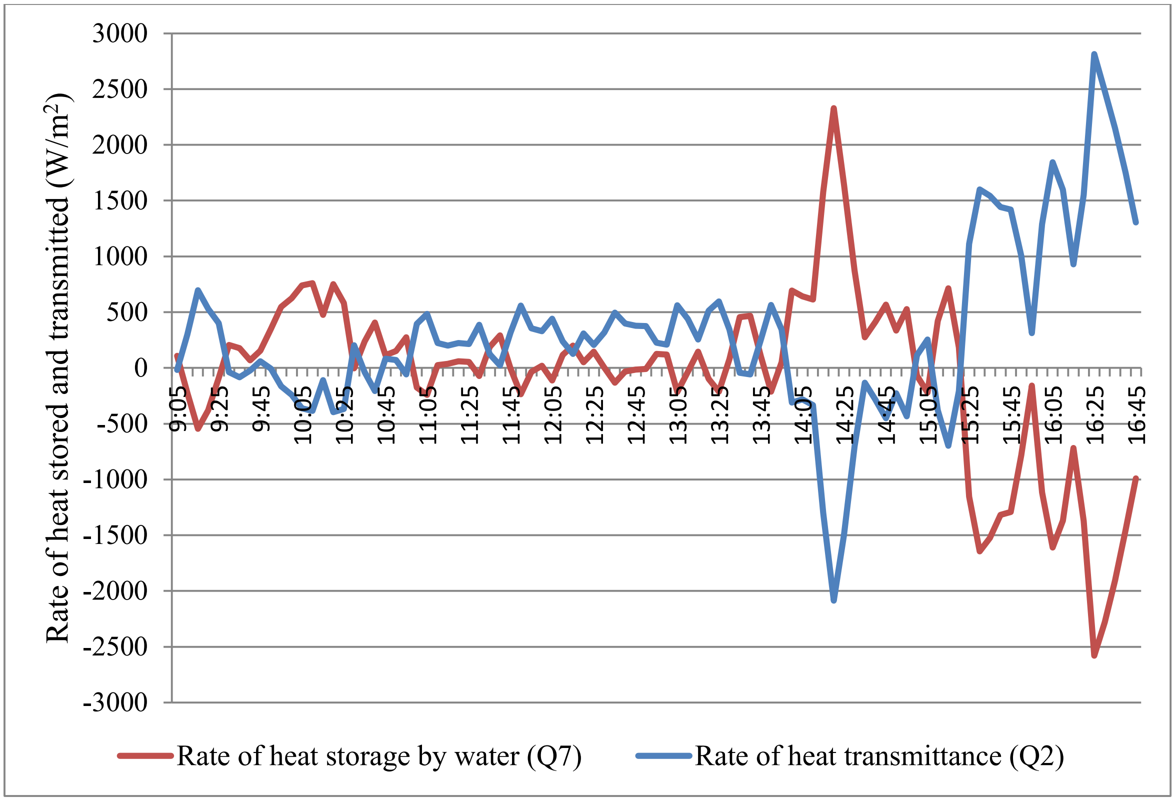

Figure 19. Graphs showing rate of heat storage by water and the rate of heat transmittance by the glazing unit.

Hypothesis 2: Allowing Flow Conditions

As shown in the trends observed in Figures 12 through 17, the water is able to flatten out thermal waves, therefore reducing the irregular fluctuations of indoor temperatures. However, as the temperature of the water in the gap increases, it radiates heat in and out of the room. These peak temperatures can be reduced by allowing the water to flow at a constant temperature in the glazing cavity through an inlet. The high convective heat transfer coefficient of the water will facilitate the dissipation of heat from the glazing surfaces, hence, maintaining an almost constant indoor temperature. Moreover, since water has a high absorption coefficient and opacity to solar near infrared radiation, the amount of heat transmitted by direct solar radiation will be reduced significantly. The equations below show the mass and volume flow rate required to dissipate the heat supplied by the sun's radiation. A change in temperature of 4°C was considered as the temperature difference in the water column to necessitate a flow condition in the cavity.

$$m = \frac{h}{c_p \times dT} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

$$Q = \frac{h}{c_p \times \rho \times dT} \ldots\ldots\ldots\ldots\ldots\ldots\ldots(4)$$

Where:

m is the mass flow rate (kg/s)

h is the heat flow rate (kW)

dt is the temperature difference

Q is the volume flow rate (m^3/s)

Cp is the specific heat capacity of water (4.184 kJ/kg-K)

ρ is the density of the fluid (kg/ m^3)

Using a heat flow rate of 543 W/m^2 for a glazing area of 1.3651 m^2, the mass flow rate to dissipate all the heat is 0.044290 kg/s, and the volume flow rate is 4.429E-5 m^3/s. The volume of the gap of the test specimen that was used is 0.0520 m^3, and therefore means a constant fluid flow velocity of 3.244E-5 m/s or 0.116 m/h is required during the peak periods to dissipate unwanted solar heat gain. This proves that hypothesis 2 can be accepted.

Hypothesis 3:

Tables 2 and 3 show the thermal and optical properties of the glass and glazing units that were used to compute the thermal performance of the glazing unit. Since they were the variables that were used in the computation and they were directly related to the thermal performance variables, hypothesis 3 can be accepted.

Conclusion

From the results and analysis of this research, the researcher was able to provide evidence to support the hypotheses stated in the Introduction section. For glazing units containing water fills, the thermal transmittance is higher, the solar heat gain coefficient is lower, and the visible light transmittance remains the same as compared to the glazing unit containing air-fill, hence, Hypothesis 1 is has been supported.

In evaluating the thermal performance of a water fill-glazing unit, it is imperative to talk in terms of rate of heat transfer and thermal storage than thermal transmittance. This is because the thermal transmittance gives no indication of the amount heat stored in a glazing unit. From the graphs in Figures 18 and 19, using water rather than air reduces heat transmitted into indoor space during peak hours of sunshine. The heat stored in the water column can then be removed from the cavity by allowing the water to flow at a velocity using the mass flow rate relation. Allowing the water to move at the right mass flow rate as indicated by the mass flow rate relation can reduce heat transfer in and out of the room by more than 50% as shown in the analysis section. Therefore, Hypothesis 2 can be supported. Moreover, since the calculation procedure was based on the thermal and optical parameters of the glass and the fluids, Hypothesis 3 can be supported.

Finallly, given that the visible light transmittance (VT) of the water-filled glazing system did not vary from the VT of the air-filled glazing unit as shown in the results of the simulations, a high VT can still be maintained. This helps to reduce the compromises that exist when a glazing unit with an emissive coating is used to reduce thermal transmittance.

Appendix A: Data

Table A1

Properties of Materials Used for the Experiments

Property	Value
Conductance of glass with air (W/m^2.K)	0.627
Thickness of glass (m)	0.00635
Width of air gap (mm)	0.038
Area of glass surface (m^2)	1.3651
Height of glass (m)	1.1684
Width of glass (m)	1.1684
Emissivity	0.84
Visible Transmittance	0.884
Area of expanded Polystyrene board (EPS) (m^2)	1.45
Thickness of EPS (m)	0.1016
Apparent conductance of EPS (W/m^{2}K)	0.049187

Table A2

Surface Temperatures of EPS and Quantity of Heat Gained or Lost through the Walls (15 August 2014)

Time	Out surface temp	In surface temp	Q (W)	Total Q (W)
9:55	25.4	28.4	0.21	0.83
10:00	25.8	28.4	0.18	0.72
10:05	26.0	29.6	0.25	1.02
10:10	26.3	29.6	0.23	0.92
10:15	26.7	30.3	0.26	1.03
10:20	27.0	30.5	0.25	0.99
10:25	27.3	30.9	0.25	1.02
10:30	27.7	30.9	0.23	0.90
10:35	28.0	30.8	0.19	0.78
10:40	28.3	31.0	0.19	0.75
10:45	28.7	31.8	0.22	0.87
10:50	28.8	32.2	0.24	0.96
10:55	29.2	32.1	0.20	0.81
11:00	29.6	30.8	0.09	0.36
11:05	29.8	31.6	0.12	0.48
11:10	29.9	33.3	0.24	0.95
11:15	30.3	32.6	0.16	0.64
11:20	30.5	33.4	0.21	0.83
11:25	30.9	32.4	0.11	0.43
11:30	31.1	33.6	0.18	0.72
11:35	31.5	32.9	0.10	0.41

Time	Out surface temp	In surface temp	Q (W)	Total Q (W)
11:40	31.7	33.4	0.12	0.49
11:45	31.8	33.6	0.13	0.52
11:50	32.3	32.1	-0.01	-0.05
11:55	32.3	33.5	0.08	0.33
12:00	32.6	32.0	-0.05	-0.18
12:05	32.5	33.1	0.04	0.17
12:10	32.8	34.3	0.11	0.43
12:15	33.0	31.5	-0.10	-0.41
12:20	33.2	30.7	-0.17	-0.69
12:25	32.9	35.5	0.18	0.74
12:30	33.3	32.6	-0.05	-0.21
12:35	33.1	33.8	0.05	0.18
12:40	33.2	33.5	0.02	0.07
12:45	33.5	31.4	-0.15	-0.59
12:50	33.2	35.5	0.16	0.64
12:55	33.2	36.6	0.24	0.96
13:00	33.1	38.0	0.34	1.37
13:05	33.4	33.8	0.03	0.10
13:10	33.6	31.7	-0.13	-0.53
13:15	33.8	31.6	-0.15	-0.61
13:20	33.3	38.1	0.33	1.33
13:25	33.7	39.3	0.40	1.59
13:30	33.5	35.9	0.16	0.66
13:35	33.8	32.3	-0.11	-0.43
13:40	34.0	32.2	-0.12	-0.49

Time	Out surface temp	In surface temp	Q (W)	Total Q (W)
13:45	33.7	40.3	0.46	1.84
13:50	33.5	41.3	0.54	2.17
13:55	33.3	42.7	0.66	2.65
14:00	34.2	33.1	-0.07	-0.29
14:05	34.1	33.1	-0.07	-0.27
14:10	33.1	37.8	0.33	1.31
14:15	32.2	42.2	0.70	2.82
14:20	31.0	41.5	0.73	2.94
14:25	31.0	41.4	0.73	2.93
14:30	31.7	44.7	0.91	3.65
14:35	32.6	35.3	0.19	0.78
14:40	34.7	32.3	-0.17	-0.67
14:45	34.4	35.7	0.09	0.36
14:50	33.2	39.3	0.42	1.70
14:55	34.2	33.9	-0.02	-0.07
15:00	34.6	32.5	-0.15	-0.59
15:05	34.4	32.2	-0.16	-0.62
15:10	33.9	36.2	0.16	0.63
15:15	32.9	38.0	0.36	1.43
15:20	32.3	42.4	0.71	2.85
15:25	31.8	40.1	0.58	2.31
15:30	33.1	36.0	0.20	0.80
15:35	32.8	38.6	0.41	1.63
15:40	33.4	36.2	0.20	0.79
15:45	33.2	35.9	0.20	0.78

Time	Out surface temp	In surface temp	Q (W)	Total Q (W)
15:50	33.4	34.7	0.09	0.36
15:55	34.0	33.3	-0.05	-0.19
16:00	33.8	32.3	-0.10	-0.42

Table A3

Temperature Data and U-value for Double-Glazing with Water on 8 Oct 2014

Time	T_{g4} −C	T_{g1} −C	T_{rm} −C	T_air −C	U-value
9:05	20.5	21.1	19.4	18.5	4.029
9:10	21.2	21.3	19.7	18.9	4.088
9:15	21.7	21.4	20.0	19.0	4.116
9:20	21.8	21.0	20.4	19.5	4.087
9:25	21.7	20.8	20.7	19.6	4.045
9:30	21.8	20.7	20.9	20.1	4.029
9:35	22.2	21.1	21.2	19.9	4.055
9:40	22.4	21.2	21.5	20.2	4.031
9:45	22.6	21.4	21.7	20.5	4.046
9:50	22.8	21.7	21.9	21.3	4.058
9:55	22.8	21.8	22.2	21.5	4.016
10:00	23.4	22.5	22.3	21.8	4.110
10:05	23.9	23.1	22.8	21.9	4.123
10:10	24.2	23.5	23.0	22.0	4.137
10:15	25.1	24.6	23.1	22.5	4.237
10:20	25.7	25.1	23.5	22.6	4.264
10:25	26.5	25.7	23.5	23.1	4.336
10:30	27.2	26.7	23.7	23.2	4.370
10:35	27.7	27.1	23.8	23.6	4.392
10:40	28.0	27.3	24.2	23.7	4.398
10:45	28.4	27.7	24.5	23.1	4.416
10:50	28.6	27.6	24.5	24.0	4.441

Time	Tg4	Tg1	Trm	T_air	U-value
	¬C	¬C	¬C	¬C	
10:55	29.1	28.3	24.9	23.6	4.468
11:00	29.1	28.3	25.1	23.1	4.463
11:05	29.0	28.1	25.2	24.1	4.455
11:10	29.2	28.2	25.2	24.6	4.472
11:15	29.3	28.5	25.5	23.5	4.458
11:20	29.1	28.2	25.6	26.5	4.444
11:25	29.2	28.4	25.9	24.7	4.452
11:30	28.8	28.0	26.4	28.0	4.375
11:35	29.0	28.4	26.0	27.9	4.428
11:40	29.6	28.9	26.1	28.8	4.466
11:45	29.8	29.5	26.2	28.9	4.482
11:50	29.9	29.4	26.4	29.5	4.479
11:55	29.2	28.8	27.3	27.6	4.363
12:00	29.0	28.3	27.1	29.1	4.369
12:05	29.1	28.5	27.0	27.8	4.362
12:10	29.0	28.5	27.2	29.4	4.351
12:20	29.6	29.2	27.2	30.5	4.421
12:25	29.5	29.2	27.7	29.4	4.364
12:30	29.9	29.7	27.8	27.8	4.397
12:35	29.7	29.4	27.6	30.2	4.398
12:40	29.6	29.2	28.2	30.3	4.330
12:45	29.3	29.1	28.5	29.3	4.248
12:50	29.7	29.4	28.4	30.3	4.327
12:55	29.8	29.7	28.5	29.5	4.325
13:00	30.1	30.1	28.8	28.5	4.320

Time	Tg4 ¬C	Tg1 ¬C	Trm ¬C	T_air ¬C	U-value
13:05	30.0	29.9	29.2	29.2	4.258
13:10	29.4	29.1	29.6	32.0	4.052
13:15	29.7	29.6	29.7	32.7	3.940
13:20	29.6	29.8	30.1	33.7	4.224
13:25	29.0	29.6	31.2	30.3	4.439
13:30	28.7	29.4	31.4	32.8	4.484
13:35	28.9	30.1	31.7	32.6	4.498
13:40	29.2	31.0	31.0	33.7	4.425
13:45	29.5	32.1	30.6	31.1	4.333
13:50	28.8	32.3	31.5	30.2	4.482
13:55	28.2	32.4	31.9	33.6	4.547
14:00	28.3	33.7	32.0	34.2	4.556
14:05	28.8	35.9	32.7	35.1	4.594
14:10	28.9	37.2	34.3	29.9	4.674
14:15	29.2	38.9	34.6	31.8	4.680
14:20	30.7	41.8	35.4	32.6	4.689
14:25	32.7	45.4	36.7	29.8	4.698
14:30	33.9	46.3	37.2	32.6	4.685
14:35	35.0	46.3	39.7	30.3	4.769
14:40	36.4	46.5	39.6	30.7	4.716
14:45	38.9	47.7	40.4	32.3	4.625
14:50	40.0	47.6	43.0	31.7	4.773
14:55	42.3	49.4	44.9	33.1	4.807
15:00	43.1	50.5	47.2	30.0	4.911
15:05	44.5	50.2	46.4	30.5	4.785

Time	Tg4 ⁻C	Tg1 ⁻C	Trm ⁻C	T_air ⁻C	U-value
15:10	45.8	51.1	46.2	33.5	4.591
15:15	47.2	52.7	48.2	33.5	4.747
15:20	49.1	54.6	49.5	33.3	4.680
15:25	49.5	54.6	48.7	32.9	4.763
15:30	47.9	52.9	47.6	30.0	4.585
15:35	46.7	51.0	48.9	29.8	4.844
15:40	44.0	46.5	48.4	31.8	4.925
15:45	43.5	46.2	51.2	30.5	5.047
15:50	41.2	42.7	53.3	32.8	5.134
15:55	42.1	44.6	54.3	29.8	5.152
16:00	41.4	43.2	54.5	30.8	5.158
16:05	39.0	40.9	55.7	30.7	5.187
16:10	38.1	39.5	54.8	30.9	5.171
16:15	36.8	39.2	54.4	29.7	5.162
16:20	35.5	38.1	54.7	27.4	5.169
16:25	29.7	31.8	49.4	26.6	5.011
16:30	25.8	26.0	46.2	26.3	4.939
16:35	23.1	22.8	44.5	25.7	4.904
16:40	20.2	19.7	43.5	26.0	4.883
16:45	18.7	17.9	42.6	25.1	4.864

Table A4

Temperature data and U-Factor for Glazing with Air on 27 Oct. 2014

Time	T_{g4} ⁻C	T_{g1} ⁻C	T_{rm} ⁻C	T_air ⁻C	U-Factor
9:20	22.8	22.4	18.2	20.8	2.529
9:25	24.0	23.0	18.8	21.3	2.619
9:30	24.8	23.4	19.6	21.9	2.657
9:35	25.5	23.7	20.2	22	2.677
9:40	25.8	23.8	20.8	22.3	2.684
9:45	26.1	24.0	21.3	22.6	2.696
9:50	26.3	24.2	21.9	22.9	2.700
9:55	26.4	24.4	22.4	23.3	2.674
10:00	26.5	24.9	23.1	23.6	2.615
10:05	26.7	25.4	23.8	23.9	2.527
10:10	27.6	27.1	24.7	24.1	2.475
10:15	28.3	28.1	25.4	25	2.395
10:20	28.5	29.1	26.4	24.8	2.510
10:25	27.5	28.0	26.3	24.1	2.507
10:30	26.8	26.8	26.4	23.5	2.383
10:35	25.7	25.5	26.5	24.2	2.480
10:40	26.2	25.8	26.9	25	2.546
10:45	26.5	26.5	27.5	24.8	2.374
10:50	26.9	27.0	28	25.7	2.494
10:55	26.5	27.3	28.7	25.4	2.633
11:00	27.0	27.8	29	26.1	2.649
11:05	26.8	27.9	29.5	25.9	2.685

Time	Tg4 ¬C	Tg1 ¬C	Trm ¬C	T_air ¬C	U-Factor
11:10	26.3	27.8	29.9	25.6	2.729
11:15	26.0	27.7	30.1	26.5	2.740
11:20	25.6	27.4	30.1	25.3	2.740
11:25	24.7	26.5	30	24.8	2.742
11:30	24.5	26.1	30	24.7	2.732
11:35	24.2	25.7	29.9	24.6	2.716
11:40	24.1	25.4	30.1	26.8	2.698
11:45	24.7	26.1	30.2	26.4	2.715
11:50	25.1	26.7	30.5	27	2.740
11:55	24.8	26.8	30.6	26.6	2.765
12:00	25.2	27.0	30.5	25.7	2.759
12:05	25.2	26.9	30.5	26	2.755
12:10	25.2	27.0	30.8	25.6	2.768
12:15	24.8	26.7	30.8	27.5	2.779
12:20	25.5	27.7	31.2	29	2.813
12:25	25.4	27.9	31.5	28.8	2.832
12:30	25.7	28.2	31.9	29.7	2.844
12:35	25.9	28.8	32.4	29.5	2.867
12:40	26.0	29.1	32.9	29.9	2.898
12:45	26.0	29.6	33.3	30	2.921
12:50	25.6	29.6	33.6	29.4	2.949
12:55	25.7	29.9	33.9	30.6	2.968
13:00	25.6	30.3	34.3	31.7	3.001
13:05	25.0	30.7	35.2	30.6	3.037
13:10	24.6	31.0	35.4	30.5	3.072

Time	Tg4 ¬C	Tg1 ¬C	Trm ¬C	T_air ¬C	U-Factor
13:15	24.3	31.8	36.3	30.6	3.115
13:20	24.3	33.0	36.9	30.1	3.147
13:25	24.2	34.2	37.9	29.6	3.191
13:30	24.1	35.6	38.8	29.4	3.225
13:35	24.0	36.4	39.8	28.6	3.248
13:40	23.4	36.2	41.3	29.9	3.264
13:45	23.7	37.4	42	30.1	3.291
13:50	23.0	37.1	43.7	29.6	3.302
13:55	23.2	37.0	44.6	30.5	3.301
14:00	23.8	38.3	45.7	29.6	3.323
14:05	24.0	38.3	46.8	29.4	3.322
14:10	22.1	36.0	47.9	29.6	3.328
14:15	22.8	36.4	48.8	29.7	3.331
14:20	24.2	38.0	49.3	29.9	3.335
14:25	23.9	38.3	50.8	29.8	3.347
14:30	23.8	38.0	51.2	31	3.372
14:35	24.3	39.0	52.8	30.3	3.371
14:40	24.8	39.5	53.9	30.7	3.379
14:45	23.1	38.4	53.9	29.8	3.382
14:50	23.1	37.6	54.2	31.5	3.380
14:55	21.9	36.8	58.1	31.4	3.279
15:00	22.9	38.1	56.7	31	3.276
15:05	23.4	38.4	57.7	32.4	3.285
15:10	22.2	38.2	57.5	29.8	3.283
15:15	20.4	36.4	58.5	30.7	3.291

Appendix B: Algorithm for Heat Transfer Analysis

$Q_1 = \gamma_{e1} G$, Reflected solar radiation at surface of outer glass……………………….(1)

$Q_2 = \tau_e G$, Solar radiation transmitted through the glazing system to the indoor environment…………………………………………………………………………...(2)

$Q_3 = h_{c1}(T_{g1} - T_a)$, Convective heat flow from surface 1 to the ambient……………(3)

$Q_4 = h_{c4}(T_{g4} - T_{rm})$, Convective heat flow from surface 4 to room space…………....(4)

$Q_5 = h_{r1}(T_{g1} - T_e)$, Radiative heat flow from surface 1 to the ambient environment, including the sky and surrounding solid surfaces…………………………………….…(5)

$Q_6 = h_{r4}(T_{g4} - T_s)$, Radiative heat flow from surface 4 to the room surfaces………..(6)

$Q_7 = \rho_w d_w C_w \frac{\partial \bar{T}_w}{\partial t}$, Rate of heat storage at the water volume…………………………(7)

$Q_8 = m_f C_f (T_{wf} - T_{wi})$, Rate of heat extraction by the water…………………….(8)

$h_{c1} = 2.8 + 3.0\vartheta$, Convective heat transfer coefficient of outer pane facing outside….(9)

$h_{r1} = \frac{\sigma(\theta_a^2 + \theta_1^2)(\theta_a + \theta_1)}{1/\varepsilon_a + 1/\varepsilon_1 - 1}$, Radiative heat transfer coefficient on the surface of the outer pane facing outside………………………………………………………………………..(10)

$h_{cw} = \frac{k}{D} Nu$, Convective heat transfer coefficient of the outer pane facing the room (cavity)……………………………………………………………………………(11)

$h_{c4} = 4.3$, Convective heat transfer coefficient of the inner pane facing room……….(12)

$h_{r4} = \frac{\sigma(\theta_4^2+\theta_s^2)(\theta_4+\theta_s)}{1/\varepsilon_4 + \frac{(1-\varepsilon_s)(H_{rm}+W_{rm})}{\varepsilon_s . 2(H_{rm}W_{rm}+H_{rm}L_{rm}+L_{rm}W_{rm})}}$, Radiative heat transfer coefficient of the inner pane facing room……………………………………………………………(13)

$Q_r = \tau_e I_n + (h_{c,4} + h_{r,4})(T_{g,4} - T_i)$, Quantity of room heat gain through window….(14)

Nomenclature

C Specific heat capacity, kJ/(kgK)

D,d thickness; depth, m

G solar irradiance, W/m^2

H height, m

h heat transfer coefficient, W/(m^{2}K)

k thermal conductivity, W/(mK)

L characteristics length, m

m mass flow rate, kg/s

Nu Nusselt number

Pr Prandtl number

Ra Rayleigh number

Re Reynolds number

Q heat flow rate, W/m^2

T temperature, ^{o}C

t time, s

v flow velocity, m/s

W width, m

Greek letters used

α absorptance

ε emittance

ɤ reflectance

Ɵ absolute temperature, K

μ dynamic viscosity, kg/(ms)

ρ density, kg/m^3

σ Stefan-Boltzmann's constant = $5.67 \times 10^{-8} W/(m^2K^4)$

τ transmittance

Subscripts

a ambient, air

c convective

e environment, effective

g	glass
i	inside
r	radiative
rm	room
s	room surface
w	water
1	weatherside glass surface
4	roomside glass surface

References

American Physical Society. (2015, January 27). *Energy units.* Retrieved from Policy and advocacy: http://www.aps.org/policy/reports/popa-reports/energy/units.cfm

American Society for Testing and Materials, ASTM C1199-12. (2012). *Standard test method for measuring the steady-state thermal transmittance of fenestration systems using hot box methods.* West Conshohocken: ASTM International. doi:10.1520/C1199-12

American Society for Testing and Materials, ASTM C1363-11. (2011). Standard test method for thermal performance of building materials and envelope assemblies by means of a hot box apparatus. West Conshohocken, PA: ASTM International.

American Society for Testing and Materials, ASTM E1423. (2014). *Standard practice for determining steady state thermal transmittance of fenestration systems.* West Conshohocken: ASTM International.

Apte, J., Arasteh, D., & Huang, Y. J. (2003). Future advanced windows for zero-energy homes. *ASHRAE Transactions, 109*(2), 871-882.

Arasteh, D., Goudey, H., & Kohler, C. (2008). Highly insulating glazing systems using non-structural center glazing layers. *The 2008 Annual Meeting. 114*, pp. 188-198. Salt Lake City: ASHRAE.

Butterworth, D. (1977). Introduction to heat transfer. Engineering design guide No. 18. Oxford: Oxford University Press.

Chow, T. T., Li, C., & Clarke, J. A. (2011). Numerical prediction of water-flow glazing performance with reflective coating. *Proceedings of Building Simulation*

2011:12th Conference of International Building Performance Simulation Association, (pp. 1127-1133). Sydney, Australia.

Chow, T. T., Li, C., & Lin, Z. (2011). Thermal Characteristics of water-flow double-pane window. *International Journal of Thermal Sciences, 50*, 140-148.

Department of Energy. (1997, January). Selecting windows for energy efficiency. *What's New in Building Energy Efficiency*.

Efficient Windows Collaborative. (2014, July 7). *Reflectance.* Retrieved from Commercial windows: http://www.commercialwindows.org/reflectance.php

Fulvio, A., Beccali, M., Cellura, M., & Mistretta, M. (2008). Building energy performance: A LCA case study of kenaf-fibres insulation board. *Energy and Buildings*.

Gil-Lopez, T., & Gimenez-Molina, C. (2013). Influence of double glazing with a circulating water chamber on the thermal energy savngs in buildings. *Energy and Buildings, 56*, 56-65.

Gueymard, C. A., & duPont, W. C. (2009). Spectral effects on the transmittance, solar heat gain, and performance rating of glazing systems. *Solar Energy, 83*, 940–953. doi:10.1016/j.solener.2008.12.012

Gustavsen, A., Jelle, B. P., Arasteh, D., & Kohler, C. (2007). *State-of-the-art highly insulating window frames - Research and market review.* Oslo, Norway: SINTEF Building and Infrastructure.

Incropera, F. P., DeWitt, D. P., Bergman, T. L., & Lavine, A. S. (2011). *Fundamentals of heat and mass transfer* (7th ed.). California, Los Angeles: John Wiley & Sons.

ISO. (2003). ISO 15099: Thermal performance of windows, doors, and shading devices...Detailed calculations. International Organization for Standards.

Jelle, B. P. (2011). Traditional, state-of-the-art and future thermal building insulation materials and solutions – Properties, requirements and possibilities. *Energy and Buildings 43*, 2549–2563. doi:10.1016/j.enbuild.2011.05.015

Josey, B. (1997). Glass for buildings - is it crystal-clear? *Structural Survey, 15*(1), 15-20. Retrieved from http://search.proquest.com/docview/216594620?accountid=15150

Judkoff, R. (2008). Increasing building energy efficiency through advances in materials. *MRS Bulletin, 33*(04), 449-454. doi:http://dx.doi.org/10.1557/mrs2008.88

Kim, J. T., & Todorovic, M. S. (2013). Tuning control of buildings glazing's transmittance dependence on the solar radiation wavelength to optimize daylighting and building's energy efficiency. *Energy and Buildings, 63*, 108-118. doi:http://dx.doi.org/10.1016/j.enbuild.2013.03.036

Kosny, J., Kossecka, E., Desjarlais, A., & Christian, J. (2001). *Dynamic thermal performance and energy benefits using massive walls in residential buildings.* Oak Ridge, TN: Oak Ridge National Laboratory.

Kosny, J., Petrie, T., Gawin, D., Childs, P., Desjarlais, A., & Christian, J. (2001). *Thermal mass - Energy savings potential in residential buildings.* Oak Ridge, TN: Oak Ridge National Laboratory.

Lawrence Berkeley National Laboratory. (2013). *THERM 6.3 / WINDOW 6.3 NFRC Simulation manual.* Berkeley, California: Lawrence Berkeley National Laboratory.

Lyons, A. (2007). *Materials for architects and builders* (3rd ed.). London: Elsevier.

Menzies, G. F., & Wherrett, J. R. (2005). Multiglazed windows: potential for savings in energy, emissions and cost. *Building Serv. Eng. Res. Technol., 26*(3), 249-258.

National Fenestration Rating Council Incorporated. (2004). NFRC 200-2004: Procedure for determining product solar heat gain coefficient and visible transmittance at normal incidence. Greenbelt, MD: National Fenestration Rating Council, Inc.

National Oceanic and Atmospheric Administration. (2015, March 23). *Glossary*. Retrieved from National Weather Service: http://w1.weather.gov/glossary/index.php?letter=d

Pe´rez-Lombard, L., Ortiz, J., & Pout, C. (2008). A review on buildings energy consumption information. *Energy and Buildings*(40), 394. doi: http://dx.doi.org/10.1016/j.enbuild.2007.03.007

Sawyer, K. (2014). windows and building envelope research and development: roadmap for emerging technologies. Washinton, DC: US Department of Energy.

Selkowitz, S. E. (1999). High performance glazing systems: Architectural opportunities for the 21st century. *Proceedings from Glass Processing Days Conference*, (pp. 1-11). Tampere, Finland. Retrieved from http://eetd.lbl.gov/node/50916

Stein, B., & Reynolds, J. S. (2000). *Mechanical and electrical equipment for buildings.* (9th ed.). New York: John Wiley & Sons, Inc.

Thomas, P. C., & Thomas, L. (1998, August). Advanced glazing systems in commercial buildings. *Environment Design Guide*, pp. 1-6.

Wasley, J. H., & Utzinger, M. (1996). *Glazing performance.* Milwaukee: Vital Signs.

Zhang, Z., Piatkowski, L., Bakker, H. J., & Bonn, M. (2011). Ultrafast vibrational energy transfer at the water/air interface revealed by two-dimensional surface vibrational

spectroscopy. *Nature Chemistry, 3*(11), 888–893.
doi:http://dx.doi.org/10.1038/nchem.1158