COMPARATIVE ANALYSIS OF GLAZING ALTERNATIVES – A CASE STUDY OF TEMPERATURE DIFFERENTIALS.

by

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ABSTRACT

MOJISOLA ADARA. Comparative Analysis of Glazing Alternatives – A Case Study of Temperature Differentials. (Under the direction of DR. GLENDA MAYO)

The demand on energy consumption is ever increasing, making it necessary to develop appropriate materials that can help maintain consumption levels. Windows in a building are very susceptible to heat loss and heat gain, which cause fluctuations in indoor temperature, and often results in the demand placed on air conditioning systems to regulate the indoor space temperature. In buildings with the appropriate type of glazing, considerable decrease in energy consumption can be observed as glazings possess thermal properties that help maintain the temperatures within the spaces. High temperatures within spaces are often from heat gain through window glazing therefore the type and design of windows are important considerations to reduce the heating and cooling needs. This study aims to examine a specific variable in glazing, temperature differential, in a hot and humid climate as an examination of one type of performance measurement. Ultimately, this can assist to provide a support for glazing selection and the design of windows in buildings.

A case study was conducted as part of a building renovation project at the University of West Florida. Research components were purposely built into the envelope of the structure which includes a 12-pane fixed window, constructed on the west side of the structure, with multiple types of glazing. Thermal sensors were attached to both the inside and outside of each pane to measure the surface conditions and readings were taken at 15-minute intervals for a period of 1 year. The main objective of the study was to assess the performance of glazing alternatives, compared to the anticipated performance based on the manufacturers' specifications, which; can assist in the selection of the most appropriate glazing.

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1 INTRODUCTION

1.1 General

Glass has been known and widely used for centuries, and further used as a glazing material for several hundred years. Window glazing is one of the most common uses of glass, but with recent developments in glazing technology, most windows especially in commercial building are created with complex coatings that enhance their function (Bell and Matthews, 1998). The enhancements with glazing types are driven by the need to reduce energy consumption in buildings without giving up the benefits windows provide to its users.

The built environment is a major consumer of energy and its environmental impacts are significant. Sustainable environment is achievable where crucial issues of energy conservation have been tackled (Hee et al., 2015). According to Huang, Niu, & Chung, (2014), the increasing levels of energy consumption in buildings can be controlled through the use energy efficient window designs. The windows in buildings are useful for creating a comfortable environment by providing ventilation, view, and lighting in a building (Stegou-Sagia, et al., 2007). The glass placed in openings is glazing and the use of glazing in building envelope facades has become a prominent way to introduce more daylight into a building. However, the glazing selection requires careful performance considerations, such as aesthetics and thermal control. This paper aims to evaluate, in a specific study, the result of temperature differentials, through a review of alternative glazing types.

1.2 Problem Statement

Although windows in buildings are multifunctional for providing ventilation and solar gain control amongst other benefits, they greatly influence the heating and cooling demands in winter and summer respectively (Cuce & Riffat, 2015). The glazing system consist of multiple layer skins, which includes an internal surface, an intermediate space and an external surface. These glazing surfaces have the capabilities to expel solar radiation and allow natural ventilation into an indoor space (when operable windows are used), thereby enhancing the thermal comfort and indoor air quality while conserving energy consumed for heating and cooling (Zhou & Chen, 2010). Regular windows often have poor U-values that result in some notable heat loss during winter and heat gain in summer which has led to the advancement of glazing technologies to help improve visual and thermal comfort of occupants while maintaining appropriate energy consumption levels.

1.3 Purpose of the research

This study aims to determine the thermal performance of four glazing alternatives against a control glazing installed in a case study using a functional building. Minimal research exists in a manner that compares the temperature control of glazing alternatives. The purpose of this research is to test the thermal control ability of five different glazing types in a predominantly hot climate. The significant difference in the thermal performance of each glazing will be validated in this study.

1.4 Research Objectives

This thesis will attempt to build on the existing knowledge of the thermal performance of glazing systems. A deeper look into the temperature differences of the glazing surfaces is intended to help provide a clear picture on the effect on the building occupants. The aim of this study is to utilize the existing standards for glazing alternatives in the context of performance with regards to heat transfer. The study involves building a glazing model of different types and a comparison analysis of the application of the glazing types by doing the following.

- Determine the thermal characteristic that may help the selection of glazing systems in buildings in warm, southern climates.
- Review past and recent literature to establish essential properties used in determining the thermal performance of various glazing systems
- Utilizing a case study, establish the best performance based on the temperature differentials between the inside and outside of the glazing.

While previous studies have determined that glazing installed in a building can influence the heating and cooling loads of the air conditioning and ventilation systems, this study takes a different approach to examine the thermal heat transfer in each glazing and test the ability of the glazing to minimize heat transfer based on the standards set the manufacturers

1.5 Research Hypothesis

It is understood that the manufacturer's specifications provide the expected performance levels for glazing. However, this research utilizes a functional building that is in operation, to test five different glazing types and their given specifications. Given the numerous variables that may affect the performance, this study only looks at the differential between the outside and inside glass temperatures. Although this is not an indication of overall performance, it is a strategic review of an important variable in southern hot climates.

1.6 Research Design

The effect of glazing has been documented through studies to show the thermal and energy benefits for building users, energy consumption control and other environmental outcomes. This research seeks to examine the effect of glazing on indoor thermal control that results in these benefits for occupants and energy control. A comparative analysis will be done on a case study of different glazing configurations under the same weather and physical conditions. The case study involved a 12-pane window, setup to provide temperature measurements to facilitate this study. The daily temperature measurements from the surfaces of each glazing was collected and gathered for analysis in this study.

1.7 Significance of the Study

Glazing is a widely used material in buildings (residential and commercial) because of the numerous benefits (ventilation, daylighting, aesthetics) it offers to its users. In spite the many advantages of glazing, problems with high solar gains/loss are still associated with glazed buildings, which can result in overheating of spaces and excess use of air conditioning system to regulate temperatures. The need to prevent overheating and control energy consumption in glazed building makes it necessary to be knowledgeable about the thermal performance of glazing installed in the envelope of a building. The significance of the study is to compare the thermal performance of different glazing types in an operable building and review as compared to the specified performance.

1.8 Scope and Limitations of the Study

The study focused on the thermal performance of glazing with a case study conducted in Pensacola, Florida, a predominantly hot climate region. The data was also gathered for a limited period of one year on a small number of glazing types. The study examined the heat transfer between the selected glazing based on how they are expected to perform (regarding the heat transfer) according to the specifications. The location of the study also limited by the set orientation since the glazing is installed on a west orientation of the building in a southern climate region.

2 LITERATURE REVIEW

2.1 Introduction

Windows are the most common fenestration style and play a very important part in providing optimum illumination as well as favorable thermal comfort levels in a building (Huang et al., 2014). The primary purpose of windows, according to Dwyer (2014) is to admit daylight for aesthetics, while maintaining a barrier against the encroachment of external weather elements into the building space. The open view also provided through these windows are considered a desirable feature especially in high-rise building where the glazing area has significant effect on building energy consumption (Huang et. Al., 2014).

According to Cetiner & Özkan, (2005), glass facades are often preferred in buildings based on a number of factors such as the amount of time taken to install it, aesthetics, durability, low maintenance required, and being lightweight. However, these facades can often pose a disadvantaged increase in loads on the cooling and ventilation systems in the building. Rezaei, et al., (2017) described windows as the part of the building most vulnerable to heat gain and heat loss resulting in a substantial need for attention to cooling and heating spaces. A high amount of electrical energy is consumed to meet this cooling and heating need using air conditioner devices to adjust temperature within living spaces and buildings.

Pérez-Lombard et al. (2008) stated that the energy consumption in residential and commercial buildings in developed countries represent 20 - 40% of the total energy used. The energy consumed is mostly used for heating or cooling space in residential buildings and for lighting in commercial buildings (Hee et al., 2015). Space heating accounts for 32-33% of the total energy consumed in residential and commercial buildings respectively according to the International Energy Agency (Ürge-Vorsatz, et al., 2015). The introduction of a glazing system in instances where there is an increase in heating and cooling loads, can help address the conflicting needs such as heating cooling and lighting (Cetiner & Özkan, 2005). The energy performance in a building is dependent on the building envelope particularly the window, thus, attention should be given to the design and planning of this fenestration to fulfil its nature and maintain a balanced energy performance (Hee et al., 2015).

With proper glazing systems and materials, there is a potential for a considerable amount of the energy consumption to be reduced. The glazing material historically used initially in windows was clear glass. Although the clear glass `was durable and permitted lighting into the building, it had very little resistance to heat flow. A proper glazing material could be useful to control solar heat gains during the summer season and to reduce cooling energy use, but in winter, the reduction of solar gains can overcome the reduction of thermal losses and increase the energy needs (Pal, et al., 2009).

2.2 Evolution in Glazings

The use of double skin facades in buildings provide opportunities to tackle problems of energy consumption and thermal balance therefore improving the sustainability of buildings (Ghaffarianhoseini et al., 2016). According to Ghaffarianhoseini (2016), the first double-skin facade (DSF) observed in a building was in Germany in 1903 with attention given to weather conditions, and daylighting improvement. The evolution of glazing began in the 1920s with the development of laminated glass and later a development of coated products in 1970s. The laminated glass made by bonding panes together with a layer of polyvinyl butyral (PVB) and subjected to heat and pressure creates a bond that improved its safety and acoustic insulation capabilities among other properties. In the 1970s, the need to have a glass that was not only safe and durable but also visually aesthetic resulted in the development of the coated glass (Dwyer, 2014). This development in glass according to Dwyer, (2014) provided additional comfort with its low-emissivity and solar control properties. A combination of both glass properties reduce the reflectance and is now widely used in buildings.

Further research into glazing according to the US Department of Energy (U.S. DOE, 1994) resulted in the creation of materials that provide improved window efficiency and performance for building users. The energy efficiency in windows is represented by the U-value and the solar heat gain coefficient. The U value is the measure of conductance of heat. Where the U-value of a window is low, the window loses less heat than one with a higher U-value (U.S. DOE, 1994).

The solar heat gain coefficient (SHGC) on the other hand was originally called a shading coefficient before the mid-90's which was used to compare glazing solar control under varying conditions. However, shortcomings were observed in the performance of the shading coefficient such as not including the frame effects in solar control, and a loss in accuracy with sun positions at higher angles which eventually resulted in its replacement by SHGC (Carmody et al., 2004). The windows standards changed from the shading coefficient to SHGC which is defined as "*that fraction of incident solar radiation that actually enters into a building through the window assembly as heat gain*" (Carmody et al., 2004). The adjustment made to SHGC considered the entire window assembly. The shading from the frame as well as the ration of glazing and frame also influenced the SHGC (Carmody et al., 2004).

Innovations in glazing over recent decades has brought about some enhanced properties and appearance options. For example insulating glass with two or more layers provides better thermal performance, tinted glazing with different colors reduces heat gain and glare while the coatings on glazing have heat resistant and aesthetic functions (John Carmody et al., 2004). The multiple layered glazing also known as insulating glazing unit (IGU) often have spacers around the edge of the glazing or contain low-conductance gases in between the glazing spaces (John Carmody et al., 2004). To ensure optimum performance, IGUs are framed with either aluminum, steel, wood plastic or a composite material. Carmody et al. (2004) suggested that technological advances in glazing gives manufacturers control over the characteristics glazing materials exhibit with solar transmittance. The properties of glazing materials such as glass or plastic are adjusted with coatings placed on their surfaces to ensure optimization for daylighting and solar heat gain control.

2.3 Glazing Selection

Façades are a main component of building envelopes that have a crucial role to play in controlling the interactions between outdoor and indoor spaces and protecting indoor environments (Ghaffarianhoseini et. Al., 2016). In making design decisions about windows, aesthetics and costs are often the major factors in usually considered. Other requirements such as air and water tightness, as well as structural and acoustical performance can also influence the window design. However, the need to reduce unwanted heat loss and heat gain has become a major energy related issue in window design. (Carmody et al., 2004). The heat exchange between glazing and the space users occurs is three major ways. They include: "the long-wave heat exchange between the human body and the window inside surface, the short wave (solar) radiation which penetrates through window glass and falls on the human body and drafts induced by cold air drainage off the window surface" (Cuce & Riffat, 2015). Windows are not a primary determinant of human thermal comfort but their impact on buildings becomes noteworthy when their inside surfaces are very hot or cold, the building occupant is very close to the window, or when solar radiation passing through the window is very high (Cuce & Riffat, 2015). To this end comprehensive energy efficiency measures can be adopted to reduce the increasing levels of energy consumed to reduce the unwanted heat loss and gain and improve building efficiency (Aldawoud, 2017).

Window glazing selection is one of the major issues in designing a window. Windows designs today focus on U-values and energy efficiency (Dwyer, 2014). The energy performance is actually determined by the U-values and the solar heat gain coefficient (SGHC) (Jaber & Ajib, 2011). The U-value indicates the rate of heat flow due to conduction, convection, and radiation through a glazing because of a temperature difference between the inside and outside. Therefore, the higher the U-value the more heat is transferred. The department of energy suggested that windows chosen should have U-values in line with the current standards set by the American society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE), U-values that are calculated for window with the frame and not just the center of the glass and finally, U-values that represent the same size and style of window. In recent years, there have been advancement in glazing to help control the heat gain and heat loss in a building. Some of the advancements include double and the triple pane glazing with different types of coatings.

2.4 Types of Glazing

The major types of coatings include low-emissivity (low-e), spectrally selective heat absorbing or reflective glazing, gas -filled windows and windows that incorporate a combination of features.

2.4.1 Low-E Glazing

The ability of a material to radiate energy is known as its ***emissivity***. Emissivity is one of the important components in window heat transfer, hence to reduce a windows emittance is to improve its insulating capabilities (Carmody & Haglund, 2012). The aim of low-e materials is to reduce heat transfer through thermal radiation (Jelle et al., 2015). According to the DOE (1994), a low-e glazing has a special coating that reduces heat transfer between windows. The coatings in a low-e glazing are thin, nearly invisible metal oxide films that placed directly over the glass surfaces or placed as a plastic film between two or more panes.

The side of the glass with low-e coatings is placed to face the air spaces within windows which blocks a significant amount of heat transfer, hence reducing the heat flow between the panes (Carmody & Haglund, 2012). Low-e coatings are applied as soft coats or hard coats. Soft coats also referred to as metal-based multilayer coatings, are applied to the glass after it has hardened (Jelle et al., 2015). Soft low-e coatings are observed to become easily damaged when exposed to water and air and have limited shelf life, however, these coatings are used because it allows a high transmission of light into a building space and offers a low U-factor very useful in winter.

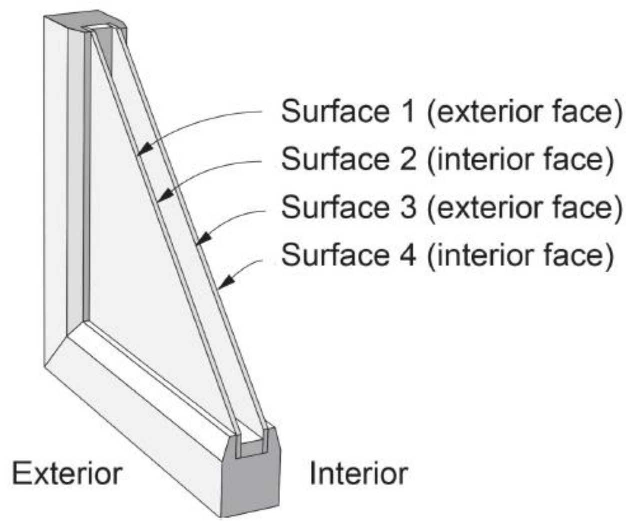

Figure 2.1: Low E glazing. (Carmody, 2012)

On the other hand, the hard low-e coatings are more durable and usable in retrofitted applications. The hard coats also referred to as pyrolytic coatings or on-line coatings are formed as a result of applying the low-e coating during the production of the glass (Jelle et al., 2015). However, in terms of energy performance, the hard coat low-e films have poorer performance than the soft coat films.

Coating Placement: In a double pane window, the placement of a low-e coating within the air gap influences the SHGC but not the U-factor (Carmody & Haglund, 2012). The low-e coating is placed on the outer surface (#3) of the inner pane during summer or heat periods to reflect the heat into living spaces (see figure 2.1). In cooling climates, the coating is placed on #2 surface to reduce solar heat gain and maximize energy efficiency.

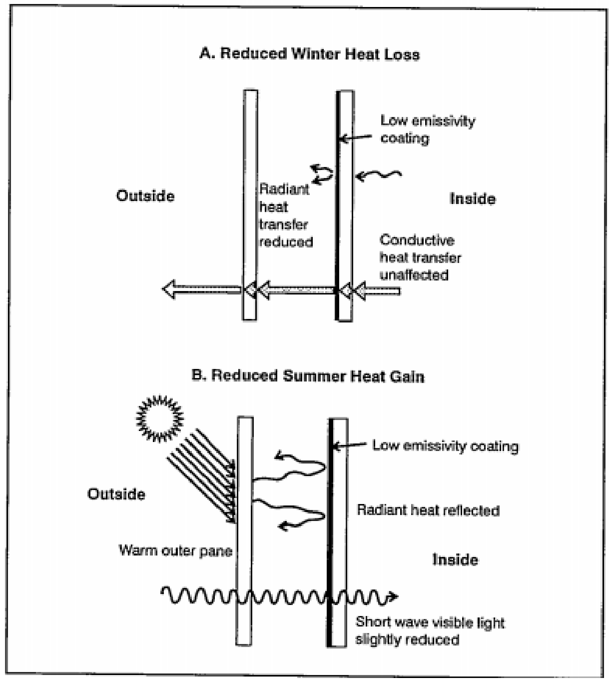

Figure 2.2: Low-e glazing reduce heat transfer. (DOE, 1994)

2.4.2 Heat Absorbing Glazings

Glass is obtained in different tint colors which can absorb the solar heat, block daylight and increase visual privacy (Carmody et al., 2004). Tinted glazing also referred to as heat-absorbing glazing, can absorb some and possibly all the solar spectrum. The solar energy absorbed by the glass are transformed to heat within the glass consequently raising the glass temperature some of which can later transfer into the facility via radiation and convection (EWC, 2019). According to DOE (1994), gray and bronze tinted windows reduce the penetration of light heat into a building. These common colors (gray, bronze and blue-green) do not overly interfere with the view and retain their transparency while fulfilling its function (Carmody et al., 2004). Traditional tinted glazing (bronze or grey) often result in a tradeoff between visible light and solar heat gain as it decreases glare but also reduces visual transmittance into a building

2.4.3 Spectrally Selective Glazing

According to Kim, et al., (2017) spectrally selective coating in glazing provide daylighting and permits high transmittance while blocking near infrared radiation that cause heat gain. This glazing is a high performing tinted glass developed to address the problem of reducing day light faced by the traditional tinted glazing (Carmody et al., 2004). Considered as the latest low-e technology, spectrally selective coatings cut out up to 70% of the heat usually transmitted through clear glass and allows the full amount of light to be transmitted into the space (DOE, 1994). Spectrally selective coatings are known to select specific portions of the energy spectrum such that the desirable wavelengths of energy are transmitted and others specifically reflected (Carmody & Haglund, 2012).

The energy savings abilities of the selective coating can reduce the space cooling requirements in hot climates by about 40% (DOE, 1994). These coatings can be applied to glass to create a system that can increase or decrease solar gains. Glazing with spectrally selective coatings are known to have the ability to maximize the amount of visible light that can be permitted into a building and minimize the amount of solar heat that can get into the building. For instance, a standard clear glass has an emittance of 0.84 over the long-wave portion of the spectrum, meaning it emits 84% of the energy possible for an object at its temperature (Carmody & Haglund, 2012) (pg 17).

2.4.4 Gas Filled Glazing

Air is a good insulator but not as good as other gases (such as argon, carbon dioxide, krypton, and xenon) which have lower thermal conductivities. The presence of air in multi-pane units provide an insulating effect for the glazing system but also gives room to the development of conduction and convection currents. In such cases, an alternative use of gas fills helps to reduce the heat transfer properties of the glazing (Deal et. al, 1998). Deal (1998) suggests that special coatings can be combined with gas-filled units to achieve high insulating values.

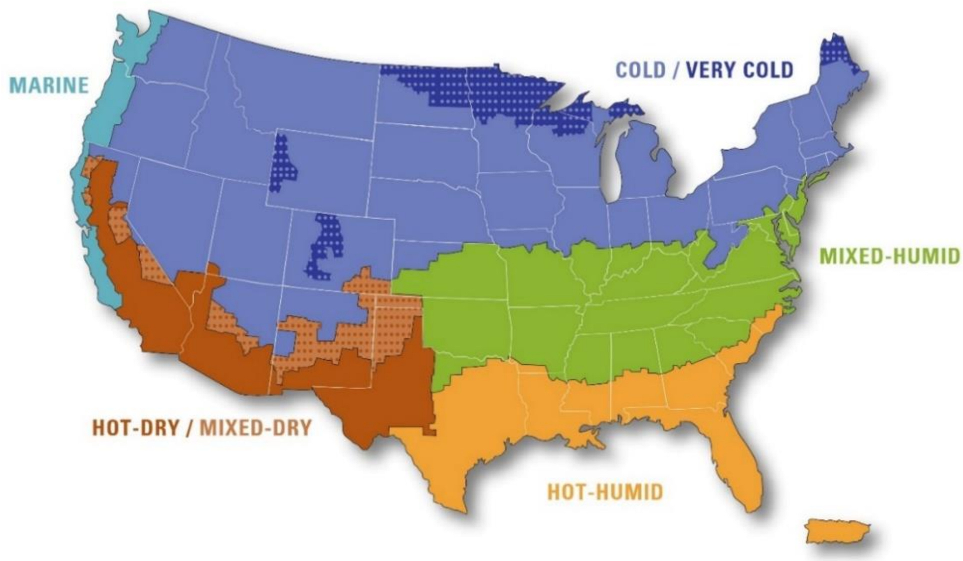

Figure 2.3: Building America Climate Zone Map (EERE,2018)

To help the window selection process, the efficient windows collaboration (EWC, 2012) created a window selection tool that uses the basic thermal and optical properties (U-factor, SHGC, VT) of a glazing to determine the most cost efficient window. The tool has been able to help users compare how energy cost are affected by the glazing types and provide information on manufacturers of specific product options. However, the tool makes no provision for selection based on the temperature balance in the different glazing options provided, which is one of the reason behind an increase in a building's heating and cooling costs. The Italian legislation according to Gasparella et. al, (2011), earlier acted on the solar transmittance of glazing with an intention to control summer solar gains by giving maximum allowable solar transmittance values in absence of other solar control devices.

2.5 Energy Related Properties of Glazings

The flow of heat through a window occurs in three major ways; radiation, convection and conduction. Conduction describes the flow of heat through a solid, convection is the transfer of heat by the movement of gases and liquids while radiation is heat travelling through space. These three methods of heat transfer interact and influence the performance of window glazings (Carmody & Haglund, 2012). There are four main properties that affect glazing energy performance and they include: transmittance, reflectance, absorption and emittance (Carmody et al., 2004). These properties refer to the way solar energy is transferred with glazing.

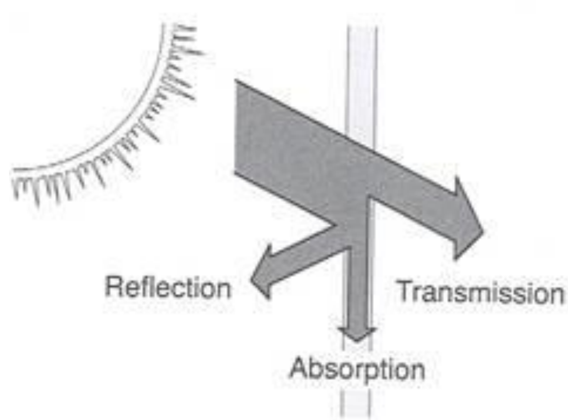

Figure 2.4: Heat flow through a glazing material. Source: Carmody et al., 2004)

2.3.1 Transmittance: refers to the amount of radiation that can pass through glazing (John Carmody et al., 2004). Transmittance can be for different types of energy or light such as visible transmittance. Visible transmittance of glazing describes that ability of the glazing to provide daylighting effectively and a clear view to the space where it is used. A good glazing should permit just the right amount of light required to allow for energy savings within a space. A good example is the tinted glass and clear glass, where the former has a lower visible transmittance. (Carmody et al., 2004). The solar heat gain to a building is reduced using a glazing with less transmittance than a clear glass (Boyce et al., 1995). This reduction is evidenced by an increase in the energy utilized for heating and a decrease in the energy utilized for cooling making low transmittance glazing the most valuable in cool climate dominated areas (Boyce et al., 1995).

2.3.2 Reflectance: Lights reflects at glass surfaces. The reflective abilities of glass depend on factors such as the type of glazing material, quality of glass surface, coatings and the angle of incidence of light (Carmody et al., 2004). For glazing, the angle at which the light strikes the glass influences the amount of light that is reflected rather than transmitted or absorbed (Carmody et al., 2004). The reflect nature of a glazing accounts for the mirror like surface it displays in low light conditions because the amount of light passing through from the darker side is less than the light reflected from the other side. The variation in the reflectance of energy by coatings on glazing account for the high-performance of low-E coatings according to (Carmody et al., 2004).

2.3.3 Absorptance: Absorption occurs where the radiant energy is neither transmitted through a glass nor reflected off the glass surface. The radiant energy absorbed by the glass is converted into heat energy, which results in the rising temperature of the glass. (Carmody et al., 2004). The absorptance of glass increases with the use of glass additives. For instance, clear glass absorbs very little visible light while dark-tinted glass absorbs more. Tints are common glass additives used to reduce the solar heat gain coefficient and control glare by blocking out some amount of radiant energy. (Carmody et al., 2004) describes absorption as the least efficient way to control energy consumption in buildings, however, its use is more valuable in greenhouses as it allows the transmission of solar energy but blocks the retransmission of low temperature heat energy generated inside the greenhouse and radiated back to the glass.

2.3.4 Emittance: According to (Carmody et al., 2004), solar energy absorbed by glass is either convected away by moving air or reradiated by the glass surface . The emissivity of glazing describes its ability to radiate energy. Heat emission is described as one of the prominent heat transfer pathways for window glazing, and when reduced can improve the window's insulating properties. Clear glass can to emit up to 84 percent of energy for an object at room temperature (Carmody et al., 2004).

2.6 Determinants of Thermal Performance of Glazings

In addition to the energy related properties that affect energy performance, Carmody (2004) identified some common energy related properties used to quantify the energy performance of glazing. They include the insulating value (U-factor), solar heat gain coefficient (SHGC): which is the ability of the glazing to control the solar heat gain, visible light transmittance (VT) and the air leakage control. The property being considered is the insulation effects of window-glazing material which characterizes the heat gain or loss through building windows and the rating factors include the solar heat gain coefficient (SHGC), the thermal transmittance (U value). The rate of heat transfer through a glazing system is considered proportional to the difference in air temperature between indoors and outdoors where air leakage is disregarded (Deal et. al, 1998).

2.6.1 U-factor (Insulating Value)

One of the major concerns about windows is their ability to control heat gains and loss. A window's capacity to withstand heat transfer is referred to as its U-factor (Carmody & Haglund, 2012). The U-factor of a glazing represents the overall heat transfer rate or insulating value. Where the temperature outside differs from inside temperature, heat is either lost or gained through the glazing by actions of conductance, convection and radiation (Carmody et al., 2004). Heat tends to flow from the inside of a window to the outside in winter and vice versa in summer. In windows, the U-factor is the total heat transfer coefficient of the system. It represents the heat flow per hour through each square foot of window for a 1 degree Fahrenheit temperature difference between the indoor and outdoor temperature (Carmody et al., 2004). U-value is expressed in units of Btu/h·ft2 ·°F (U.S.) or W/m 2 ·°K. According to Carmody et al. (2004), the U-factor of the glazing are influenced by some factors. They include the total number of glazing layers, the dimension of the glazing, type of glass within their cavity and the attributes of the coatings on the glazing surface. In a case where the U-factor on a glazing in a vertical position has been determined, a change in the mounting angle affects the glazing's U-factor. Hence the lower the U-factor of a glazing the higher the resistance to heat flow and the better the insulating properties. Such low U-factors are most useful in heat-dominated climates and beneficial in cold-dominated climates (Carmody & Haglund, 2012).

2.6.2 Solar Heat Gain Coefficient (SHGC)

The term solar heat gain originates from the direct radiation from the sun or reflected from the ground and other surfaces (Carmody & Haglund, 2012). The solar control characteristic in glazing was initially referred to as the shading coefficient (SC) until the mid-90's when it was changed to solar heat gain coefficient by the NFRC and ASHRAE. Heat is gained through windows by direct or indirect solar radiation and where solar radiation transmit into the interior of a building, some gets absorbed into the glazing frame thereby contributing to the overall solar heat gain factor (John Carmody et al., 2004). Solar heat gain coefficient represents the window's ability to control heat gain through windows. SHGC is a notable factor that determines the cooling loads in buildings and is expressed as a dimensionless number from 0 to 1. Hence the lower a window's SHGC, the less the solar heat it transmits and vice versa (Carmody & Haglund, 2012). Energy consumption is observed to increase as SHGC increases in the absence daylight controls. A double-pane insulating glass unit (IGU) usually has a SHGC of about 0.70. This value decreases when a tint is added to the glass and can be decreases even more when adding a low-solar gain low-e coating. (Carmody & Haglund, 2012). Although solar heat gain provides heat in the winter, it can also result in overheating in the summer. In order to get the best balance of solar heat gain in a building, factors such as climate, orientation, and shading conditions need proper consideration (Carmody & Haglund, 2012).

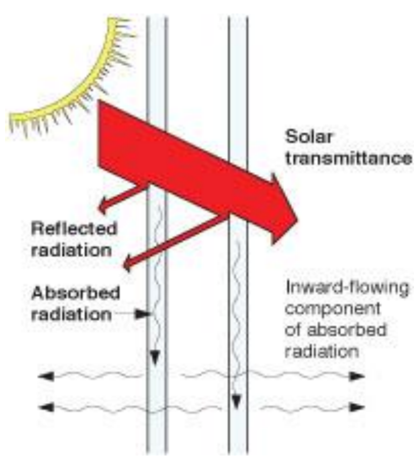

Figure 2.5: Components of Solar heat gain. Source: (Carmody et al., 2004)

2.6.3 Visible Transmittance (VT)

This is an optical property of glazing indicates the amount of visible light transmitted through a glass. VT is an important factor in determining also known as visible light transmittance, this property impacts energy consumption by providing daylighting that reduces energy to be consumed on electric lighting (Carmody et al., 2004). Hence a high VT indicates that there is more daylight in a space which is capable of reducing electric lighting and the associated cooling loads (Carmody et al., 2004). The value of a VT mostly varies between 0 and 1. These values are mostly influenced by the glazing type, the number of panes and the type of coatings used on the glazing (Carmody & Haglund, 2012). For instance, the VT value of double and triple pane windows vary between 0.30-0.07. VT also decreases where low-e coating or tint is added to a glazing. The use of tint in glazing can reduce the amount of solar energy transmitted through the glass and inhibit the amount of daylight (EWC, 2019). To tackle the problem of reduced visual transmittance from the traditional tint glazing, a high-performance tinted glazing known as spectrally selective glazing can be used in such a facility.

2.6.4 Air Leakage

Air leakage through cracks and the frame of windows can result in heat gain or loss in spaces. A lack of tightness in the connection between glass and the window frames can result in condensation, infiltration and corrosion of the glass and metals elements (Mylona, 2007). AL as a property is often quantified in the amount of air (cubic feet or cubic meters per minute) passing through a unit area of window (square ft or square meter) under given pressure conditions. The lower the AL, the less possibility for air to pass through cracks in a window Hence, a window with an AL less than 0.30, should not be selected (Carmody &

Haglund, 2012). Air leakages in windows can be from improper installation. Irrespective of the type of glazing and frame used in a window, the performance of that window depends a lot on the installation. A properly installed window must prevent air leakage and reduce heat loss and condensation around the window

2.7 Factors That Influence Glazing Performance

In designing low energy buildings, construction details of walls, floors, roofs and window need to be properly considered (Hassouneh et al., 2010). The glazing system is considered the weakest part of the building and responsible for significant amount of heat gains and loss (Alwetaishi, 2017). However, it provides a thermally tolerable internal environment and reduces building energy consumption. Understanding the thermal and energy performance of glazing requires an understanding of the heat transfer relationships between building parameters and external parameters (Jaber & Ajib, 2011). The thermal load resulting from fenestration need to be managed by an air conditioning system since windows permit the penetration of sun rays into a space of a building (Hassouneh et. Al., 2010). This thermal load is a negative element in summer, and a positive one in cold weather. The thermal performance of glazing is not only based on the material used but also depends on other features such as dimensional characteristics and other component properties (Alwetaishi, 2017). Carmody & Haglund, (2012) highlighted some key factors that influence the performance of glazing to include the glazing area, shading and orientation.

2.7.1 Glazing Area

The need for limiting window areas to control energy use have been reduced by high performance windows (J Carmody & Haglund, 2012). The glazing area has a notable impact on energy use especially where conventional windows are used but the impact can be reduced with the introduction of low-e windows. For instance, the low U factor in triple-glazed low-e windows limits heat loss to a great extent that the glazing area may not be considered as a factor in heating energy use. Carmody (2012), suggests that the increased energy use in cooling season (Northern zone) caused by solar heat gain through large glazing areas can be controlled by shifting the window area to preferred orientations and employing shading strategies.

2.7.2 Shading

Shading devices have been used to control solar gain and daylighting through windows for a longtime. An increased solar gain in winter and a decreased solar gain in summer are desirable in heating and cooling climatic conditions respectively. Shading provides glare control and thermal comfort but more shaded conditions in buildings can increase heating costs in cold climates (J Carmody & Haglund, 2012). The best way to shade a window is on the outside before the sun hits the window. According to (Zhou & Chen, 2010), the shading system provided over a glazing installed in the façade of a building can protect the building from solar heat gains in summer or act as a preheater for air in winter. It is vital to have a detailed knowledge of the thermal properties of the shading device to be used in a building to ensure its effectiveness. A good example of the shading devices utilized in building are roll screen and venetian blinds. Overhangs, awnings, solar screens and landscaping are also good examples of effective exterior shading elements. For hot climates, Carmody suggests that a combination of good shades with a low SHGC window is one of the best ways to reduce solar heat gain. The authors further recognize that the use of windows with low SHGC is more important than shading and such windows can reduce energy costs for different weather conditions.

Through a review of the thermal and optical properties of glazing with venetian blinds, shading devices were seen to play an important role in solar gain control and in the amount of daylight received through windows (Breitenbach et al., 2001). For an optimal design and effective use of these shading devices, the authors (Breitenbach et al., 2001) emphasized the importance of being knowledgeable about the thermal properties of the shades before they are installed in the building. The study considered two types of glazing with integrated Venetian blinds. The first with an adjustable blind which gave flexible control of luminous and total solar energy transmittance suitable in actual weather conditions and user requirements while the second type was with a fixed blind at an angle that can reduce transmittance at high solar altitudes and provide seasonal control of heat gain. The study concluded that the performance of a glazing was a function of the angle of incidence of the venetian blind and further developed a model that can predict the performance of the glazing used in the study based on the angle of incidence of the shading device (Breitenbach et al., 2001). Although the model will be useful to evaluate the performance of the glazing used in the research, its application across other types of glazing and for glazing without shading is limited.

2.7.3 Orientation

Window orientation in a building is mostly determined by the views and other factors other than solar gain (Carmody & Haglund, 2012). According to Carmody, orienting a window according to the zone they exist can control solar heat gain and reduce energy costs. Buildings in the northern zone require a lot of heating and a window orientation towards the south can increase the solar heat gain and reduce heating energy use. In a central zone that requires both heating and cooling, orienting the window towards the south will result in high solar heat gain. Although this is beneficial during the winter, some shading devices can be used to reduce the heat gain in summer. In the southern zone, where the climate is cooling dominated, the windows are mostly oriented towards the north or to the south where overhangs can be used to reduce the impact of the sun. In cases where windows with lower SHGCs are used, the impact of the window orientation is negligible, however, where windows with high SHGC are used in areas of intense heat, orientation has a significant impact. In a review of the influence of window designs on glazing performance, Carmody (2012), concluded that high performance windows can increase efficiency at any orientation. For instance, a triple-glazed low-e windows in a north-facing orientation reduces energy use than a double-glazed window in a south-facing orientation.

2.8 Review of Existing Literature in Glazing Performance

Glazing and facades have been a notable element of architectural design expression. Glass facades are used in building projects for the aesthetics, thermal insulation and daylighting potential they offer. Glazing is an important part of a window, and the presence of window glazing in buildings provide not only daylighting benefits but also energy efficiency through heat gain or loss (Hee et al., 2015). Most window components are known to have glazing and the glazing can either be a single pane of glass or a multilayer pane with air spaces in between (Carmody et al., 2004). Over the years, there have been studies in different countries focused on the potential energy and thermal performance of various building envelope improvements and glazing. This goes to show that there is an increasing interest in glazing as an important building material (Manz & Menti, 2012).

In an analysis of the performance of glazing, Jelle et al. (2012) highlighted thermal resistance also referred to as U-value, as one of the properties to be considered in the selection process. Jelle et al., (2012) reviewed vacuum glazing, solar cell glazing, self-cleaning glazing, and low-emissivity coatings etc. in their study to determine their thermal performance. Stegou-Sagia et al., (2007) through a study on the impact of glazing on energy consumption in Greece suggested that the opportunities to improve energy performance exist in the design process of the buildings. In this study, different types of glazing were used to simulate a probable energy consumption in an office and residential building using parameters such as the type of the glazing and the percentage of the glazing area. Although glazing offers benefits of daylighting and natural views, the energy that is consumed to regulate the temperature within the building increases where the glazing has poor insulation values (Stegou-Sagia et al., 2007). The area in the building simulation with clear glass in the study showed high level of heat gain resulting in more energy consumption. In addition to the energy consumption analysis, the study also aimed to examine whether thermal comfort conditions within the building comply with the international standards. The ASHRAE defines comfort conditions in terms of operative temperature to range between 68 and 80 F. With the problem of thermal discomfort concentrated in summer months and not so intense in winter, the study partially indicates; based on occupant's behavior, that the results regarding the thermal comfort are overestimated. The thermal comfort standard can act as a guideline but cannot be applied globally (Stegou-Sagia et al., 2007). However, where building designers prioritize lighting and cooling in glazing parameters, comfort and energy conservation can be attained (Stegou-Sagia et al., 2007).

Jaber & Ajib, (2011) in their research to determine the effect of glazing choices on energy demand in three different climatic zones, described windows as a two-sided knife with one side being "useful" and the other "harmful". An analysis of the influence of windows type confirmed the choice of glazing to be a critical factor in the effectiveness of solar energy (Jaber, S., & Ajib, S., 2011). The research supports the fact that a good glazing design can decrease heating and cooling requirements by a review of the effect of a window's U-value; which is a vital property of the window, on energy demand. Samples of a single, double and triple glazed window were used in the evaluation of the study. The double and triple glazing used had two and three panes of glass respectively, sandwiched together with a layer of air or inert gas between each pane. The study examined the effect of a window's U-value; which is a vital property of the window, on energy demand using samples of a single, double, and triple glazed windows. Although each glazing performed differently in each climatic zone, Jaber & Ajib, (2011) concluded that the triple glazed window had the best performance in thermal resistance than the other window types and up to 24% energy savings is possible with a properly glazed window.

Manz and Menti, (2012) presented an analysis of the energy performance of glazing in eight different European locations. The study highlights how the extensive use of glass in building envelopes still constitute major problems such as overheating building in summer, thermal losses in winter and a lack of thermal comfort. In terms of the energy flow, Manz & Menti, (2012) stated that glazing can be characterized by two parameters namely the total solar energy transmittance (incoming solar energy converted to heat energy inside the building space) and the thermal transmittance (amount of heat transferred through the glazing and the temperature difference between the interior and exterior). The study focused on winter season to show the impact of glazing quality, façade orientation and climate on the gain-to-loss ratio. The triple insulating exhibited the highest gain-to-loss ratios with the best ratios observed at south facades and worst at north facades.

In a similar study on glazing systems energy performance, Gasparella et al., (2011) stated that the energy performance of a window is dependent on its thermal transmittance, glazing solar transmittance, and the air leakage due to the airtightness of the frame during installation. The study concludes that the most effective thermal insulating glazing has low solar transmittance, which reduces solar gains. The study also recognizes the triple glazing as the most effective thermal insulating glazing.

Double skin glazing provides an advantage over single glass glazing in high rise building according to (Cetiner & Özkan, 2005). These advantages include providing natural ventilation, daylighting and solar heat gain reduction. (Cetiner & Özkan, 2005) aimed to determine a more appropriate glazing alternative between the single and double type façade by reviewing their performance criteria, constraints, as well as their energy and cost efficiency. The result of the study indicate that the double skin glass façade is more energy efficient than the single skin glass façade and the single skin glass façade on the other hand proved to be most cost efficient.

Ghaffarianhoseini et al., (2016) described double skin facades as "a building façade covering one or more levels with multiple glazed skins, separated by an air gap". In exploring the advantages of the double skin façades (DSFs), Ghaffarianhoseini et al., (2016) laid emphasis on the role building envelopes can play in improving energy efficiency and indoor thermal comfort. DSFs have been characterized with multiple skins which is an enhancement of traditional facades to be used in cold and hot climates.

Ghaffarianhoseini et al., (2016) through this study highlighted major benefits of the use of DSFs "including energy consumption reduction, ventilation, air-flow and thermal comfort enhancement, daylighting and glare control, sound insulation, noise reduction and acoustic enhancement and visual and aesthetic quality enhancement. Thermal comfort ranks high among the most important issues to be considered in the selection of glazing material (Suhendri et al,. 2018). Suhendri et al., (2018) focused on hot and humid climates in a study to examine the thermal and daylighting performance of glazing materials. Thermal comfort, a major issue associated with hot and humid climates, emanates from solar radiation that penetrates into a building through the glazing. The study compared the performance of multilayered glazing and recognized that argon filled glazing as the most suitable material for hot climates. The study also concluded that the single layered glazing has better thermal performance than the double and triple glazing.

The increasing energy consumption demand arises from the use of air conditioning systems to regulate the temperature of building spaces. Rezaei et al., (2017) recognized that proper window glazing can be used to reduce energy consumed in cooling and heating building spaces due to heat gain and heat loss through windows. In the conclusion of the study, Rezaei et al., (2017) determined that the use of smart glazing; whose properties change when exposed to variables such as heat, light; are most suitable on hot climates.

Hassouneh et al., (2010) examined the influence of windows glazing on energy and thermal balance in a building using a self-developed software. The software calculated the solar heat gain and cooling load factor to select the most energy efficient windows that can save more energy and reduce heating load in winter. In the design of energy efficient buildings, details such as windows, walls and roofs need proper consideration. It is well known that windows lose more heat than what is gained, hence, a low energy house is said to have little to no glazing. However, mew technological development in glazing provide these energy benefits as well as comfort to the end users. The study (Hassouneh et al., 2010) examined eight different types of glazing and found that increasing the surface area of a glazing or using a combination of glazing types can save energy costs in winter. Although the study examined the thermal balance in the building, there is no examination of actual temperature control by glazing within the building. The study used mathematical methods to simulate the heat gain and energy efficiency on the building without having the actual information of the building and concluded that "increasing the area of glazing can provide a good opportunity to save energy" (Hassouneh et al., 2010). Fang, Hyde, Hewitt, Eames, & Norton, (2009) also evaluated the thermal balance of a vacuum glazing and confirmed that the overall heat transfer coefficient and temperature profiles along the central line of a vacuum glazing were in line with the predictions of their 2D and 3D finite models.

Nilsson & Roos (2009) in the research on the thermal properties of glazing coatings demonstrated the importance of selecting climate appropriate glazing. Climatic areas showing high heat levels require low-e coatings with a high g-value on the glazing to allow for adequate energy gain. Glazing products now available on the market possess properties that can convert a window into a resource for energy saving in the building where they are used (Nilsson & Roos, 2009). The energy ratings of different glazing were evaluated in a study across different Indian climates (Singh & Garg, 2009) to help the process of selecting glazing for a building. Singh & Garg, (2009) studied ten types of glazing some of which included clear glass, low-e coated glass and tinted glass across five climatic conditions.

Based on this study, energy savings are influenced by factors such as the climatic conditions, orientation of the window as well as some building parameters (roofs, walls). Additionally, Tsikaloudaki et al., (2015) considered the energy performance of glazing in Europe by calculating the cooling energy index as well as the weighted energy needs for different window in a residential and office building. The study showed that the windows with significant solar transmittance properties contribute to the minimization of energy consumption while the presence of low thermal transmittance prevent the transfer of heat to the outside environment thereby resulting in higher cooling energy.

Alwetaishi, (2017) in a study on the impact of glazing to wall ratio, recognized the glazing system as a fragile part of buildings with direct solar heat because of its transparent materials, which needs much consideration by designers especially in regions with high solar radiation. Although several researches have been conducted on glazing performance, most of the studies have focused on glazing in residential building giving minor attention to educational buildings (Alwetaishi, 2017). These studies discuss the use of glazing for its cost and energy efficiency, but none examined the temperature control abilities of the glazing.

In a similar study of the energy performance of modern glass facade systems, Aldawoud, (2017) described a building facade system as a vital element capable of influencing building energy performance and overall environmental impact. The study used an energy model to develop a framework to examine the effectiveness of various different glass facade systems. The results of the study showed the Double Low-e spectrally selective and double electrochromic absorptive glass as the most energy performing glass with a potential to save up to 60% of the energy when compared to the clear glass. Although the study compared the energy performance of glazing, the author had a shortfall in identifying a source of energy consumption as the basis for the comparison. The author suggests that reduction of heat loss through the glass is attainable by optimizing the glazing gap between the two glass panes when filled with air. The glazing with a gap width of 13mmwas seen to perform better than a glazing with a gap width of 3mm or 6mm. This goes to show that selecting a glazing with a reasonable amount of gap in between the panes can help achieve optimal performance. Aldawoud (2017) through his study also showed that the type of gas fill in a glazing can affect the energy efficiency of the glazing itself. Glazing filled with inert gases (argon and krypton) performed better than the ones filled with air. Arıcı et al., (2015) further evaluated the flow and heat transfer occurrence in multiple pane windows. Through the development of numerical computations for different gap widths and outdoor temperatures, the authors revealed that the temperature flow in the cavities of multiple pane windows differ from one another. The study suggests that heat loss through windows can be reduced by increasing the number of window panes. Hence, for this study, the five glazing alternatives selected each have double layers with a gap of 12.5mm. To ensure that different properties are captured in the analysis, alternatives with air and argon will be compared.

CONCLUSION

There is an increased demand for sustainable design in buildings as a bid to improve indoor environment while conserving energy consumption. According to Selkowitz (2011), where the undesired thermal losses can be minimized, the desired solar gain and daylight from the windows will provide energy benefits for the building. The glazing system is a promising technique that can reduce solar heat gain in the summer and provide some level of thermal insulation during winter seasons (Zhou & Chen, 2010). Double glazing is known to reduce heat loss by more than 50% when compared to single glazing (Carmody & Haglund, 2012)pg 17. Significant changes have occurred in glazing and facade design over the years, laying the groundwork for additional technical breakthroughs in the coming years. Advanced glazing will be dynamic elements in facades that are fully integrated into building operations, providing daylighting and natural ventilation, and operated in a manner that not only reduces energy costs but also enhances occupant comfort and performance.

3 METHODOLOGY

3.1 Introduction

To evaluate the thermal performance of five glazing alternatives, this study was conducted in a functional campus building in Pensacola, Florida at the University of West Florida. The location is known for its high temperatures and humidity almost all year round; and maintaining the solar heat gain during the winter and minimizing heat gain during the summer months within a facility is a major concern for building users. The window was installed with four chosen glazing alternatives and a control glazing.

3.2 Building Description

To evaluate the thermal performance of a selected number of window glazing, the study was conducted in a controlled setting. The building is part of the Community Outreach, Research and Education (C.O.R.E.) laboratory on the university campus in Pensacola. This building measured approximately 40 ft x 100 ft. (12.2 m x 30.5 m) with the research window installed on the west side of the structure. A windowpane built with the research parameters, was installed into the building and utilized to gather the needed data. The research window as seen in Figure 3.1 is oriented towards the west with fifteen panes of the different glazing. Each column in the windowpane consists the different selected glazing itemized with their properties as shown in section 3.5 below.

Figure 3.1: Front view of building with Glazing Setup

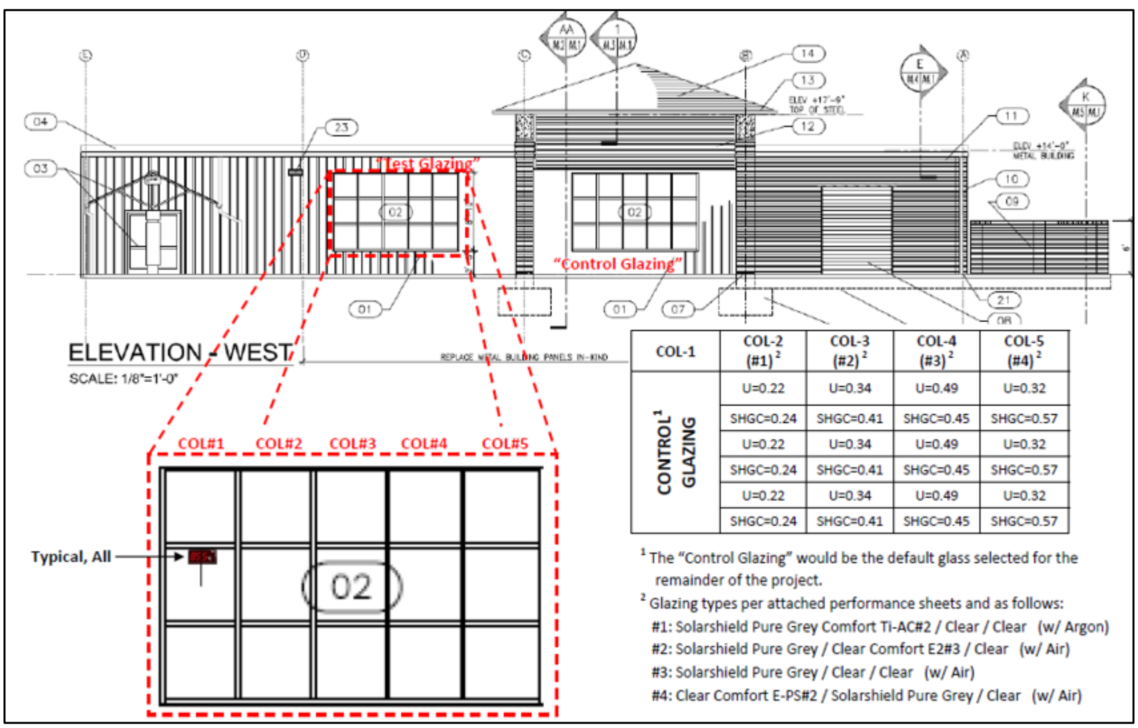

Figure 3.2: Glazing Cell Types and Arrangement

3.3 Location Description

The thermal performance analysis was conducted in a location that represents one of the identified climate zones in the United States (see Figure 2.3). The location selected for the project case study was Florida with consideration of the existing climatic condition (Hot, Humid). The state of Florida is often referred to as the sunshine state and has a climate characterized by its warm to hot summers for a large part of the year. The state is popular for its high temperatures, high humidity and heavy rainfall. During the winter, the state has approximately twice the amount of sunlight than other states within the same quadrant of the nation. The average temperature in Florida range between the lower 50ºs to upper 60ºs in during the cold months (January) and between 81F and 83F during the hot months (July/August).

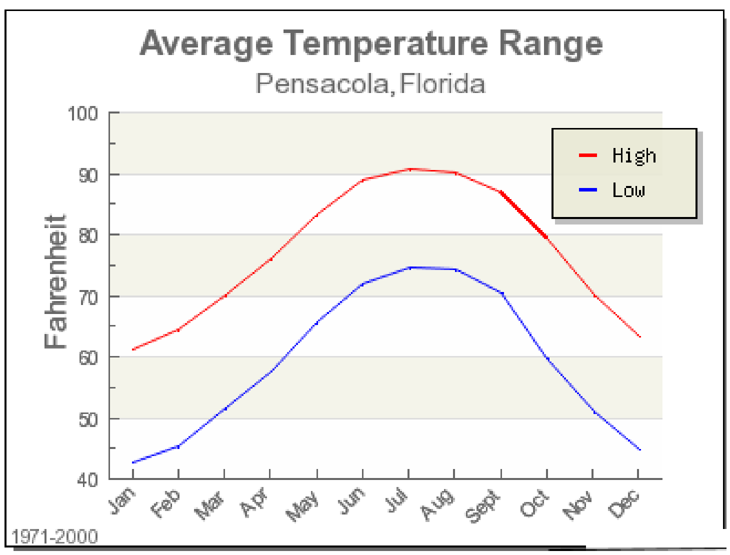

Figure 3.3: Pensacola Average Temperature. Source: RSS Weather (taken 2018)

The sun in Florida generally reaches a higher angle than farther north and consequently its power to heat. The city of Pensacola where the study will be carried out, shows the average temperature (Figure 3.3**)** reaching as high as 90°. The summer months in Pensacola are usually hot for comfort but the use of air conditioning system in buildings make it a whole lot bearable.

3.4 Seasonal Selection

The seasons for this study were chosen using the meteorological breakdown of seasons which is a subdivision into 3-months periods where; winter is December, January, and February; spring is March, April, and May; summer is June, July and August; and autumn is September, October, and November. The breakdown defines the winter months as the three coldest months, the summer as the three warmest months while spring and fall are the transition months between the two seasons (Trenberth, 1983).

Table 3.1: Meteorological seasons with the corresponding dates and length of each season

	Winter	**Spring**	**Summer**	**Fall**
Dates	1 Dec.-28 Feb	1 Mar.-31 May	1 June-31 Aug.	1 Sept.-30 Nov.
Length	90	92	92	91

3.5 Glazing Alternatives

The study utilized five different glazing types, selected with consideration of the thermal properties they possess. These selected glazing constitute the 15-pane window installed in the research laboratory for the study. Each glazing will be evaluated against the other alternatives to determine their differences in thermal performance. The glazing types include the following

- Glass C1 (Control Glazing) – a standard Single Clear Glass selected as the default glass. U-value is ≥ 0.7.

- Glass C2 - Solarshield Pure Grey Comfort T-AC#2 Clear with Argon gas. The insulating glass unit is composed of the following:
    - ➢ Exterior pane: 6mm (Solarshield pure grey comfort)
    - ➢ Airspace: 12.5mm
    - ➢ Interior pane 6mm (clear)
- Glass C3 - Solarshield Pure Grey / Clear Comfort E2#3 Clear with Air. The insulating glass unit is composed of the following:
    - ➢ Exterior pane: 6mm (solarshield pure grey)
    - ➢ Airspace: 12.5mm
    - ➢ Interior pane 6mm (clear comfort)

Table 3.2: Summary of details of the glazing systems (Glass 1-4)

		Glass C2	Glass C3	Glass C4	Glass C5
Visible Light	Transmittance	28%	35%	38%	36%
Solar Energy	Transmittance	15%	25%	29%	25%
	Reflectance - outdoors (ER)	14%	7%	6%	12%
U. V. Light	Transmittance	0	0	0	0
	Damaged weighted index - ISO	18%	23%	26%	26%
U-Values	Air/Argon	0.22	0.34	0.49	0.32
Other Values	(SHGC)	0.24	0.41	0.45	0.57
	Shading Coefficient	0.28	0.47	0.52	0.66
	Light to Solar Heat Gain ratio	1.17	0.85	0.84	0.63

- Glass C4 - Solarshield Pure Grey Comfort Clear with Air. The insulating glass unit is composed of the following:

- Exterior pane: 6mm (solarshield pure grey)
- Airspace: 12.5mm
- Interior pane 6mm (clear)

- Glass C5 - Solarshield Pure Grey Clear Comfort E-PS#2 Clear with Air. The insulating glass unit is composed of the following:
    - Exterior pane: 6mm (solarshield pure grey)
    - Airspace: 12.5mm
    - Interior pane 6mm (clear)

3.6 Glazing Rankings

As earlier described, the performance of glazing types are majorly determined by the U-factor and SHGC properties they possess. The U-factor determines how well the window insulates while the SHGC measures how much heat from the sun comes through a window. Hence, a lower SHGC would result in less heat transmitted through the window.

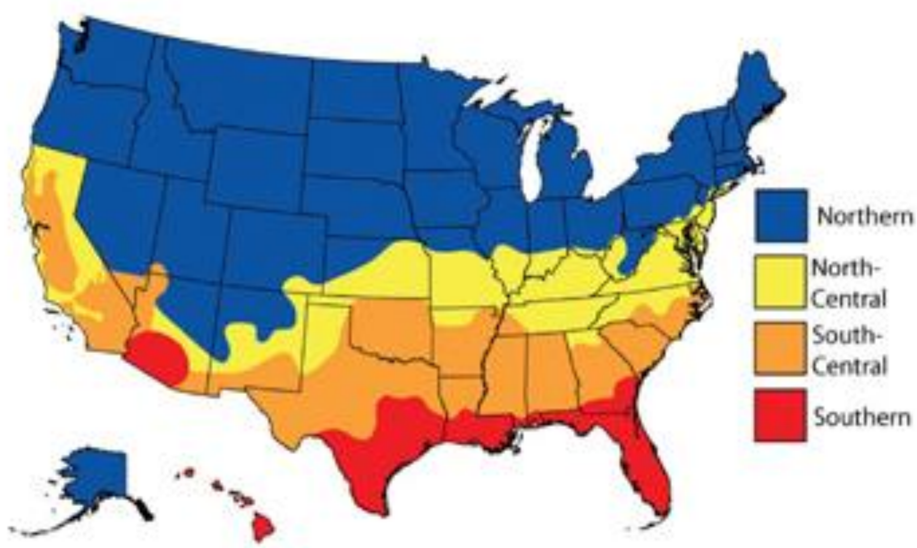

Figure 3.4: Climate Region for Window Selection Source: Energy Star (taken 2019)

Energy star provides required specifications for the U-factor and SHGC to guide the selection of windows in different climate zones as illustrated in Figure 3.4 and Table 3.3. In the southern climate zone, mostly characterized as hot and humid, the manufacturers specifications (Table 3.2) for optimal energy performance of the window is a SHGC less than or equal to 0.27. However, designers still need to take into consideration the need for heat gain during the winter season when selecting the SHGC value for the building window.

Table 3.3: Energy Star Window requirements for US climate zones

	Windows		
Climate Zone	U-factor	SHGC	
Northern	≤ 0.30	Any	Prescriptive
	= 0.21	≥ 0.35	Equivalent Energy Performance
	= 0.32	≥ 0.40	
North - Central	≤ 0.32	≤ 0.40	
South - Central	≤ 0.35	≤ 0.30	
Southern	≤ 0.60	≤ 0.27	

Based on these requirements, the glazing types selected for this study were ranked on a predictive thermal performance basis using their U-values itemized in Table 3.1. The glazing was ranked from the best to the least performance (Table 3.3) using the color codes in Figure 3.5, where deep green represents the best performing glazing and the red color represents the glazing with the least performance. This ranking indicates that glass C1 performs optimally in the winter season, but ranks low in performance in the summer season requiring more cooling loads to maintain thermal comfort within the facility. It also indicates that glass C2 has the best performance in summer but has the least performance in the winter while the C3 maintains the same level of performance in all seasons when compared to the other alternatives.

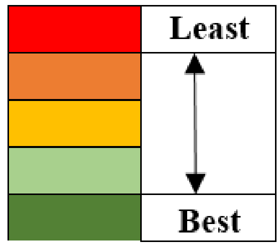

Figure 3.5: Ranking Color Code

Table 3.4: Glazing types ranking based on expected thermal performance

Ranking	**Winter**	**Spring**	**Summer**	**Fall**
C1				
C2				
C3				
C4				
C5				

3.7 Research Methodology

This study examined the thermal performance of several glazing options under real weather conditions using a statistical analysis of the data collected over a year from the case study facility. As mentioned earlier, the study obtained data from a 12-pane storefront built with different types of glazing. The window was constructed in a prefabricated metal building with five rows of different types of glazing and thermal sensors placed at the same location behind each glazing unit (inside and outside) to measure the surface temperatures. An outdoor reference temperature was documented as a base temperature to measure the glazing against. The temperature of the inside and outside of each glazing cell was collected using a building monitoring system for a year and includes sampling from each season (spring, summer, fall and winter)

3.8 Data Collection

- Selected four glazing alternatives based on the SHGC and U-factor values which was used to create a 15-pane window for the study with a row of the control glazing.
- Installed a temperature sensor on the interior and exterior surfaces of the glazing sample to take temperature measurements. The sensor, known as a K-thermocouple, is one of the most common type of thermocouple that provides a reliable and wide temperature range.
- Recorded measurements over a one-year period to capture the different seasons – spring, summer, fall and winter. The measurements included both the inside and outside of each glazing cell and was collected using a building monitoring system.
  a. Record both interior and exterior temperature (°F)
  b. Time of the measurements – 15 mins interval
  c. Multiple readings – 3 readings per time interval

A sample of the data collected is shown in Table 3.4. With the multiple readings taken per time interval during the data collection, each time measurements was represented as an average of the multiple readings during the analysis

Table 3.5: Sample of Raw Data

Date	Time	Glass - Ext - C1 R1	Glass - Ext - C1 R2	Glass - Ext - C1 R3
2017-01-01	00:00:00	65.2	65.3	65.0
2017-01-01	00:15:00	65.4	65.5	65.2
2017-01-01	00:30:00	65.5	65.7	65.3
2017-01-01	00:45:00	65.9	66.0	65.7

4 DATA ANALYSIS, RESULTS AND DISCUSSIONS

This study utilized a quantitative approach for the analysis of the data. The analysis provided the thermal performance of each glazing and a ranking based on the temperature differences. The analysis was completed using repetitive measures analysis of variance (ANOVA) calculations carried out in a statistical software (SPSS). The analysis determined the statistical significant differences between the temperature difference results for each season based on the indicators below

- When (Exterior Temp > Interior Temp) then, temperature difference is positive
- When (Exterior Temp < Interior Temp) then, temperature difference is negative

The statistical significance difference showed the difference amongst the glazing alternatives. The temperature difference between the interior and exterior surface temperature was used as the dependent variable to determine the thermal performance and confirm the statistical difference between the inside and outside panes of the glazing C1, C2, C3, C4 and C5.

To assess the performance of each glazing type, it was necessary to analyze the data in seasons of Winter (December - February), Spring (March - May), Summer (June - August) and Fall (September - November) for better comparisons. A statistical analysis repetitive measure, an analysis of variance (ANOVA) test, was conducted to evaluate the statistical differences between each glazing performance in this study. The aim of this study is to help guide the glazing type selection in buildings to improve thermal comfort and reduce energy consumption especially in hot and humid climates.

4.1 WINTER

The maximum, average and minimum ambient temperature for each day in the winter months (December – February) are shown in Figure 4.1. As illustrated in the figure below, the average daily ambient temperature in the winter varied as low as 33 °F and as high as 72 °F. A maximum temperature of 88 ºF and minimum temperature of 24 ºF was recorded during this time. The lower temperatures were generally experienced at night and the maximum temperatures during the day.

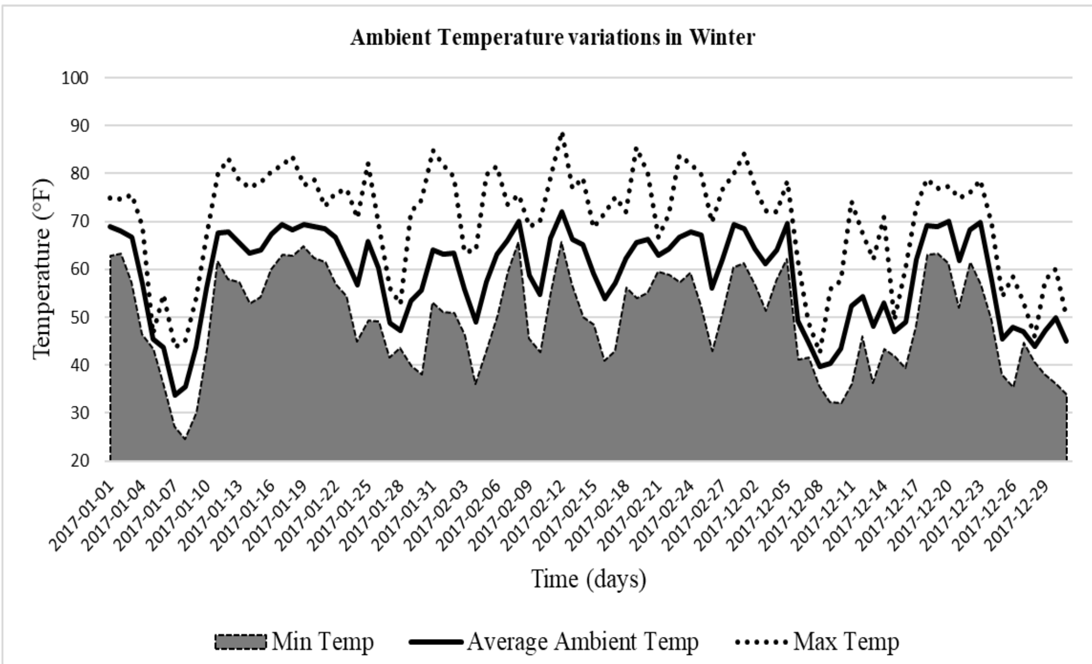

Figure 4.1: Ambient Temperature Variations during Winter

4.1.1 Glazing Surface Temperatures

The interior and exterior surface temperatures for each glazing unit installed in the window were measured throughout the year and Figure 4.1.2 represents the exterior surface temperatures for each glazing plotted against each other through the winter. The record showed that the exterior surface temperature varies as high as 93 ºF and as low as 28 ºF where the ambient temperature varied between 24 ºF and 88 ºF. The average exterior temperature for the control glazing (C1) and glazing C2, C3, C4, C5 are 62.18 ºF, 62.08 ºF, 61.78 ºF, 61.15 ºF and 61.83 ºF respectively. The points where the lines overlap each other represent similarities in the temperature measured for all the glazing types during this period and points that do not overlap show the differences between each glazing as seen in Figure 4.2.

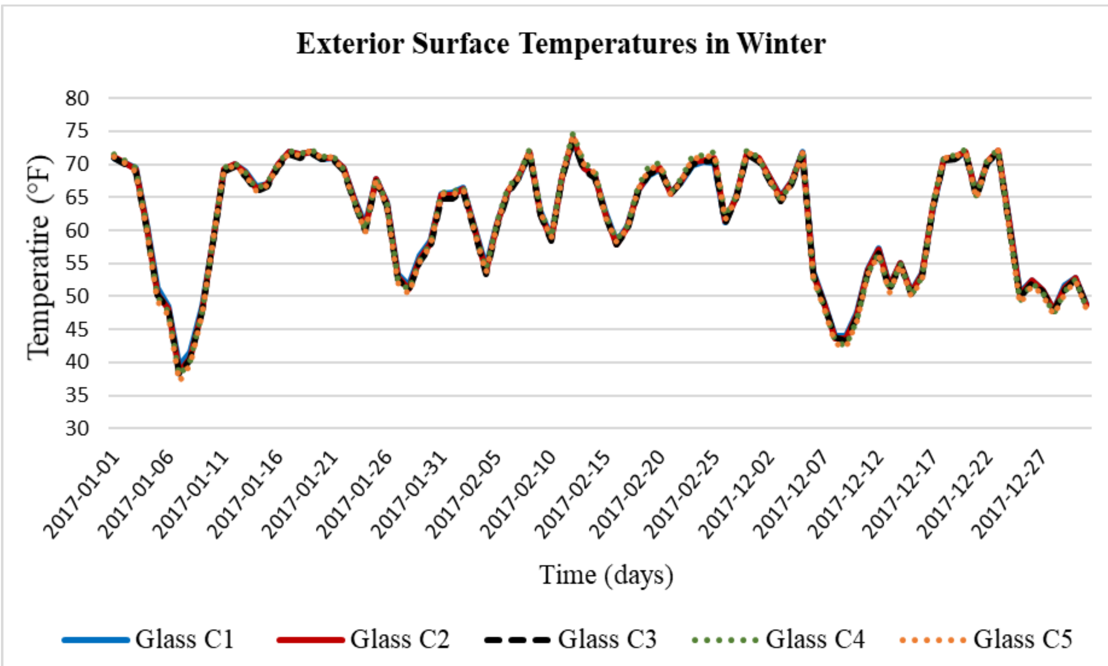

Figure 4.2: Average Exterior Surface Temperature for Winter

The interior surface temperatures for each glazing plotted against each other during the winter season are represented in Figure 4.3. The record showed that the interior surface temperature varies as high as 83 ºF and as low as 43 ºF where the ambient temperature remains between 24 ºF and 88 ºF. The average interior temperature for the control glazing (C1) and glazing C2, C3, C4, C5 were 64.78 ºF, 65.02 ºF, 65.57 ºF, 64.93 ºF and 64.92 ºF respectively. The points where the lines overlap also represents the similarities in the temperature measured for all the glazing types during this period and points that do not overlap show the differences between each glazing as seen in Figure 4.3.

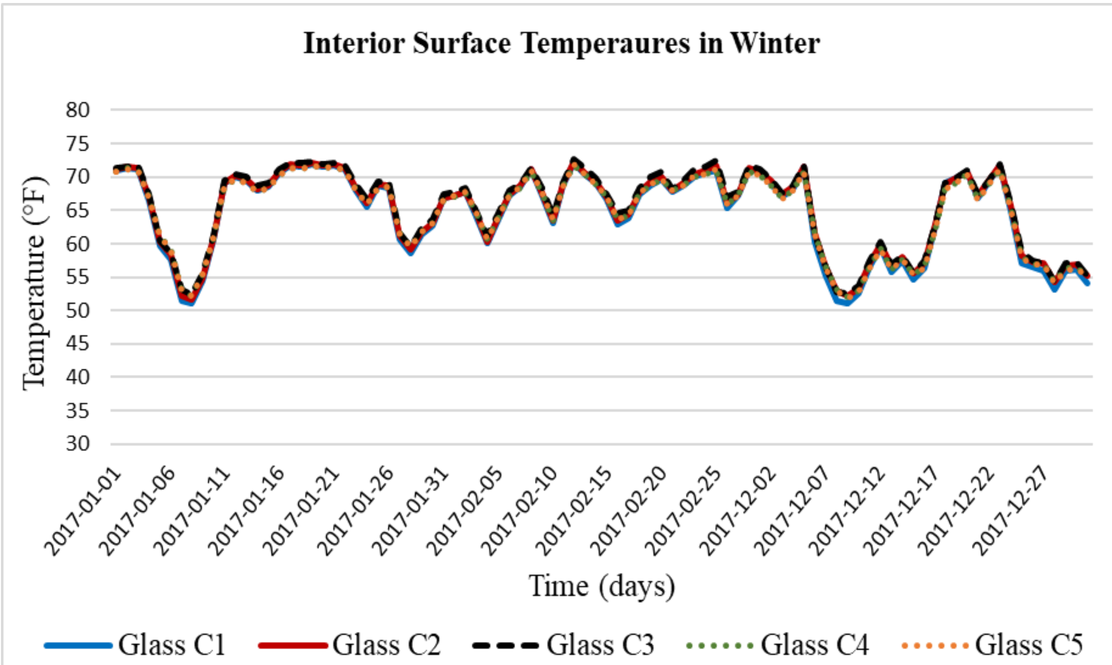

Figure 4.3: Average Interior Surface Temperature for Winter

4.1.2 Thermal Performance Analysis

The thermal performance measurement was determined by the mean temperature differences between the exterior and interior surface temperatures. In this study, the temperature difference for each glazing was calculated by subtracting the interior surface temperature from the exterior surface temperature for every ¼ hr measurement taken on each day. Hence, when exterior temperature is more than interior temperature i.e Ext. Temp > Int. Temp, the temperature difference was positive and when exterior temperature is less than interior temperature i.e Ext. Temp < Int. Temp, the temperature difference was observed to be negative.

Ext. Temp – Int. Temp = Δ Temp. Diff

The analysis of variance was carried out on the temperature difference to determine whether the thermal performances for each glazing are statistically different. The results show the overall means (M) and standard deviation (S.D) for C1 (M=-2.59, S.D=3.71), C2 (M=-3.12 S.D=4.28, C3 (M=-3.79 S.D=3.91), C4 (M=-2.78 S.D=5.34) and C5 (M=-3.09 S.D=5.35), which indicates that the glazing are statistically different.

Table 4.1: Descriptive Statistics for each Glazing in Winter

	Mean	Std. Deviation
Glass C1	-2.59	3.71
Glass C2	-3.12	4.28
Glass C3	-3.79	3.91
Glass C4	-2.78	5.34
Glass C5	-3.09	5.35

The ANOVA results showed a P-value of 0.0 which was significantly less than the alpha value of 0.5 set for the study. This indicates that there is a statistical difference between the performances of C1, C2, C3, C4 and C5 in the winter at 95% confidence level [F (1,8454) = 4007.797]. The details of the evaluation in the ANOVA Table 4.2 below confirms the statistical difference with a P-value of 0.000.

Table 4.2: ANOVA analysis outputs for Temperature differences (C1 - C5)

Source	**Sum of Squares**	**df**	**Mean Square**	**F**	**P-value**
Glazing Type	399794	1	399794	4007.797	0.00E+00
Error	843320.7	8454	99.754		

The null hypothesis is rejected with the result of the ANOVA. To determine where the statistical difference exists between the mean differences of each glazing, a follow up post-hoc test was conducted. This post-hoc test provides a pairwise comparison between each glazing and uses the P value (Table 4.3) to indicate where the statistical difference exists. The P value for each paired comparison (C1, C2), (C1, C3), (C1, C4) (C1, C5), (C2, C3), (C2, C4), (C3, C4), (C3, C5), and (C4, C5) are less than 0.5 which makes the thermal performances statistically different from one another. However, C2 and C5 had a p-value of 0.771, which, shows that there is no statistical difference in their thermal performance of in Winter.

Table 4.3: ANOVA Post-Hoc pairwise comparison results

Glazing Type	**Glazing Alternatives**	**Mean Difference between Alternatives**	**Std. Error**	**P-value**
C1	C2	0.531	0.009	0
	C3	1.195	0.013	0
	C4	0.190	0.022	0
	C5	0.501	0.023	0
C2	C3	0.664	0.012	0
	C4	-0.341	0.016	0
	C5	-0.03	0.017	0.771
C3	C4	-1.005	0.021	0
	C5	-0.694	0.022	0
C4	C5	0.310	0.006	0

Using the paired comparison provided from the post-hoc test, the temperature difference for C1 and C2 in the winter are presented in Figure 4.4. The records show that the temperature difference for C1 varies between -12.07 °F and 1.54 °F while C2 varies between -13.72 °F and 1.79 °F. The average temperature difference of C1 (-2.59 °F) when compared to C2 (-3.12 °F) was increased by about 0.53 °F. The analysis of variance showed that there is a statistical difference in performance between both C1 and C2 with a p-value (0.000). Based on the assumption that the lower the temperature difference, the better the performance in winter, the records in the figure below indicates C2 as a better performing glazing than C1.

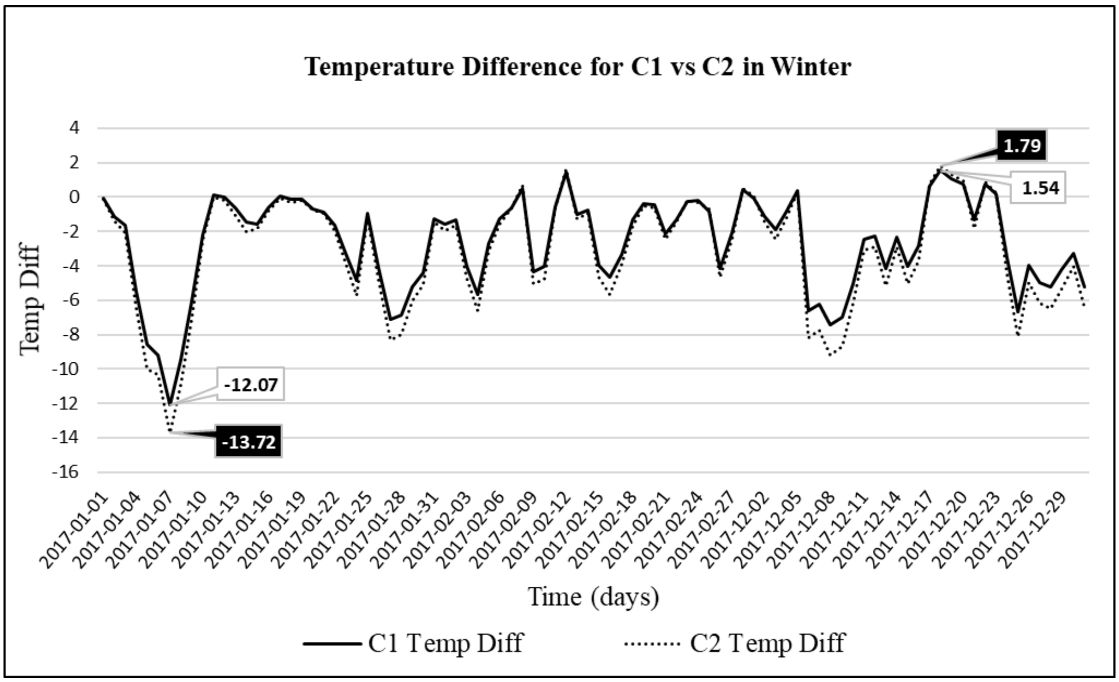

Figure 4.4: Temperature difference variation for C1 vs C2 in Winter

The temperature difference for C1 and C3 in the winter are presented in Figure 4.5. The records show that the temperature difference for C1 varies between -12.07 °F and 1.54 °F while C3 varies between -14.84 °F and 1.32 °F. The average temperature difference of C1 (-2.59 °F) when compared to C3 (-3.79 °F) was increased by about 1.20 °F. The analysis of variance showed that there is a significant difference in performance between both C1 and C3 even though a very close performance was observed between 17-Dec and 21-Dec. Based on the assumption that the lower temperature difference means the better the performance in winter, the records below indicates C3 as a better performing glazing than C1.

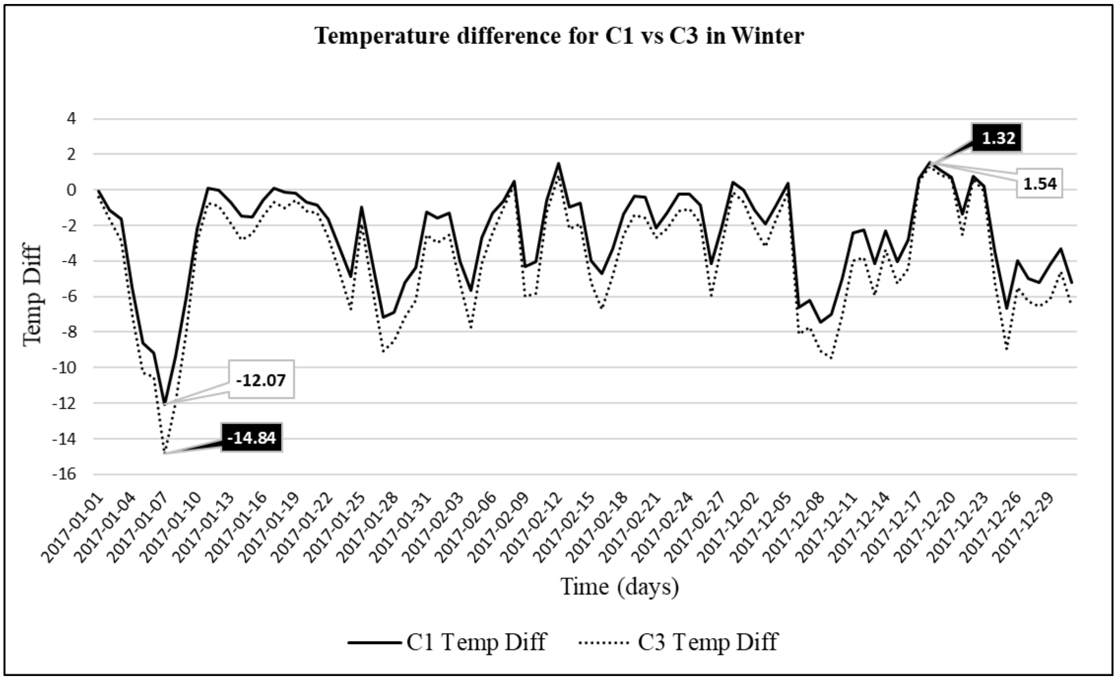

Figure 4.5: Average Temperature Difference Variation for C1 vs C3 in Winter

The temperature difference for C1 and C4 in the winter are presented in Figure 4.6. The records show that the temperature difference for C1 varies between -12.07 °F and 1.54 °F while C4 varies between -15.01 °F and 3.06 °F. The average temperature difference of C1 (-2.59 °F) when compared to C4 (-2.78 °F) was increased by about 0.19 °F. The analysis of variance showed that there is a significant difference in performance between both C1 and C4 through the winter period as seen in Figure 4.6. It was observed that there were multiple fluctuations in performance between both glazing all through this period. However, C1 has a lower total temperature difference than C4 and based on the assumption that the lower temperature difference means the better the performance in winter, the records indicates C1 as a better performing glazing than C4.

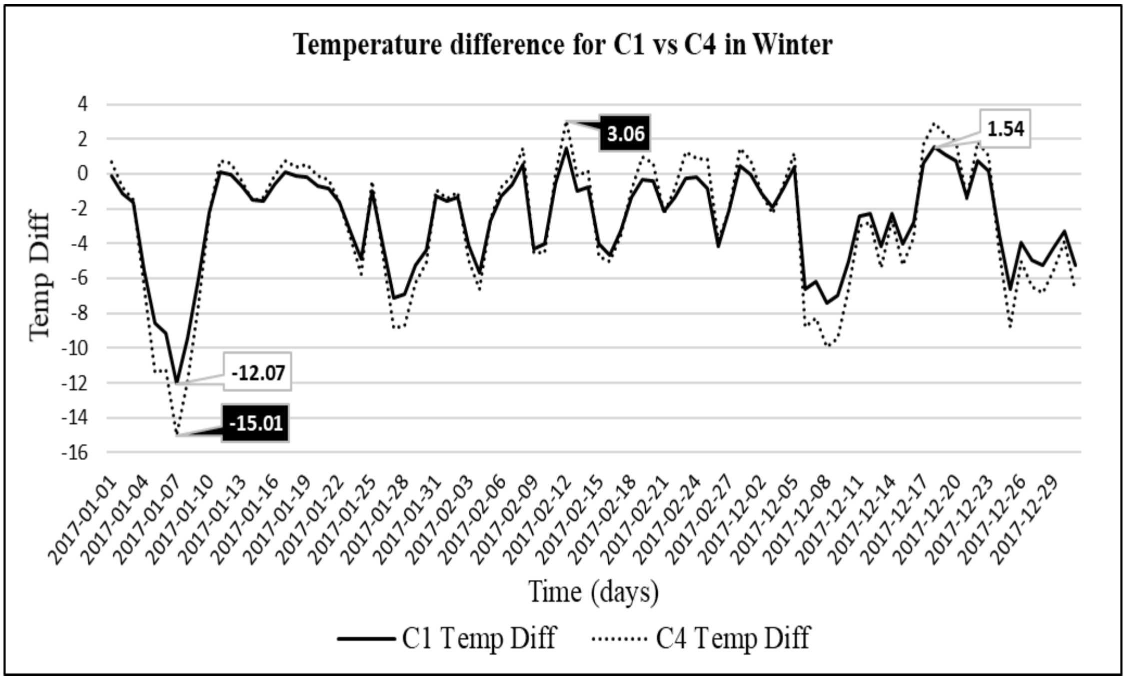

Figure 4.6: Average Temperature Difference Variation for C1 vs C4 in Winter

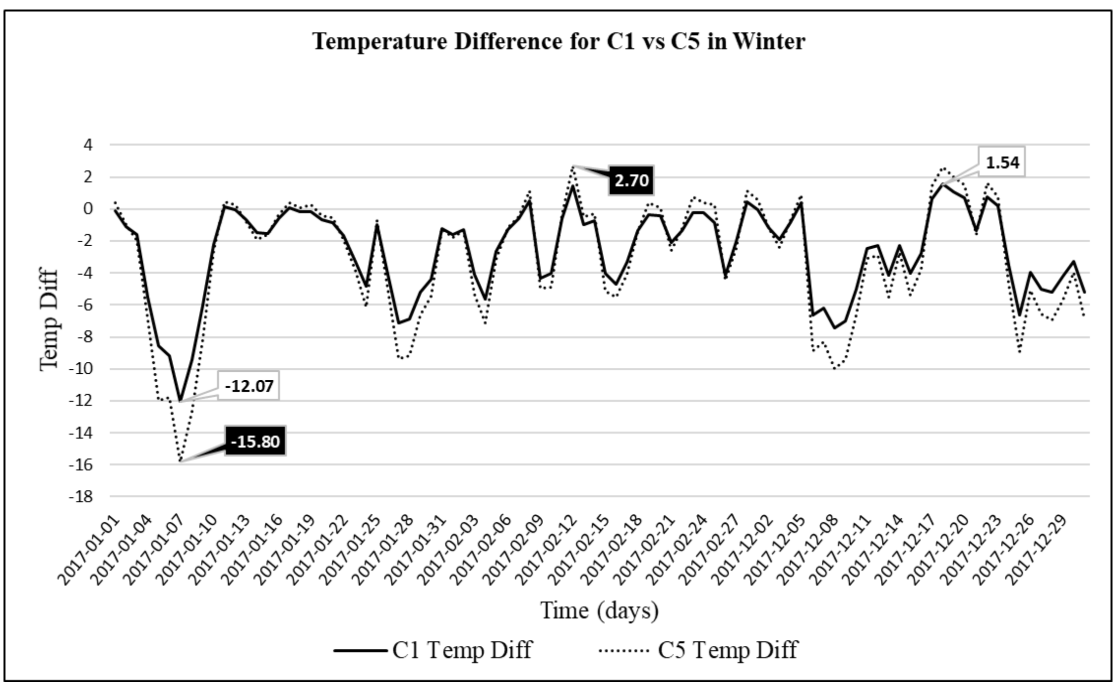

Figure 4.7: Average Temperature Difference Variation for C1 vs C5 in Winter

The temperature difference for C1 and C5 in the winter are presented in Figure 4.7. The records show that the temperature difference for C1 varies between -12.07 °F and 1.54 °F while C5 varies between -15.8 °F and 2.7 °F. The average temperature difference of C1 (-2.59 °F) when compared to C5 (-3.09 °F) was increased by about 0.50 °F. The analysis of variance showed that there is a significant difference in performance between both C1 and C5 through the winter period as seen in Figure 4.7. Even though multiple fluctuations were observed in performance of both glazing through this period, C1 still has a lower total temperature difference value than C5 and based on the assumption that the lower temperature differences the better the performance in winter, the records below indicate C1 as a better performing glazing than C4.

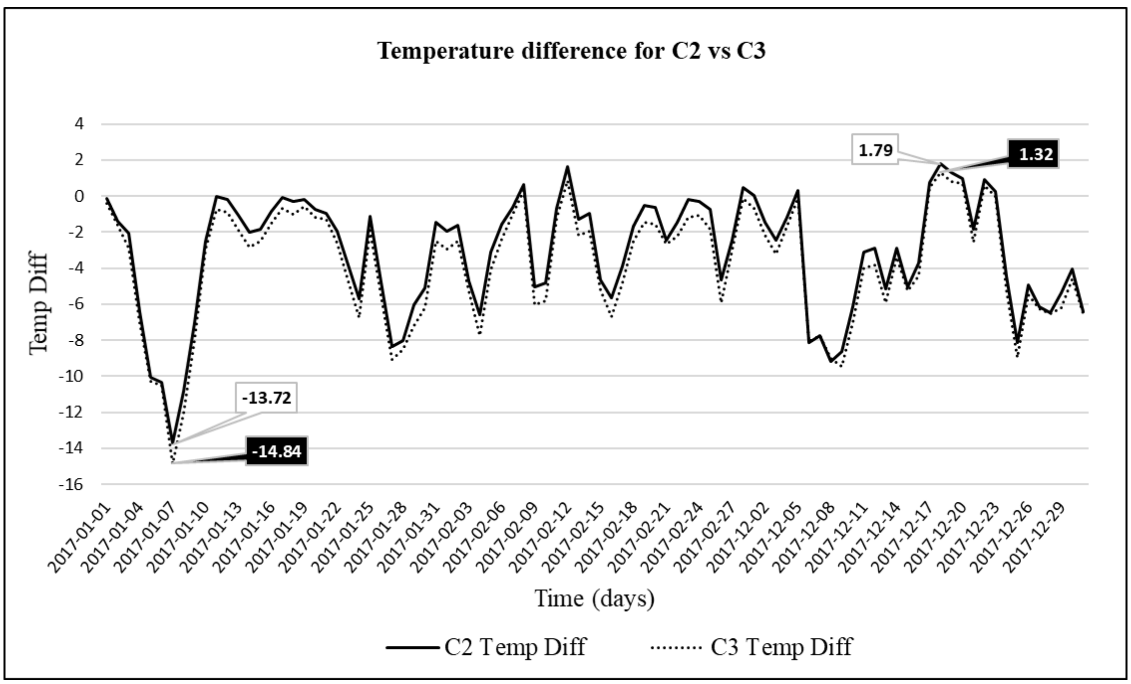

Figure 4.8: Average Temperature Difference Variation for C2 vs C3 in Winter

The temperature difference for C2 and C3 in the winter are presented in Figure 4.8. The records show that the temperature difference for C2 varies between -13.72 °F and 1.79

°F while C3 varies between -14.84 °F and 1.32 °F. The average temperature difference of C2 (-3.12 °F) when compared to C3 (-3.79 °F) was increased by about 0.67 °F. The analysis of variance showed that there is a significant difference in performance between both C2 and C3 as seen in Figure 4.8. The total temperature difference for the C3 is less than C2. Based on the assumption that the lower the temperature difference, the better the performance in winter, the records indicates C3 as a better performing glazing than C2.

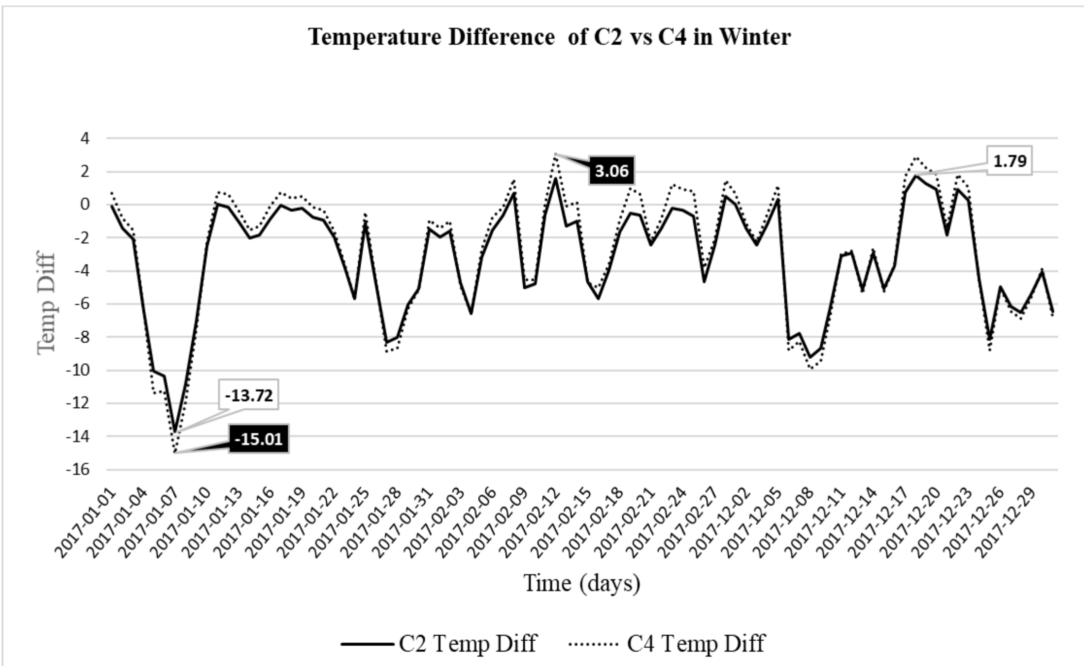

Figure 4.9: Average Temperature Difference Variation for C2 vs C4 in Winter

The temperature difference for C2 and C4 in the winter are presented in Figure 4.9. The records show that the temperature difference for C2 varies between -13.72 °F and 1.79 °F while C4 varies between -15.01 °F and 3.06 °F. The average temperature difference of C2 (-3.12 °F) when compared to C4 (-2.78 °F) was increased by about 0.34 °F. The analysis of variance showed that there is a significant difference in performance between both C2 and C4 as seen in the Figure 4.9. The total temperature difference for the C2 is less than

C4. Based on the assumption that the lower the temperature difference, the better the performance in winter, the records indicates C2 as a better performing glazing than C4.

The temperature difference for C2 and C5 in the winter are presented in Figure 4.10. The records show that the temperature difference for C2 varies between -13.72 °F and 1.79 °F while C5 varies between -15.8 °F and 2.7 °F. The average temperature difference of C2 (-3.12 °F) when compared to C5 (-3.09 °F) was reduced by about 0.03 °F. The analysis of variance showed that there is no significant difference in performance between both C2 and C5 (see Table 4.3) which accounts for the similarity seen in Figure 4.10. However, the total temperature difference for C2 is less than C5. Based on the assumption that the lower the temperature difference, the better the performance in winter, the records below indicates C2 as a better performing glazing than C5.

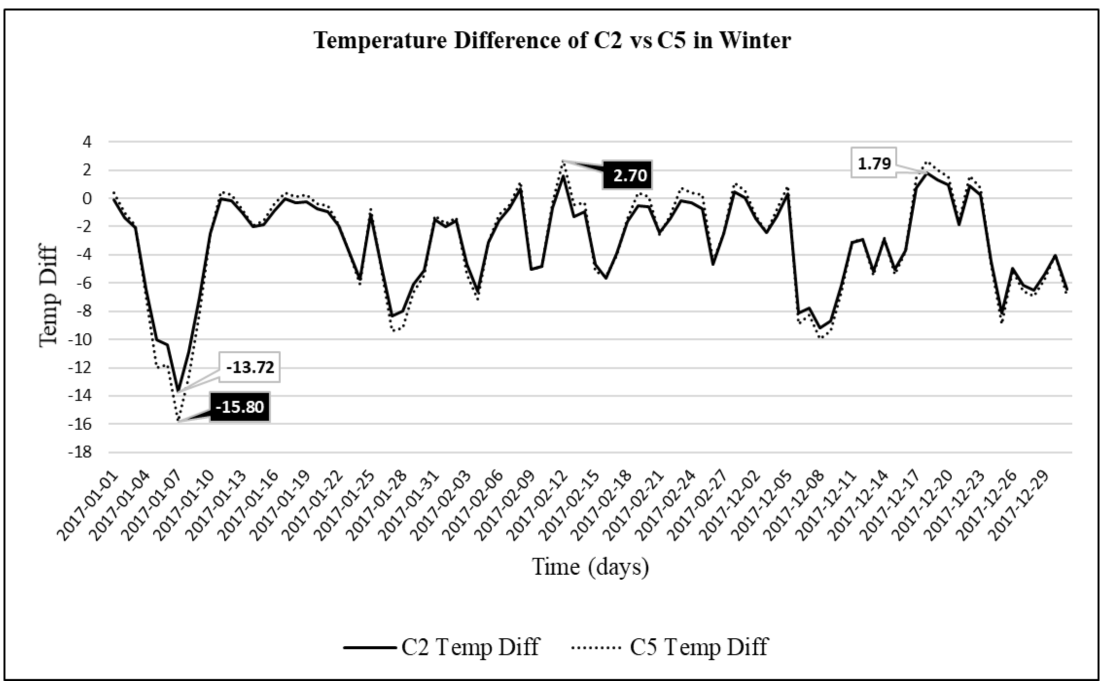

Figure 4.10: Average Temperature Difference Variation for C2 vs C5 in Winter

The temperature difference for C3 and C4 in the winter are presented in Figure 4.11. The records show that the temperature difference for C3 varies between -14.84 °F and 1.32 °F while C4 varies between -15.01 °F and 3.06 °F. The average temperature difference of C3 (-3.78 °F) when compared to C4 (-2.78 °F) was increased by about 1.0 °F. The analysis of variance showed that there is a significant difference in performance between both C3 and C4 as seen in Figure 4.1-11. The total temperature difference for the C3 is less than C4. Based on the assumption that the lower the temperature difference, the better the performance in winter, the records below indicates C3 as a better performing glazing than C4.

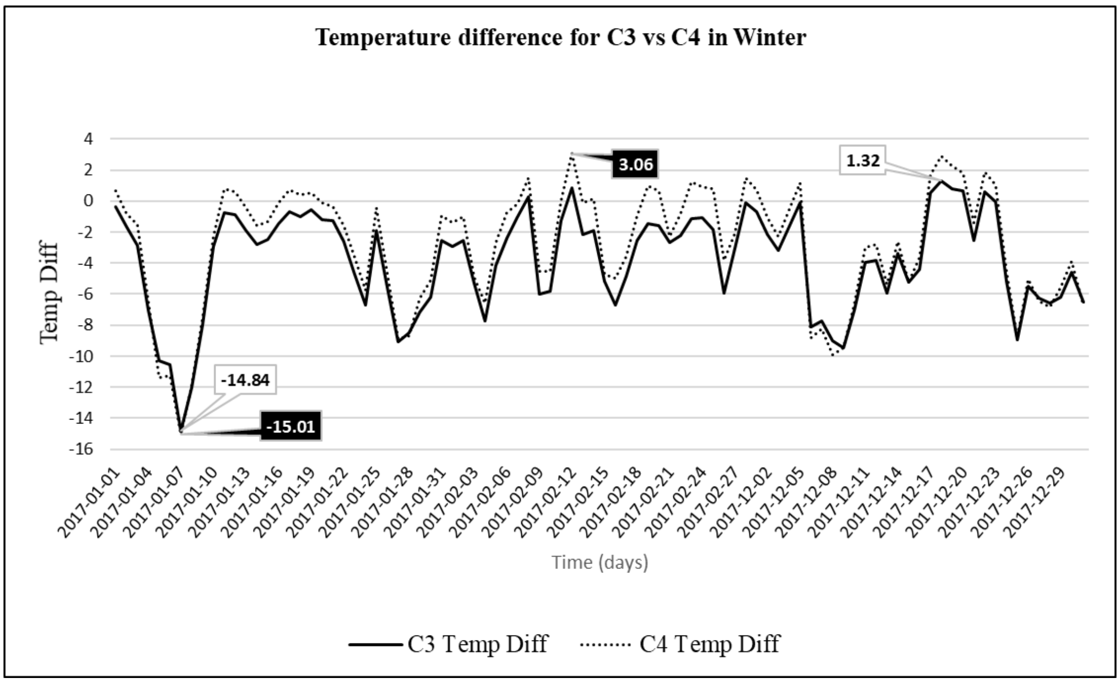

Figure 4.11: Average Temperature difference variation for C3 vs C4 in Winter

The temperature difference for C3 and C5 in the winter are presented in the Figure 4.12. The records show that the temperature difference for C3 varies between -14.84 °F and 1.32 °F while C5 varies between -15.8 °F and 2.7 °F. The average temperature difference of C3

(-3.78 °F) when compared to C5 (-3.09 °F) was reduced by about 0.69 °F. The analysis of variance showed that there is a significant difference in performance between both C3 and C5 as seen in Figure 4.12. The total temperature difference for the C3 is less than C5. Based on the assumption that the lower the temperature difference, the better the performance in winter, the records below indicates C3 as a better performing glazing than C5.

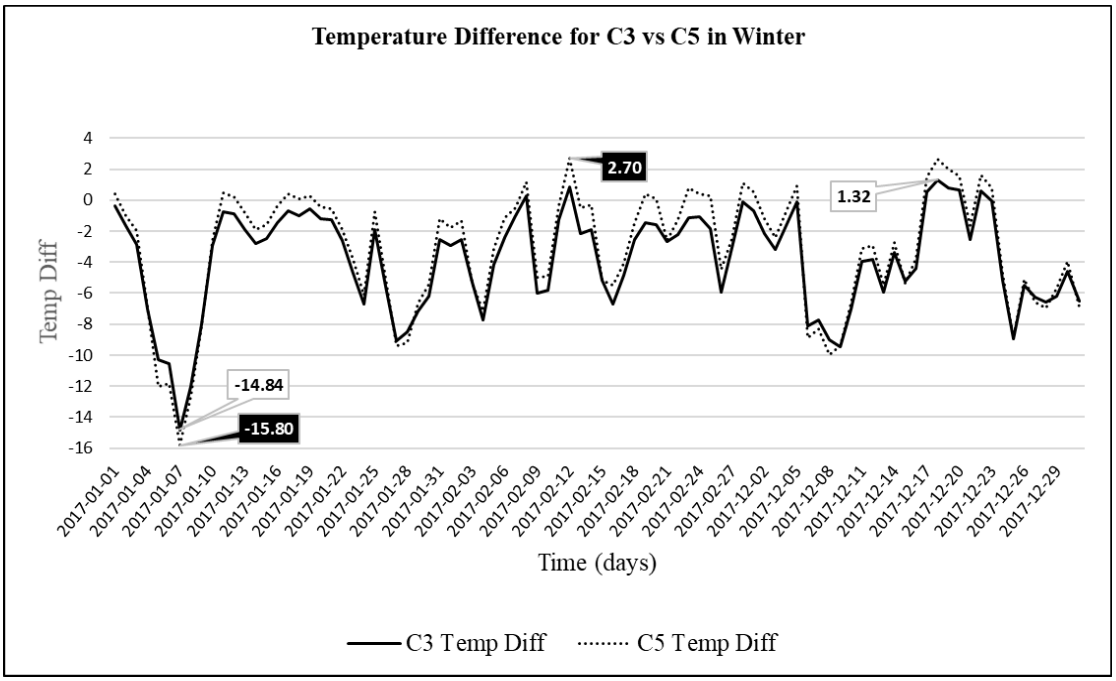

Figure 4.12: Average Temperature difference variation for C3 vs C5 in Winter

The temperature difference for C4 and C5 in the winter are presented in the Figure 4.13. The records show that the temperature difference for C4 varies between -15.01 °F and 3.06 °F while C5 varies between -15.8 °F and 2.7 °F. The average temperature difference of C4 (-2.78 °F) when compared to C5 (-3.09 °F) was reduced by about 0.31 °F. There is a significant difference in performance between both C4 and C5 as seen in Figure 4.13. The total temperature difference for the C4 is more than C5. Based on the assumption that the lower the temperature difference, the better the performance in winter, the records below indicates C5 as a better performing glazing than C4.

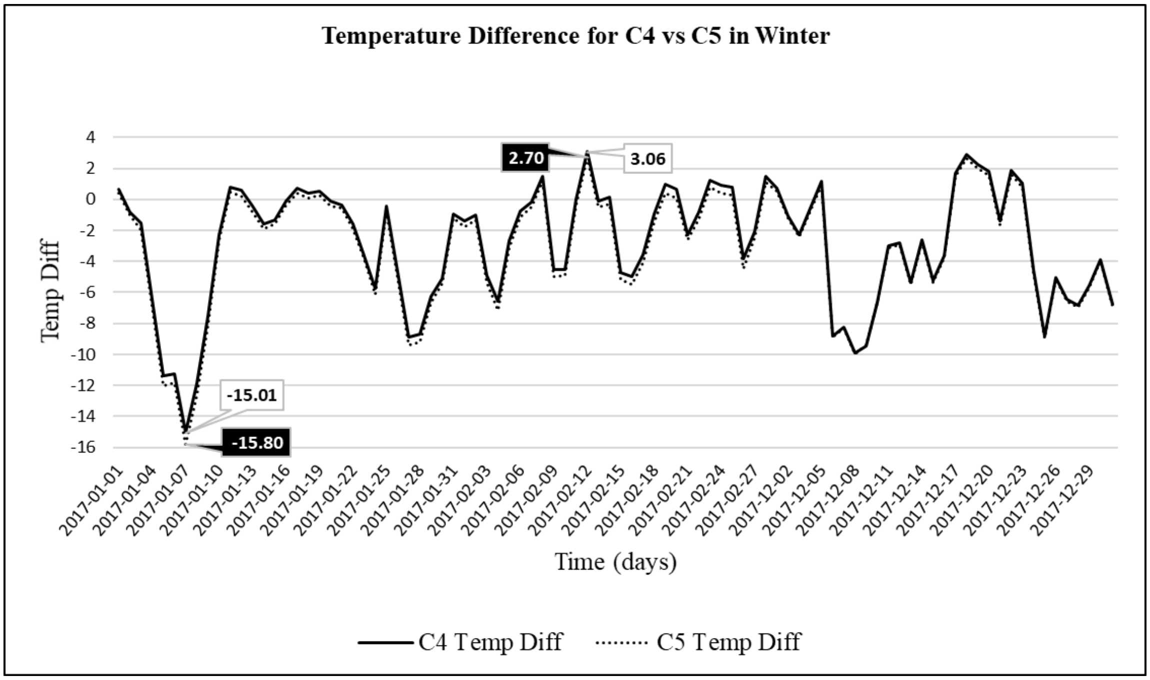

Figure 4.13: Average Temperature difference variation for C4 vs C5 in Winter

4.2 SPRING

The maximum, average and minimum ambient temperature between the day and night in the spring months are shown in Figure 4.14. As illustrated in the figure below, the average daily temperature in the spring months varied between 45 ºF and 81 ºF. The maximum temperature was 89 ºF and the minimum temperature measured as 34 ºF. Similar to the winter, the lower temperatures were also experienced at night and the maximum temperatures during the day.

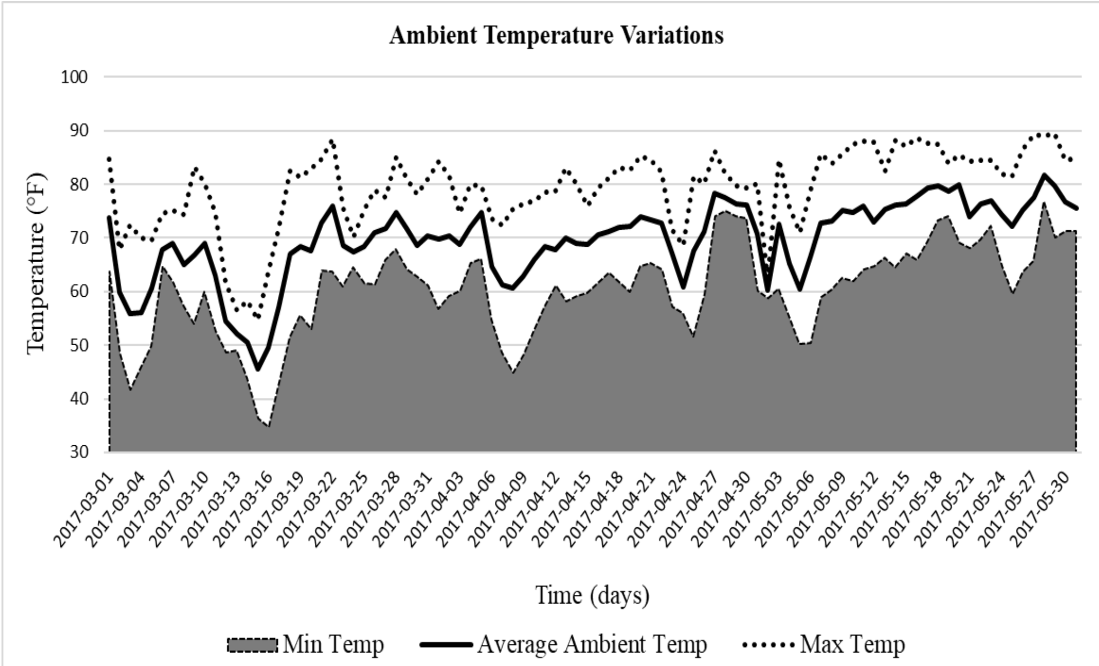

Figure 4.14: Ambient temperature for the Spring months

4.2.1 Glazing Surface Temperatures

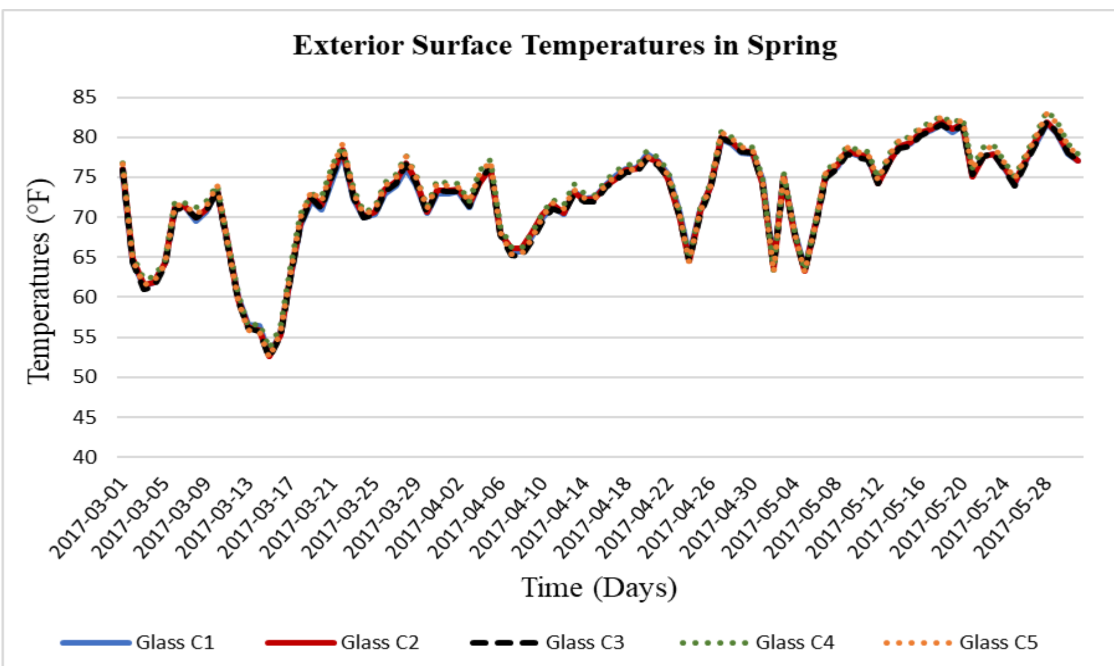

Figure 4.15: Average Exterior Surface Temperature for the Spring months

The interior and exterior surface temperatures for each glazing unit was recorded for the spring season. The Figure 4.15 represents the exterior surface temperatures for each glazing plotted against each other through this season. The record showed that the exterior surface temperature varies as high as 99 ºF and as low as 39 ºF where the ambient temperature varies between 34 ºF and 89 ºF.

The average exterior temperature for the control glazing (C1) and glazing C2, C3, C4, C5 are 71.15 ºF, 71.3 ºF, 71.9 ºF, 70.62 ºF and 70.76 ºF respectively. The points where the lines overlap each other represent similarities in the temperature measured for all the glazing types during this period and points that do not overlap show the differences between each glazing as seen in Figure 4.15.

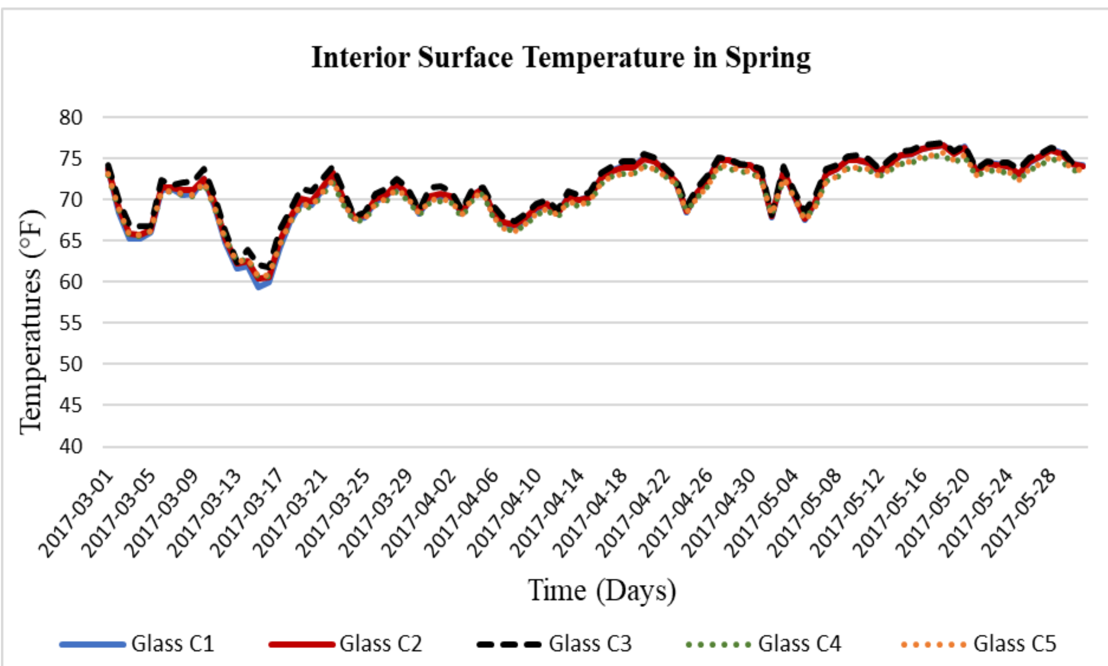

Figure 4.16: Average Interior Surface Temperature for the Spring months

The interior surface temperatures for each glazing plotted against each other during the spring season is presented in Figure 4.16. The record showed that the interior surface temperature varies as high as 85 ºF and as low as 51 ºF where the ambient temperature in the spring varies between 34 ºF and 89 ºF. The average interior temperature for the control glazing (C1) and glazing C2, C3, C4, C5 are 71.15 ºF, 71.3 ºF, 71.9 ºF, 70.62 ºF and 70.76 ºF respectively. The points where the lines overlap each other represent similarities in the temperature measured for all the glazing types during this period and points that do not overlap show the differences between each glazing as seen in Figure 4.16.

4.2.2 Thermal Performance Analysis

The thermal performance measurement was determined by the mean temperature differences between the exterior and interior surface temperatures. The temperature difference for each glazing was also calculated by subtracting the interior from the exterior temperature. Hence, when exterior temperature is more than interior temperature i.e Ext. Temp > Int. Temp, the temperature difference was positive and when exterior temperature is less than interior temperature i.e Ext. Temp < Int. Temp, the temperature difference was observed to be negative.

$$\text{Ext. Temp} - \text{Int. Temp} = \Delta \text{ Temp. Diff}$$

The analysis of variance carried out on the temperature difference results indicates that there is a statistical difference between the performances of each glazing. The results provide the overall means (M) and standard deviation (S.D) for C1 (M=1.465, S.D=4.26), C2 (M=1.41 S.D=4.98, C3 (M=0.57 S.D=4.6), C4 (M=2.72 S.D=6.84) and C5 (M=2.27 S.D=6.2).

Table 4.4: Descriptive Statistics of each Glazing in Spring

	Mean	Std. Deviation
Glass C1	1.465	4.26258
Glass C2	1.4103	4.9784
Glass C3	0.5649	4.59525
Glass C4	2.7155	6.83604
Glass C5	2.2707	6.20013

The details of the ANOVA evaluation in Table 4.5 indicates the statistical difference with a P-value of 0.000 and based on these results, the null hypothesis was rejected with the result of the ANOVA.

Table 4.5: ANOVA analysis outputs for Temperature differences (C1 - C5)

Source	**Sum of Squares**	**df**	**Mean Square**	**F**	**P-value**
Glazing Type	122738.95	1	122738.95	930.748	0
Error	1139632.145	8642	131.871		

To determine where the statistical differences exist between the mean differences of each glazing, a follow up post-hoc test was conducted. This post-hoc test provides a pairwise comparison between each glazing and uses the P value to indicate where the statistical difference exists. From Table 4.6, the mean temperature differences for each glazing types are seen to be statistically different from one another. Each paired comparison (C1, C2), (C1, C3), (C1, C4) (C1, C5), (C2, C3), (C2, C4), (C2, C5), (C3, C4), (C3, C5), and (C4, C5) has a P-value less than 0.5.

Table 4.6: ANOVA post hoc pairwise comparison results

Glazing Type	Glazing Alternative	Mean Difference between Alternatives	Std. Error	P-value
C1	C2	0.055	0.019	0.04
	C3	0.900	0.022	0
	C4	-1.250	0.043	0
	C5	-0.806	0.029	0
C2	C3	0.845	0.022	0
	C4	-1.305	0.041	0
	C5	-0.860	0.026	0
C3	C4	-2.151	0.042	0
	C5	-1.706	0.027	0
C4	C5	0.445	0.033	0

The temperature difference for C1 and C2 in the spring are presented in the Figure 4.17. The records show that the temperature difference for C1 varies between -6.57 °F and 5.58 °F while C2 varies between -7.81 °F and 5.83 °F. The average temperature difference of C1 (1.47 °F) when compared to C2 (1.41 °F) was increased by about 0.06 °F. Although the performance looks similar, the analysis reveals there is a statistical difference in performance between both C1 and C2 as seen in Figure 4.4. Based on the assumption that the higher the temperature difference, the better the performance in spring, the records in Figure 4.2.4 indicates C1 as a better performing glazing than C2.

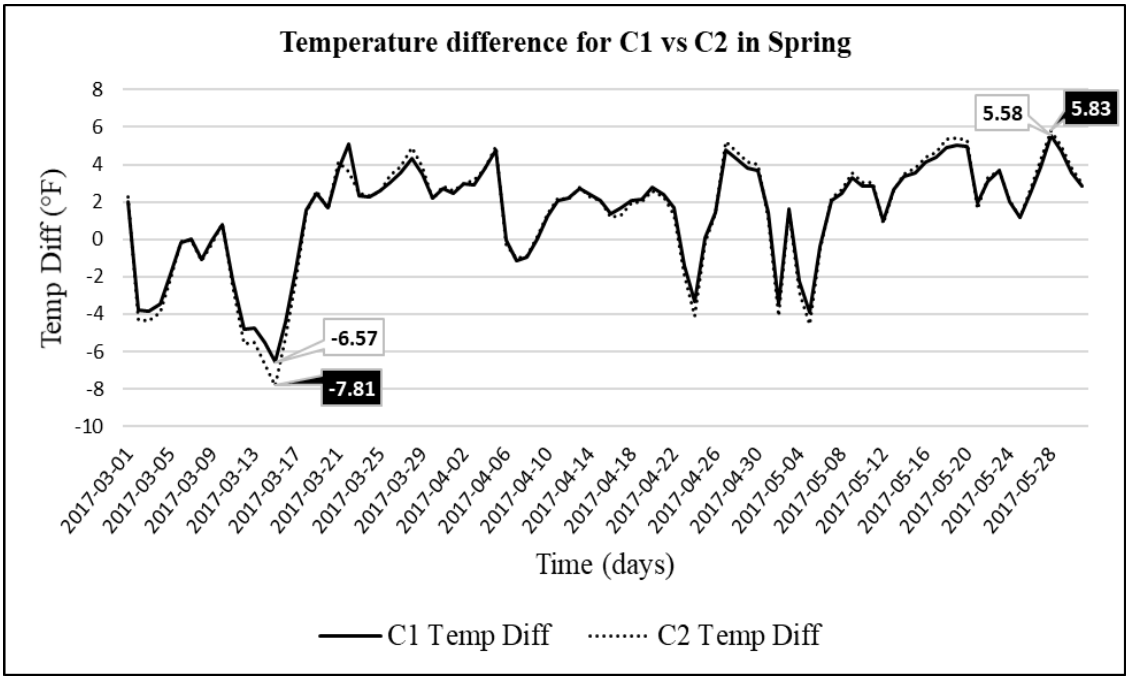

Figure 4.17: Average Temperature Difference Variation for C1 vs C2 in Spring

The temperature difference for C1 and C3 in the spring are presented in the Figure 4.18. The records show that the temperature difference for C1 varies between -6.57 °F and 5.58 °F while C3 varies between -9.64 °F and 5.62 °F. The average temperature difference of C1 (1.47 °F) when compared to C3 (0.57 °F) was increased by about 0.9 °F. The details in Figure 4.18 show the significant difference in performance between both C1 and C3 though a very close performance was seen between 27-Apr and 02-May. Based on the assumption that the higher temperature difference means the better performance in spring, the records below indicates C1 as a better performing glazing than C3.

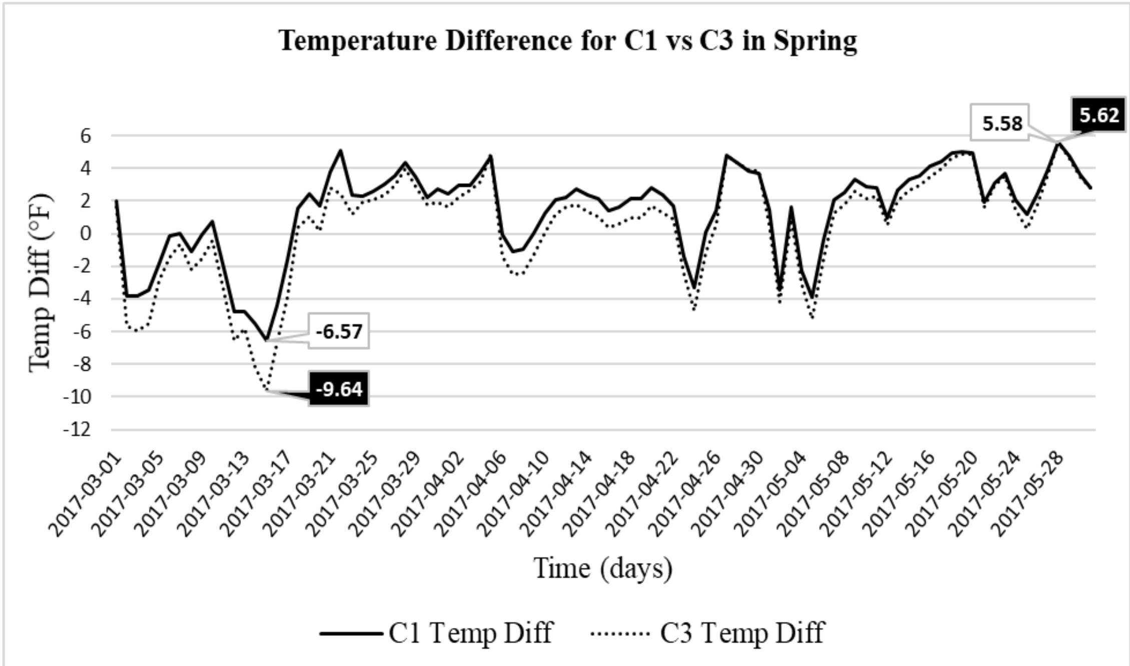

Figure 4.18: Average Temperature Difference Variation for C1 vs C3 in Spring

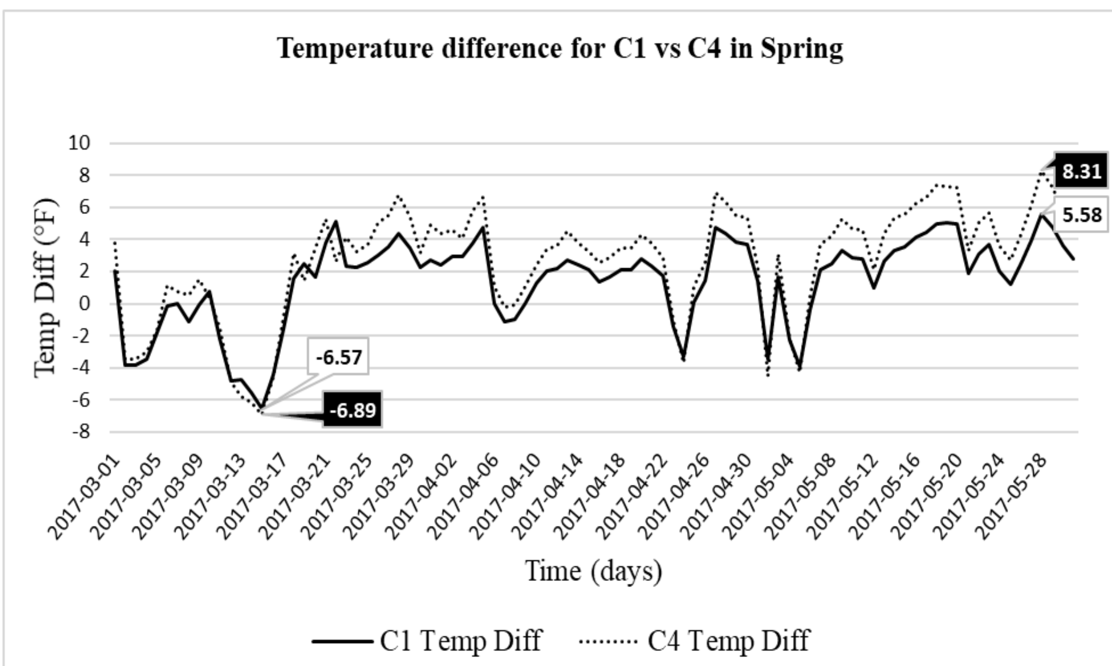

Figure 4.19: Average Temperature Difference Variation for C1 vs C4 in Spring

The temperature difference for C1 and C4 in the spring are presented in Figure 4.19. The records show that the temperature difference for C1 varies between -6.57 °F and 5.58 °F while C4 varies between -6.89 °F and 8.31 °F. The average temperature difference of C1 (1.47 °F) when compared to C4 (2.72 °F) was increased by about 1.25 °F. The details in Figure 4.19 show the significant difference in performance between both C1 and C4 through the spring period. It was observed that C1 has a lower total temperature difference than and based on the assumption that the higher temperature difference means the better performance in spring, the records below indicates C4 as a better performing glazing than C1.

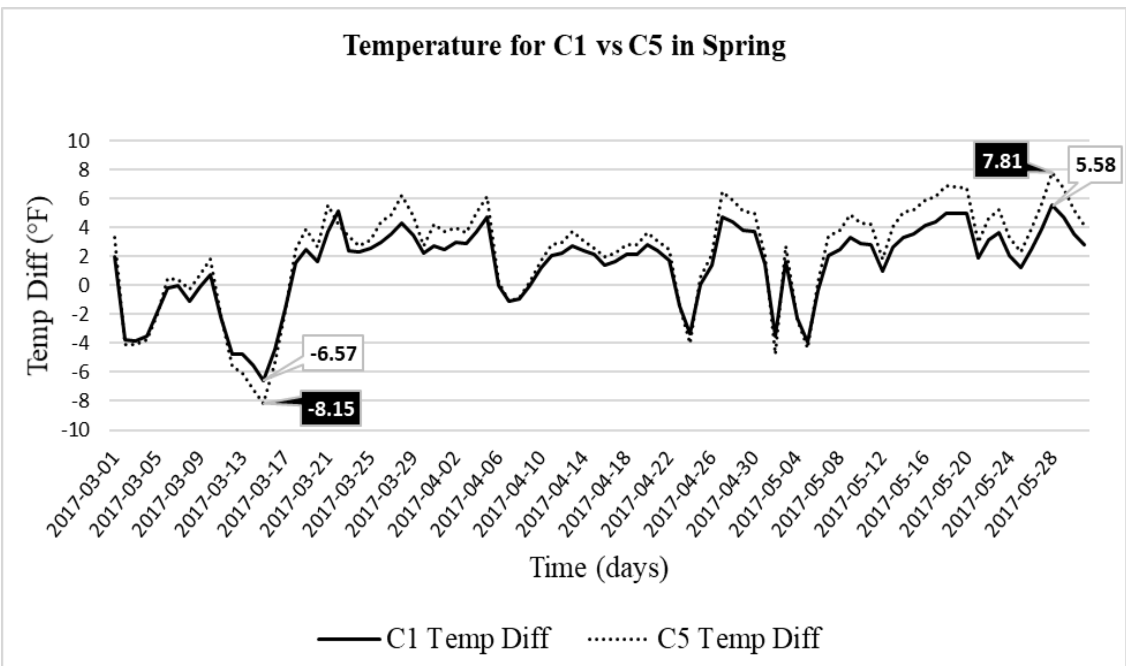

Figure 4.20: Average Temperature Difference Variation for C1 vs C5 in Spring

The temperature difference for C1 and C5 in the spring are presented in Figure 4.20. The records show that the temperature difference for C1 varies between -6.57 °F and 5.58 °F while C5 varies between -8.15 °F and 7.81 °F. The average temperature difference of C1

(1.47 °F) when compared to C5 (2.27 °F) was increased by about 0.81 °F. The details in the Figure 4.20 show the significant difference in performance between both C1 and C5 through the spring period. The temperature difference for C5 is consistently higher that C1 except for a brief period of 4 days between 12-Mar and 16-Mar. This makes the total temperature difference for C5 higher than C1 and based on the assumption that the higher temperature difference makes a better performance in Spring, the records indicate C5 as a better performing glazing than C1.

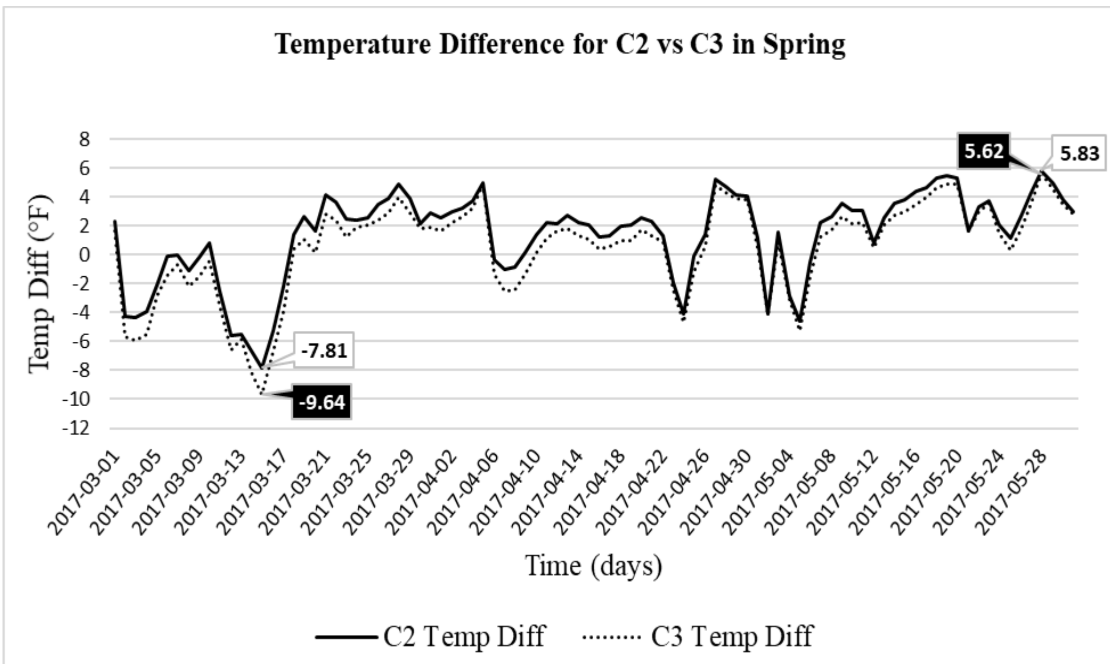

Figure 4.21: Average Temperature Difference Variation for C2 vs C3 in Spring

The temperature difference for C2 and C3 in the spring are presented in the Figure 4.21. The records show that the temperature difference for C2 varies between -7.81 °F and 5.83 °F while C3 varies between -9.64 °F and 5.62 °F. The average temperature difference of C2 (1.41 °F) when compared to C3 (0.57 °F) was increased by about 0.85 °F. There is a significant difference in performance between both C2 and C3 as seen in Figure 4.21. The total temperature difference for the C3 is less than C2. Based on the assumption that the higher the temperature difference, the better the performance in spring, the records below indicates C2 as a better performing glazing than C3.

The temperature difference for C2 and C4 in the spring are presented in the Figure 4.22. The records show that the temperature difference for C2 varies between -7.81 °F and 5.83 °F while C4 varies between -6.89 °F and 8.31 °F. The average temperature difference of C2 (1.41 °F) when compared to C4 (2.72 °F) was increased by about 1.305 °F. There is a significant difference in performance between both C2 and C4 as seen in Figure 4.22. The total temperature difference for the C2 is less than C4. Based on the assumption that the higher the temperature difference, the better the performance in spring, the records below indicates C4 as a better performing glazing than C2.

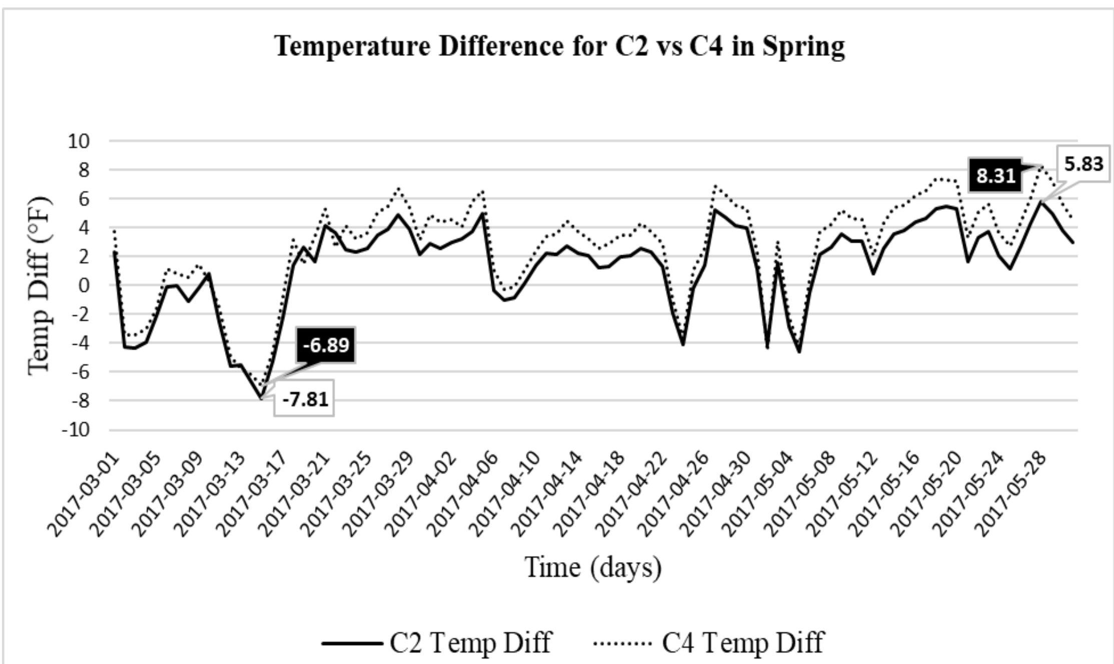

Figure 4.22: Average Temperature Difference Variation for C2 vs C4 in Spring

The temperature difference for C2 and C5 in the spring are presented in the Figure 4.23. The records show that the temperature difference for C2 varies between -7.81 °F and 5.83

°F while C5 varies between -8.15 °F and 7.81 °F. The average temperature difference of C2 (1.41 °F) when compared to C5 (2.27 °F) was reduced by about 0.86 °F. There is a significant difference in performance between both C2 and C5 as seen in the Figure 4.23. The total temperature difference for C2 is less than C5 and based on the assumption that the higher the temperature difference, the better the performance in spring, the records below indicates C5 as a better performing glazing than C2.

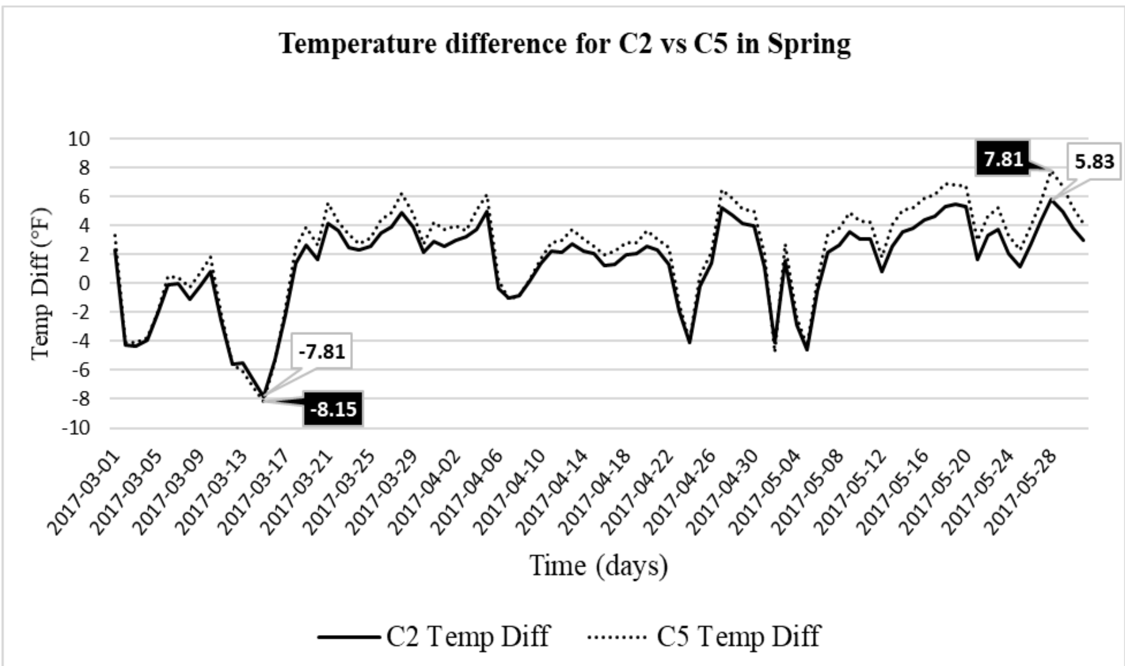

Figure 4.23: Average Temperature Difference Variation for C2 vs C5 in Spring

The temperature difference for C3 and C4 in the spring are presented in the Figure 4.24. The records show that the temperature difference for C3 varies between -9.64 °F and 5.62 °F while C4 varies between -6.89 °F and 8.31 °F. The average temperature difference of C3 (0.57 °F) when compared to C4 (2.72 °F) was increased by about 2.15 °F. There is a significant difference in performance between both C3 and C4 as seen in Figure 4.24. The total temperature difference for the C3 is less than C4. Based on the assumption that the higher the temperature difference, the better the performance in spring, the records below indicates C4 as a better performing glazing than C3.

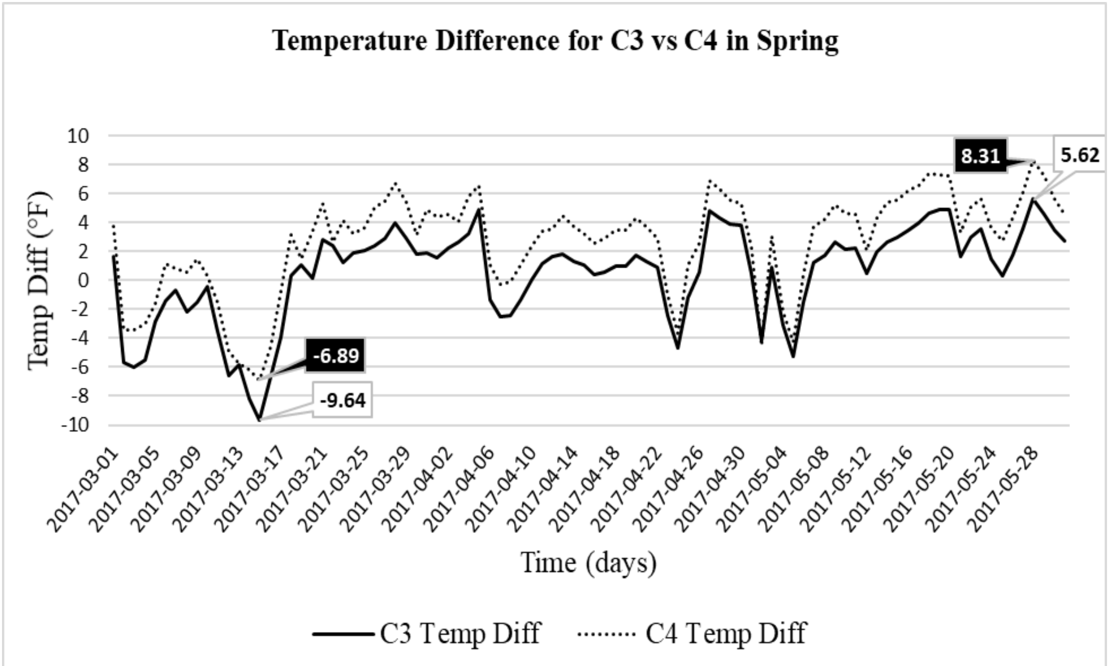

Figure 4.24: Average Temperature Difference Variation for C3 vs C4 in Spring

The temperature difference for C3 and C5 in the spring are presented in the Figure 4.25. The records show that the temperature difference for C3 varies between -9.64 °F and 5.62 °F while C5 varies between -8.15 °F and 7.81 °F. The average temperature difference of C3 (0.57 °F) when compared to C5 (2.27 °F) was increased by about 1.71 °F. There is a significant difference in performance between both C3 and C5 as seen in Figure 4.25. The total temperature difference for the C3 is less than C5. Based on the assumption that the higher the temperature difference, the better the performance in spring, the records below indicates C5 as a better performing glazing than C3.

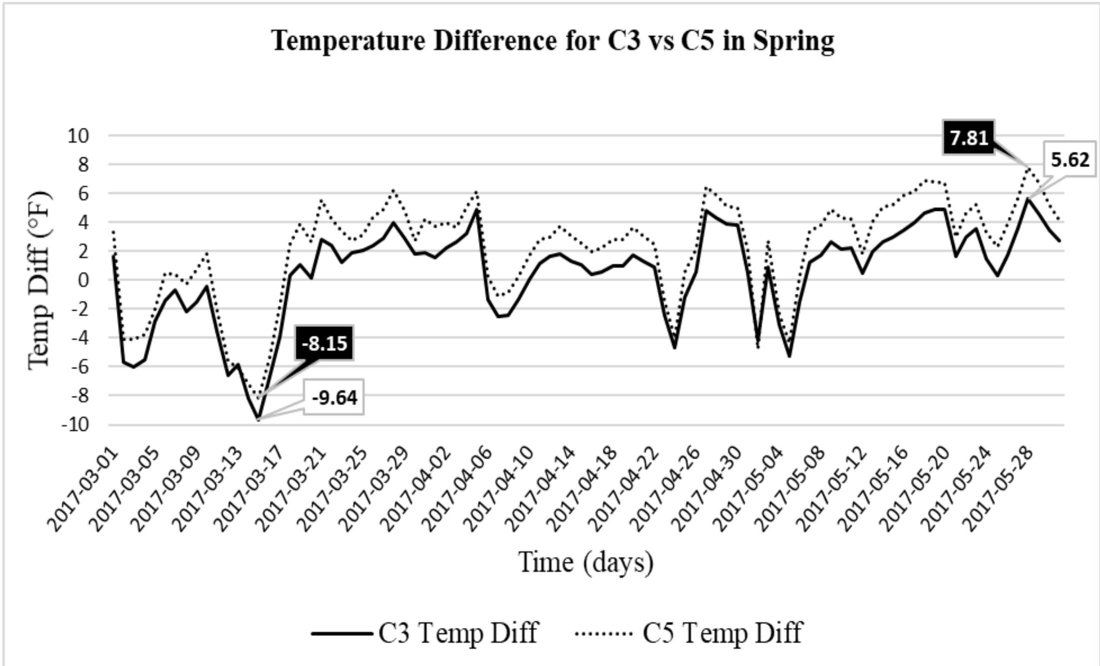

Figure 4.25: Average Temperature Difference Variation for C3 vs C5 in Spring

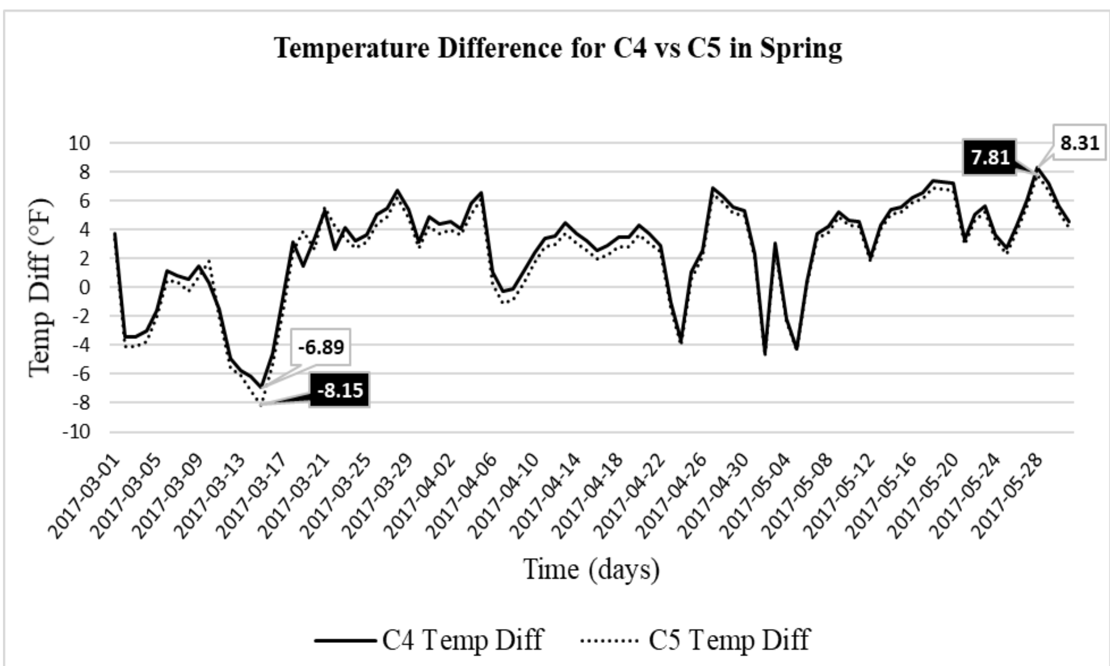

Figure 4.26: Average Temperature Difference Variation for C4 vs C5 in Spring

The temperature difference for C4 and C5 in the spring are presented in Figure 4.26. The records show that the temperature difference for C4 varies between -6.89 °F and 8.31 °F while C5 varies between -8.15 °F and 7.81 °F. The average temperature difference of C4 (2.72 °F) when compared to C5 (2.27 °F) was reduced by about 0.31 °F. There is a significant difference in performance between both C4 and C5 as seen in Figure 4.26. The total temperature difference for the C4 is more than C5. Based on the assumption that the higher the temperature difference, the better the performance in spring, the records below indicates C4 as a better performing glazing than C5.

4.3 SUMMER

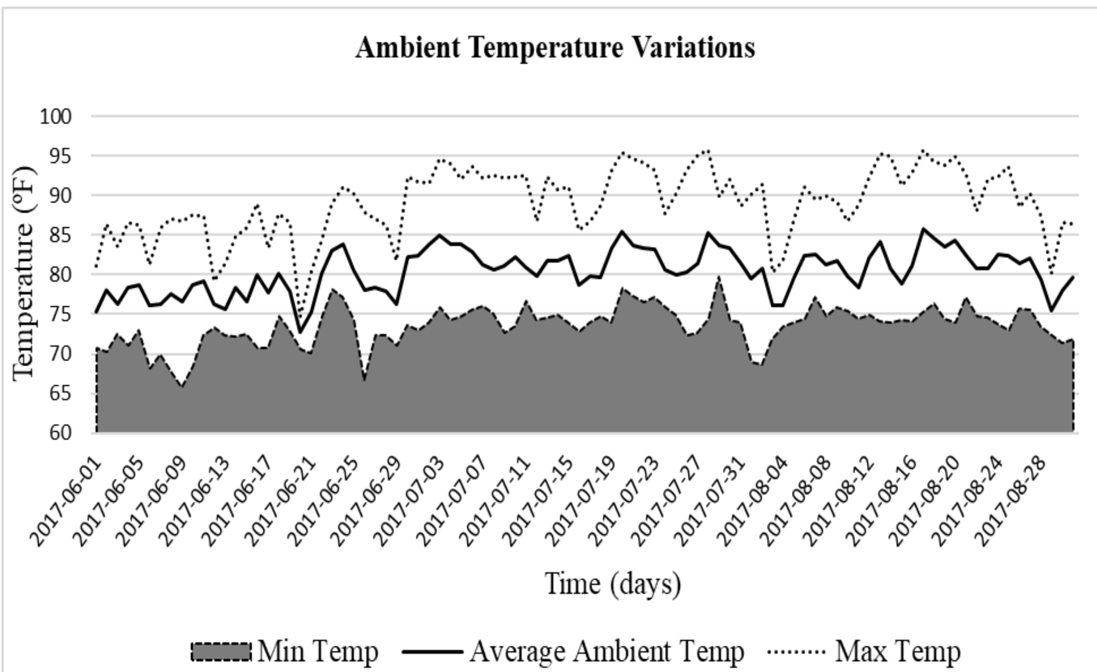

Figure 4.27: Ambient Temperature for the Summer Months

The maximum, average and minimum ambient temperature between the day and night in the summer months are shown in Figure 4.27. As illustrated in Figure 4.27, the average daily temperature in the summer months varied between 73ºF and 85ºF. The maximum temperature was 95ºF and the minimum temperature measured as 65ºF. The temperature generally drops during the night and attained the maximum measurement during the day.

4.3.1 Glazing Surface Temperatures

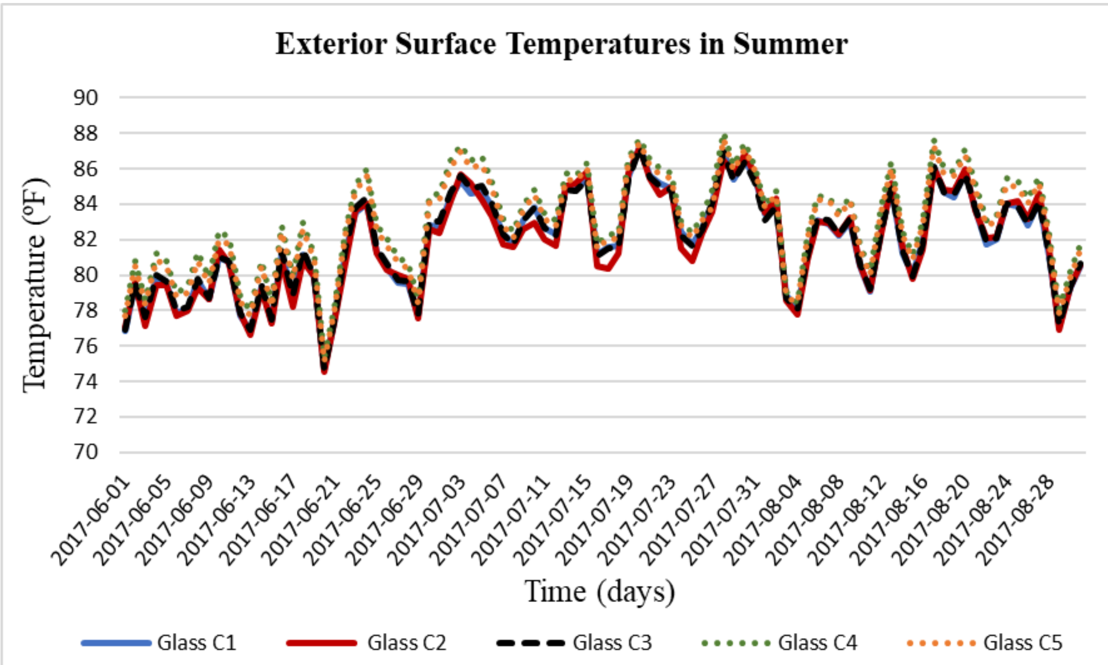

Figure 4.28: Average Exterior Surface temperature for the summer months

The interior and exterior surface temperatures for each glazing unit were measured throughout the summer season. The Figure 4.28 represents the exterior surface temperatures plotted against each other through the summer. The record showed that the exterior surface temperature varies as high as 88 ºF and as low as 74 ºF where the ambient temperature in the summer varies between 72 ºF and 85 ºF. The average exterior temperature for the control glazing (C1) and glazing C2, C3, C4, C5 are 81.92 ºF, 81.82 ºF, 81.97 ºF, 83.09 ºF and 82.78 ºF respectively. The pattern in Figure 4.28 shows points where the lines overlaps which indicates similarities in the temperature measured for the glazing types during this period. The glazing exterior surface temperatures are consistently higher than the ambient temperature. The impact from direct sunlight can heat the glazing surface through absorption more than the ambient air temperature (Crump, 2014).

In Figure 4.29, the interior surface temperatures for each glazing plotted against each other during the summer. The record showed that the exterior surface temperature varies as high as 94 ºF and as low as 70 ºF where the ambient temperature in the summer varies between 72 ºF and 85 ºF. The average interior temperature for the control glazing (C1) and glazing C2, C3, C4, C5 are 78.59 ºF, 78.06 ºF, 78.57 ºF, 77.23 ºF and 77.32 ºF respectively. The pattern in Figure 4.29 shows the consistent difference and similarities in the temperature measured for all the glazing types. Although the average ambient temperature is higher than the interior temperatures for most days, the days between 07-July and 06-August are periods where the interior temperature is higher than the ambient temperature.

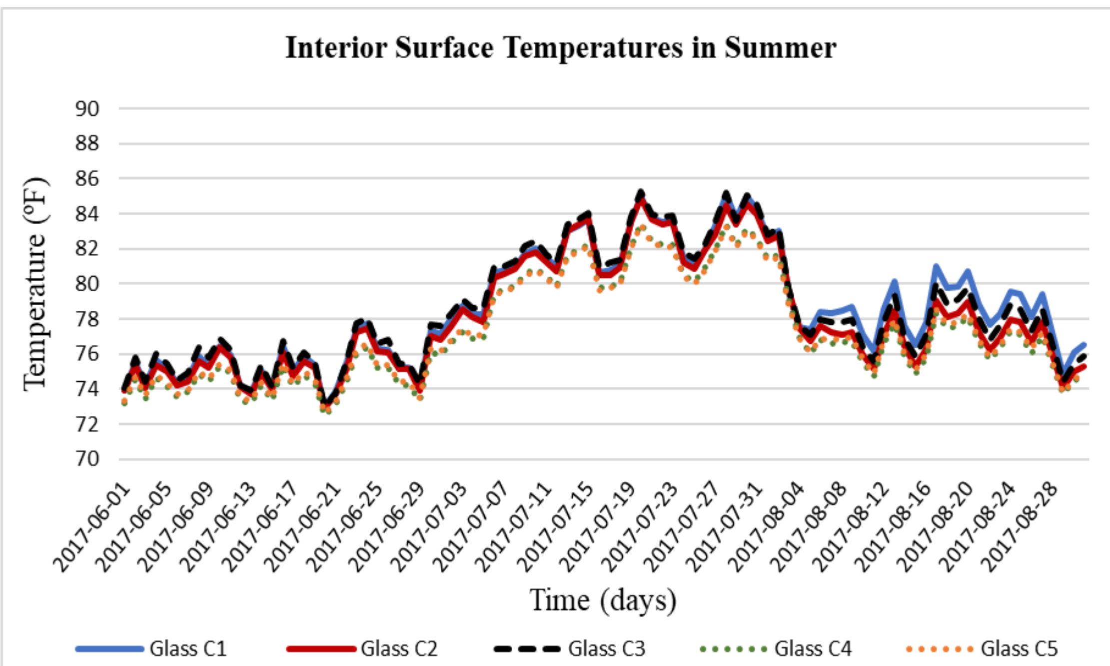

Figure 4.29: Average Interior Surface Temperature for the Summer Months

4.3.2 Thermal performance analysis for summer

The thermal performance measurement for this study was determined by the mean temperature differences between the exterior and interior surface temperature. The temperature difference for each glazing was calculated by subtracting the interior from the interior temperature. Hence, when exterior temperature is more than interior temperature i.e Ext. Temp > Int. Temp, the temperature difference was positive and when exterior temperature is less than interior temperature i.e Ext. Temp < Int. Temp, the temperature difference was observed to be negative.

$$\text{Ext. Temp} - \text{Int. Temp} = \Delta \text{ Temp. Diff}$$

The analysis of variance carried out on the temperature difference results indicates that there is a statistical difference between the performance of glazing C1 (M=3.29, S.D=3.47), C2 (M=3.73 S.D=3.72, C3 (M=3.40 S.D=2.85), C4 (M=5.79 S.D=4.91) and C5 (M=5.35 S.D=5.41).

Table 4.7: Descriptive Statistics for each Glazing in Summer

	Mean	Std. Deviation
Glass1	3.29	3.47
Glass2	3.73	3.72
Glass3	3.40	2.85
Glass4	5.79	4.91
Glass5	5.35	5.41

The details of the ANOVA evaluation in Table 4.8 indicates the statistical difference with a P-value of 0 which was significantly less than the alpha value of 0.5 set for the study.

This indicates that there is a statistical difference between the performances of C1, C2, C3, C4 and C5 in the winter at 95% confidence level [F (1, 8737) = 12772.3] .

Table 4.8: ANOVA analysis output for glazing during summer (C1- C5)

Source	Sum of Squares	df	Mean Square	F	P-value
Glazing Types	812316	1	812316	12772.3	0
Error	555673	8737	63.6		

The null hypothesis is rejected with the result of the ANOVA. To determine where the statistical differences exist between the mean differences of each glazing, a follow up post-hoc test was conducted.

Table 4.9 ANOVA post hoc pairwise comparison results

Glazing Type	Glazing Alternative	Mean Difference between alternatives	Std. Error	P-value
C1	C2	-0.437	0.031	0
	C3	-0.112	0.023	0
	C4	-2.501	0.04	0
	C5	-2.058	0.048	0
C2	C3	0.325	0.021	0
	C4	-2.064	0.037	0
	C5	-1.621	0.045	0
C3	C4	-2.389	0.033	0
	C5	-1.946	0.042	0
C4	C5	0.443	0.039	0

This post-hoc test provides a pairwise comparison between each glazing and uses the P value (Table 4.9) to indicate where the statistical difference exists. From Table 4.9, the mean temperature differences for each glazing types is statistically different from one another. Each paired comparison (C1, C2), (C1, C3), (C1, C4) (C1, C5), (C2, C3), (C2, C4), (C2, C5), (C3, C4), (C3, C5), and (C4, C5) has a P-value less than 0.5.

The temperature difference for C1 and C2 in the summer are presented in Figure 4.30. The records show that the temperature difference for C1 varies between -0.69 °F and 6.59 °F while C2 varies between -1.17 °F and 7.14 °F. The average temperature difference of C1 (3.29 °F) when compared to C2 (3.73 °F) was increased by about 0.44 °F. There is a statistical difference in performance between both C1 and C2 as seen in the Figure 4.30 and based on the assumption that the higher the temperature difference, the better the performance in summer`, the records indicates C2 as a better performing glazing than C1.

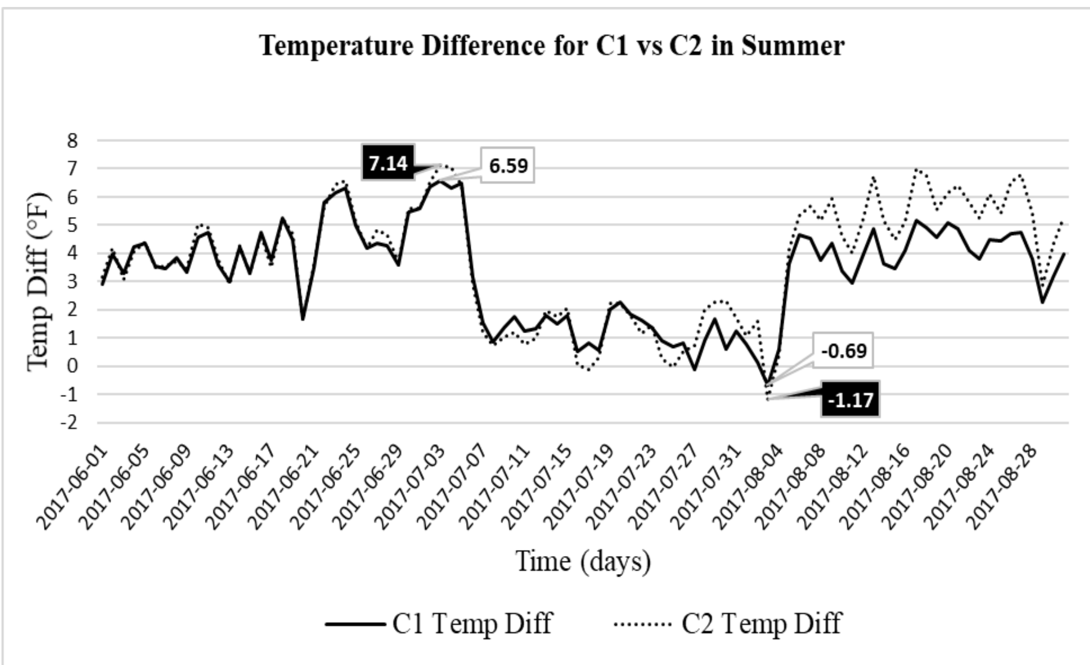

Figure 4.30: Temperature difference variation for C1 vs C2 in Summer

The temperature difference for C1 and C3 in the summer are presented in the Figure 4.31. The records show that the temperature difference for C1 varies between -0.69 °F and 6.59

°F while C3 varies between -1.03 °F and 6.55 °F. The average temperature difference of C1 (3.29 °F) when compared to C3 (3.403 °F) was increased by about 0.112 °F. The details in the Figure 4.31 show the significant difference in performance between both C1 and C3. Based on the assumption that the higher temperature difference means the better performance in spring, the records below indicates C3 as a better performing glazing than C1.

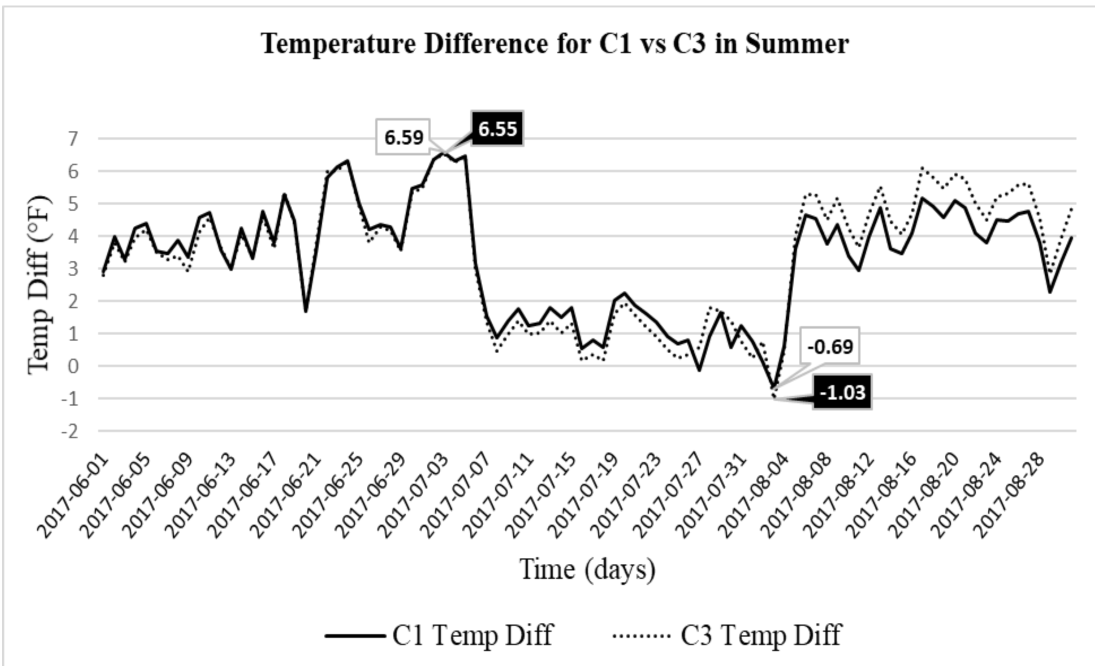

Figure 4.31: Temperature difference variation for C1 vs C3 in summer

The temperature difference for C1 and C4 in the summer are presented in Figure 4.32. The records show that the temperature difference for C1 varies between -0.69 °F and 6.59 °F while C4 varies between -0.02 °F and 10.07 °F. The average temperature difference of C1 (3.29 °F) when compared to C4 (5.79 °F) was increased by about 2.5 °F. The details in Figure 4.32 show the significant difference in performance between both C1 and C4 through the summer period. It was observed that C1 has a lower total temperature difference than and based on the assumption that the higher temperature difference means the better performance in winter, the records below indicates C4 as a better performing glazing than C1.

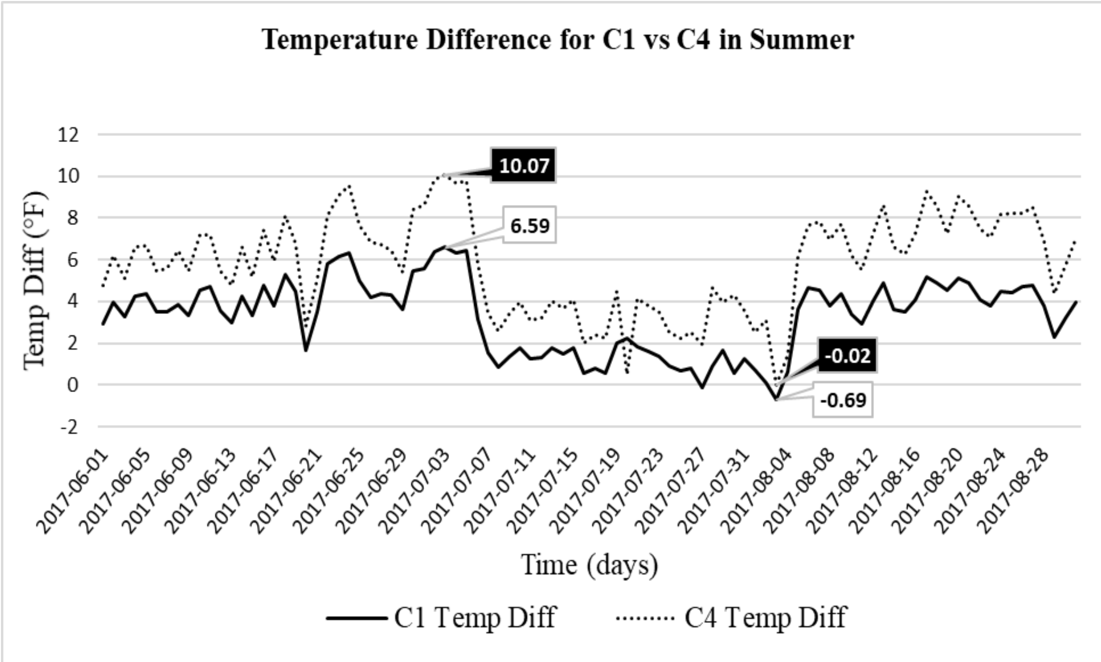

Figure 4.32: Average Temperature difference variation for C1 vs C4 in summer

The temperature difference for C1 and C5 in the summer are presented in Figure 4.33. The records show that the temperature difference for C1 varies between -0.69 °F and 6.59 °F while C5 varies between -3.36 °F and 9.51 °F. The average temperature difference of C1 (3.29 °F) when compared to C5 (5.35 °F) was increased by about 2.06 °F. The details in Figure 4.33 show the significant difference in performance between both C1 and C5 through the summer period. The total temperature difference for C5 is higher than C1 and based on the assumption that the higher temperature difference makes a better performance; the records indicate C5 as a better performing glazing than C1.

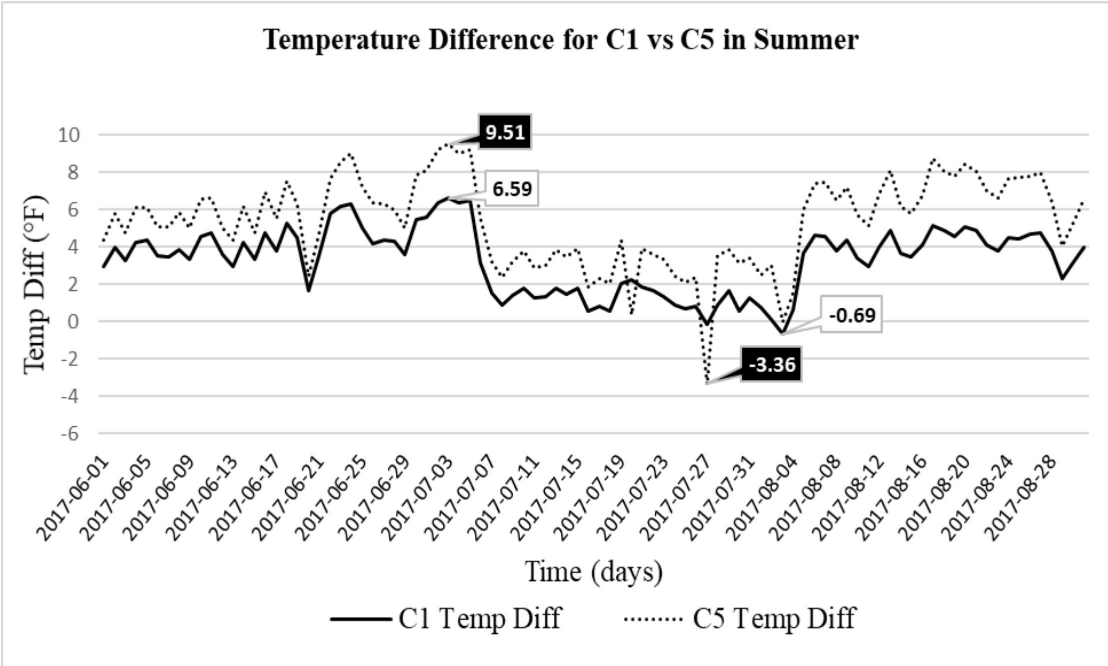

Figure 4.33: Average Temperature difference variation for C1 vs C5 in summer

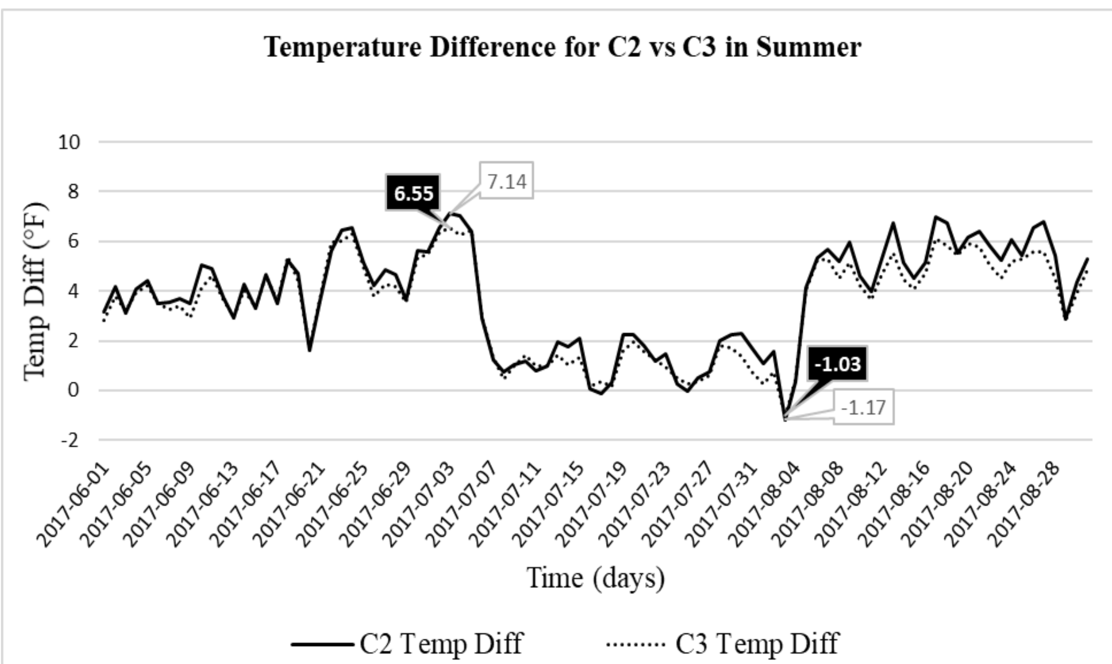

Figure 4.34: Average Temperature difference variation for C2 vs C3 in Summer

The temperature difference for C2 and C3 in the summer are presented in Figure 4.34. The records show that the temperature difference for C2 varies between -1.17 °F and 7.14 °F while C3 varies between -1.03 °F and 6.55 °F. The average temperature difference of C2 (3.73 °F) when compared to C3 (3.40 °F) was reduced by about 0.33 °F. There is a significant difference in performance between both C2 and C3 as seen in Figure 4.34. The total temperature difference for the C3 is less than C2. Based on the assumption that the lower the temperature difference, the better the performance in summer, the records below indicates C2 as a better performing glazing than C3.

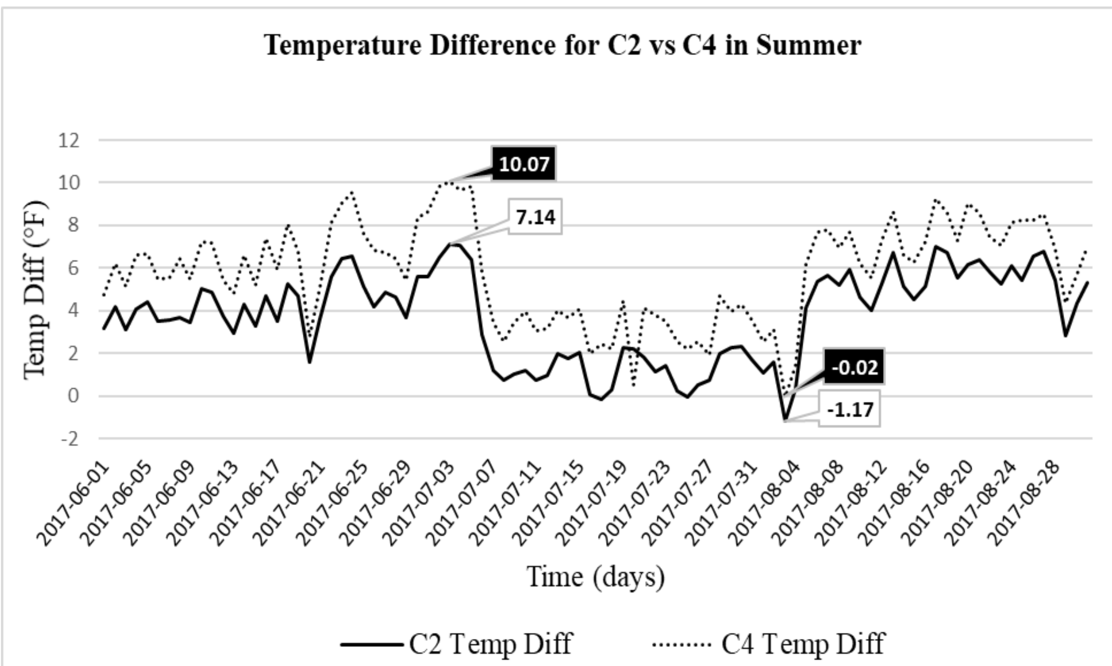

Figure 4.35: Average Temperature difference variation for C2 vs C4 in Summer

The temperature difference for C2 and C4 in the summer are presented in Figure 4.35. The records show that the temperature difference for C2 varies between -1.17 °F and 7.14 °F while C4 varies between -0.02 °F and 10.07 °F. The average temperature difference of C2 (3.73 °F) when compared to C4 (5.79 °F) was increased by about 2.06 °F. There is a significant difference in performance between both C2 and C4 as seen in Figure 4.35. The total temperature difference for the C2 is less than C4 and based on the assumption that the higher the temperature difference, the better the performance in summer, the records below indicates C4 as a better performing glazing than C2.

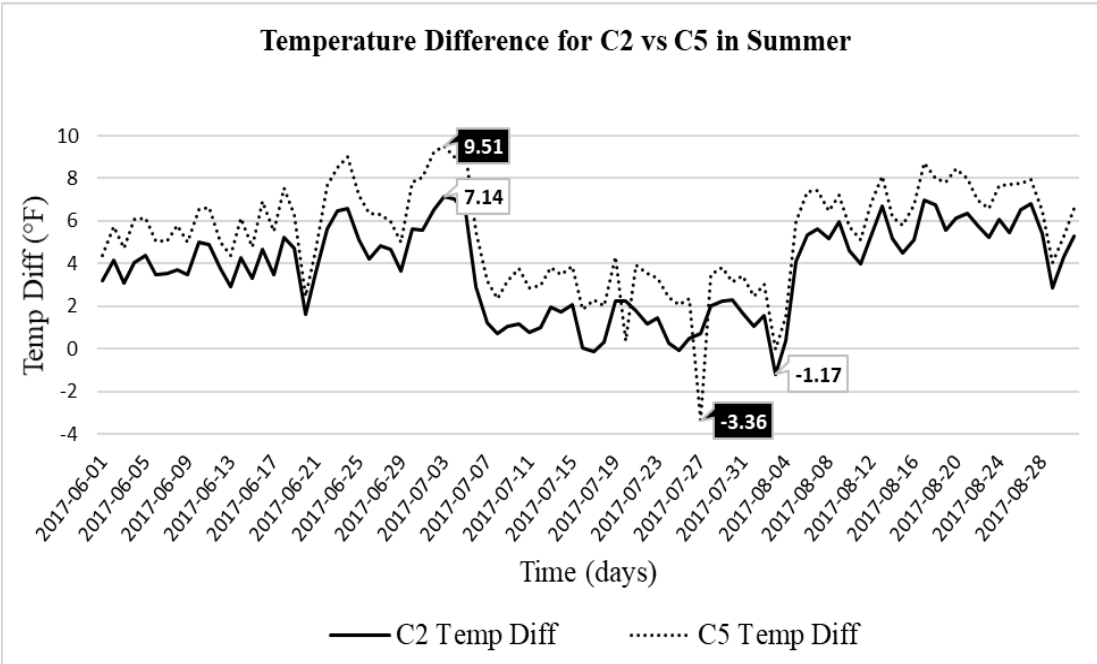

Figure 4.36: Average Temperature difference variation for C2 vs C5 in Summer

The temperature difference for C2 and C5 in the summer are presented in Figure 4.36. The records show that the temperature difference for C2 varies between -1.17 °F and 7.14 °F while C5 varies between -3.36 °F and 9.51 °F. The average temperature difference of C2 (3.73 °F) when compared to C5 (5.35 °F) was increased by about 1.62 °F. There is a significant difference in performance between both C2 and C5 as seen in Figure 4.36. The total temperature difference for C2 is less than C5 and based on the assumption that the higher the temperature difference, the better the performance in summer, the records below indicates C5 as a better performing glazing than C2.

The temperature difference for C3 and C4 in the summer are presented in Figure 4.37. The records show that the temperature difference for C3 varies between -1.03 °F and 6.55 °F while C4 varies between -0.02 °F and 10.07 °F. The average temperature difference of C3 (3.40 °F) when compared to C4 (5.79 °F) was increased by about 2.39 °F. There is a significant difference in performance between both C3 and C4 as seen in Figure 4.37. The total temperature difference for the C3 is less than C4 and based on the assumption that the higher the temperature difference, the better the performance in summer, the records below indicates C4 as a better performing glazing than C3.

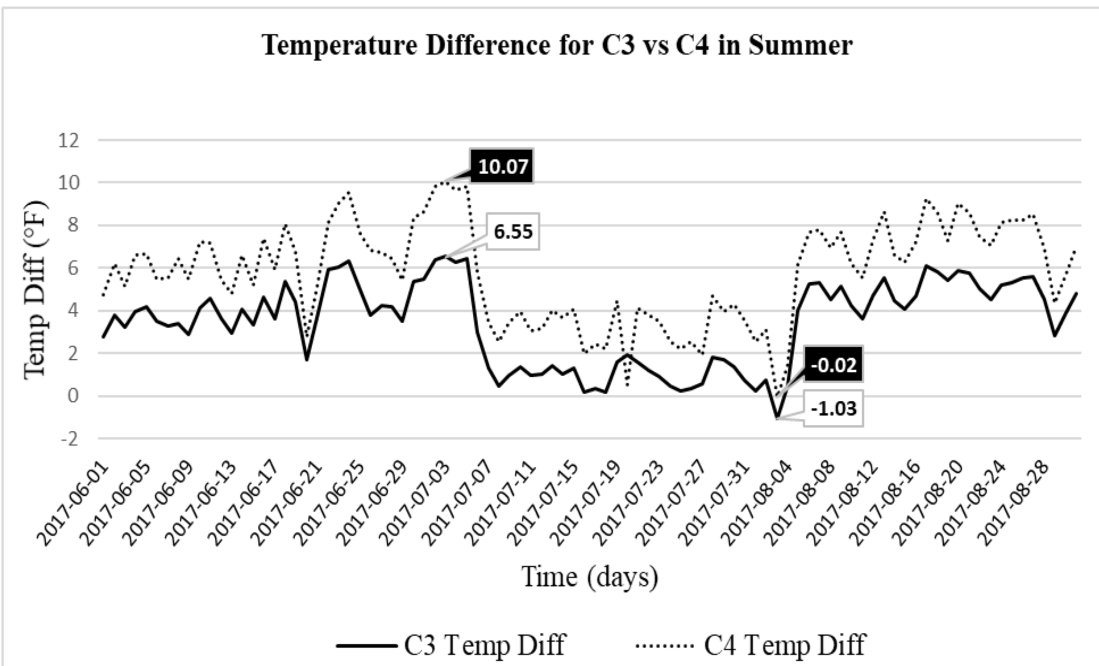

Figure 4.37: Average Temperature difference variation for C3 vs C4 in Summer

The temperature difference for C3 and C5 in the summer are presented in Figure 4.38. The records show that the temperature difference for C3 varies between -1.03 °F and 6.55 °F while C5 varies between -3.36 °F and 9.51 °F. The average temperature difference of C3 (3.40 °F) when compared to C5 (5.35 °F) was increased by about 1.95 °F. There is a significant difference in performance between both C3 and C5 as seen in Figure 4.38. The total temperature difference for the C3 is less than C5. Based on the assumption that the higher the temperature difference, the better the performance in summer, the records indicates C5 as a better performing glazing than C3.

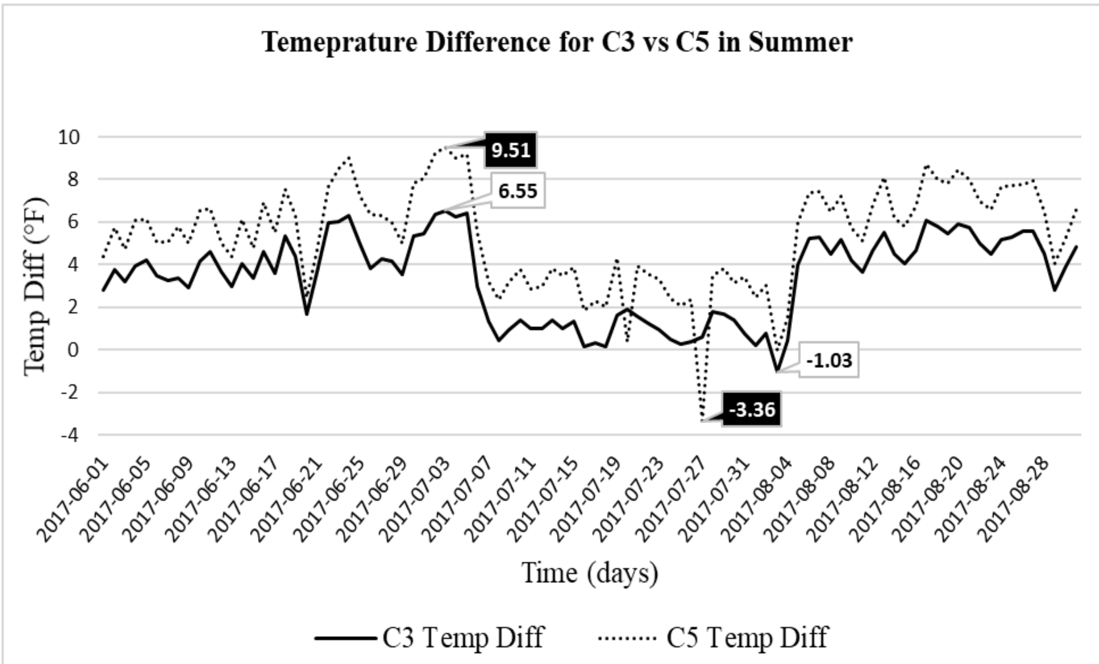

Figure 4.38: Average Temperature difference variation for C3 vs C5 in Summer

The temperature difference for C4 and C5 in the summer are presented in Figure 4.39. The records show that the temperature difference for C4 varies between -0.02 °F and 10.07 °F while C5 varies between -3.36 °F and 9.51 °F. The average temperature difference of C4 (5.79 °F) when compared to C5 (5.35 °F) was reduced by about 0.44 °F. There is a significant difference in performance between both C4 and C5 as seen in Figure 4.39. The total temperature difference for the C4 is more than C5. Based on the assumption that the higher the temperature difference, the better the performance in summer, the records below indicates C4 as a better performing glazing than C5.

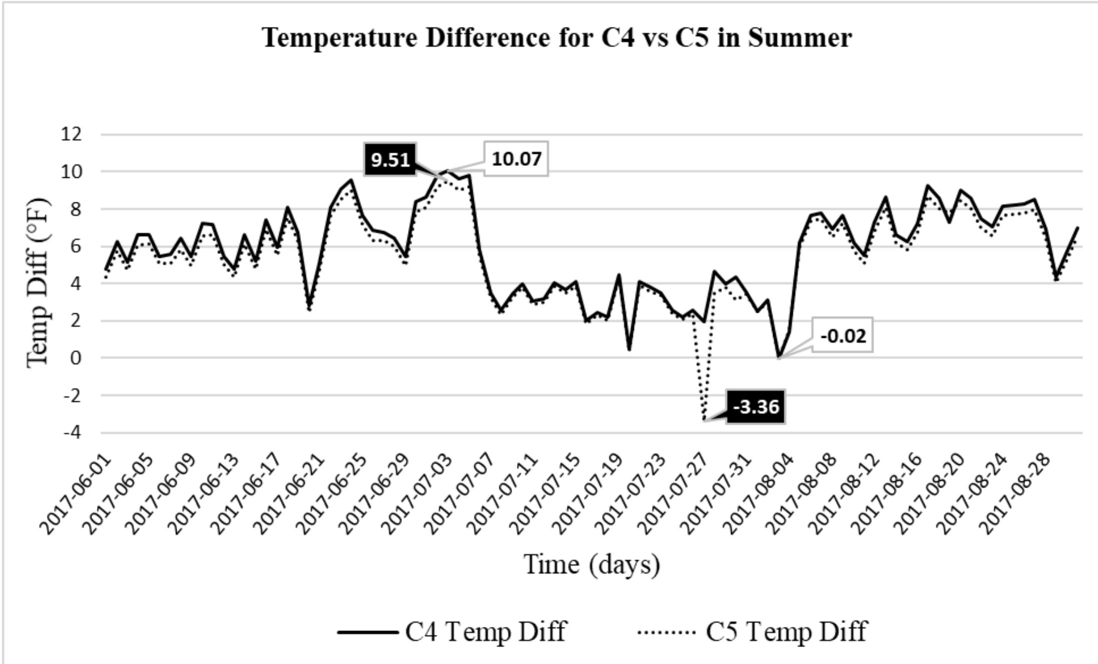

Figure 4.39: Average Temperature difference variation for C4 vs C5 in Summer

4.4 FALL

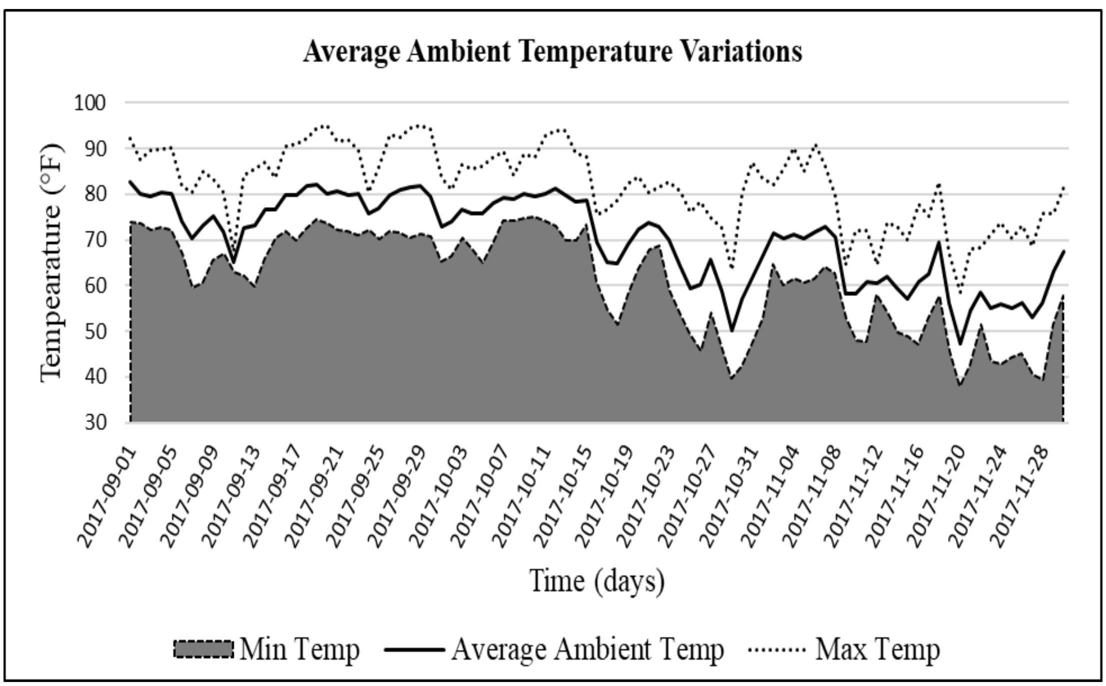

Figure 4.40: Average ambient temperature for the Fall months

The maximum, average and minimum ambient temperature between the day and night in the fall season (September- November) are shown in Figure 4.40. As illustrated in the figure below, the average daily ambient temperature in the fall season months varied between 47ºF and 82ºF. The maximum temperature was 95ºF and the minimum temperature measured as 38 ºF. The temperature was also observed to drop during the night and attained the maximum measurement during the day.

4.4.1 Glazing Surface Temperatures

The interior and exterior surface temperatures for each glazing unit were measured throughout the fall season. The exterior surface temperatures of each glazing are plotted against each other through the fall as seen in Figure 4.41. The record showed that the exterior surface temperature varies as high as 99 ºF and as low as 42 ºF where the ambient temperature in the summer varied between 38 ºF and 95 ºF.

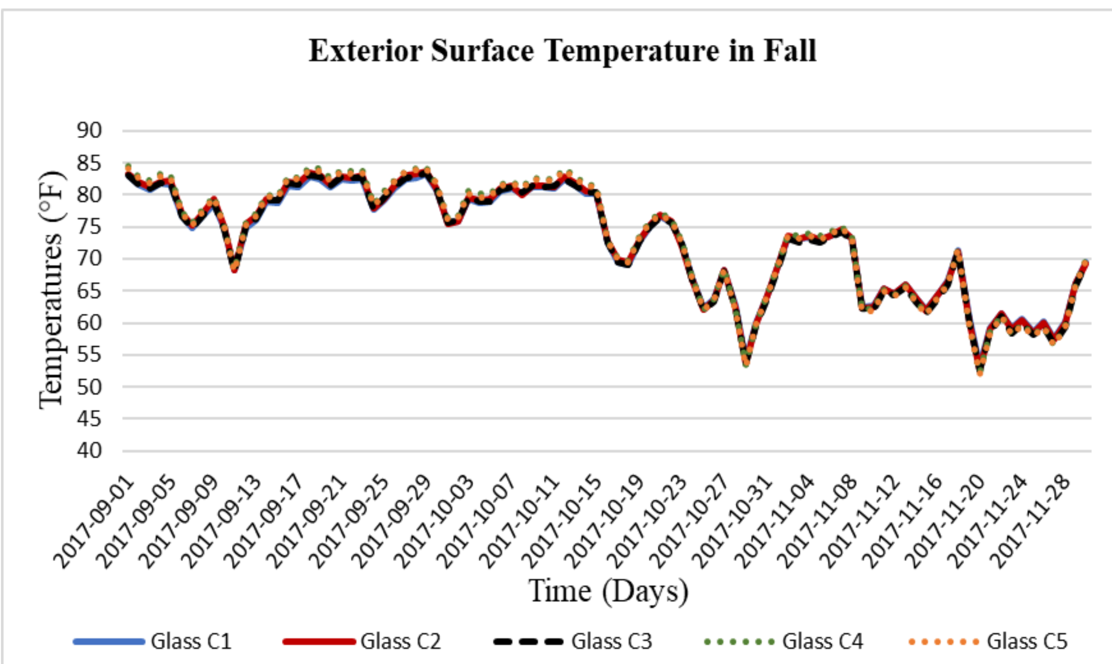

Figure 4.41: Average exterior surface temperature for the Fall months

The average exterior temperature for the control glazing (C1) and glazing C2, C3, C4, C5 are 72.87 ºF, 73 ºF, 72.76 ºF, 73.40 ºF and 73.18 ºF respectively. The points where the lines overlap in Figure 4.41 also shows the similarities in the temperature measured for all the glazing types during this period. .

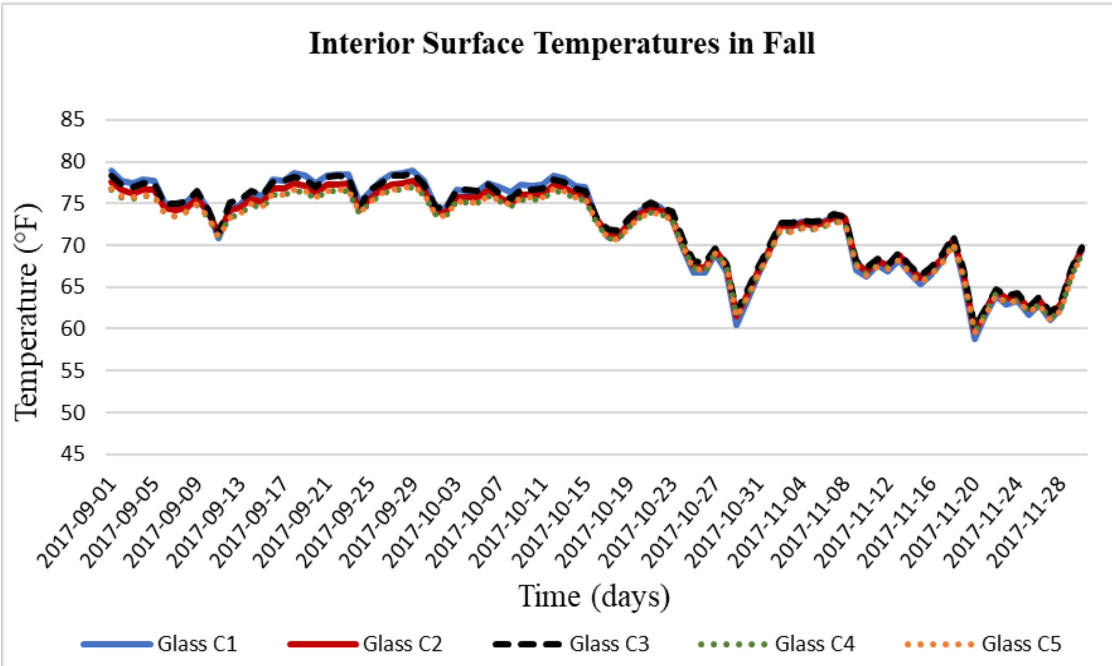

Figure 4.42: Average Interior Surface temperature for the Fall months

The interior surface temperatures for each glazing plotted against each other during the fall period is presented in Figure 4.42. The record showed that the interior surface temperature varies as high as 93 ºF and as low as 52 ºF where the ambient temperature in the summer varies between 38 ºF and 95 ºF. The average interior temperature for the control glazing (C1) and glazing C2, C3, C4, C5 are 72.35 ºF, 72.08 ºF, 72.64 ºF, 71.54 ºF and 71.56 ºF respectively. The points that overlap in Figure 4.42 also shows the similarities in the temperature measured for all the glazing types. Although the average ambient temperature is higher than the interior temperatures for most days, the days between 07-July and 06-August are periods where the interior temperature is higher than the ambient temperature.

4.4.2 Thermal Performance Analysis for Fall

The thermal performance measurement for this study was determined by the mean temperature differences between the exterior and interior. The temperature difference for each glazing was calculated by subtracting the interior from the interior temperature. Hence, when exterior temperature is more than interior temperature i.e Ext. Temp > Int. Temp, the temperature difference was positive and when exterior temperature is less than interior temperature i.e Ext. Temp < Int. Temp, the temperature difference was observed to be negative.

$$\text{Ext. Temp} - \text{Int. Temp} = \Delta \text{ Temp. Diff}$$

The analysis of variance carried out on the temperature difference results indicates that there is a statistical difference between the performances of glazing. The results show the overall means (M) and standard deviation (S.D) for C1 (M=0.52, S.D=3.97), C2 (M=0.91 S.D=5.40, C3 (M=0.12 S.D=4.75), C4 (M=1.76 S.D=7.08) and C5 (M=1.59 S.D=6.32).

Table 4.10: Descriptive Statistics for each Glazing in Fall

	Mean	Std. Deviation
GlassC1	0.52	3.97
GlassC2	0.91	5.40
GlassC3	0.12	4.75
GlassC4	1.76	7.08
GlassC5	1.59	6.32

The details of the ANOVA evaluation in Table 4.11 indicates the statistical difference with a P-value of 0 which was significantly less than the alpha value of 0.5 set for the study.

This indicates that there is a statistical difference between the performances of C1, C2, C3, C4 and C5 in the winter at 95% confidence level [F (1,8639) = 300.034]

Table 4.11: ANOVA analysis output for glazing during fall

Source	Sum of Squares	df	Mean Square	F	P-value
Glazing Types	41538.29	1	41538.29	300.034	0
Error	1196029	8639	138.445		

To determine where the statistical differences exist between the mean differences of each glazing, a follow up post hoc test was conducted. The details of the post hoc results through a pairwise comparison between each glazing (Table 4.12) indicates the statistical difference where the P value is less than 0.5.

Table 4.12: ANOVA post hoc pairwise comparison results

Glazing Type	Glazing Alternatives	Mean Difference between Alternatives	Std. Error	P-value
1	2	-.0389	0.022	0
	3	0.407	0.018	0
	4	-1.234	0.047	0
	5	-1.072	0.031	0
2	3	0.796	0.023	0
	4	-.0845	0.044	0
	5	-0.682	0.027	0
3	4	-1.641	0.042	0
	5	-1.479	0.029	0
4	5	0.162	0.037	0

From the Table 4.12, the mean temperature differences for each glazing types are seen to be statistically different from one another. Each paired comparison (C1, C2), (C1, C3),

(C1, C4) (C1, C5), (C2, C3), (C2, C4), (C2, C5), (C3, C4), (C3, C5), and (C4, C5) has a P-value less than 0.5.

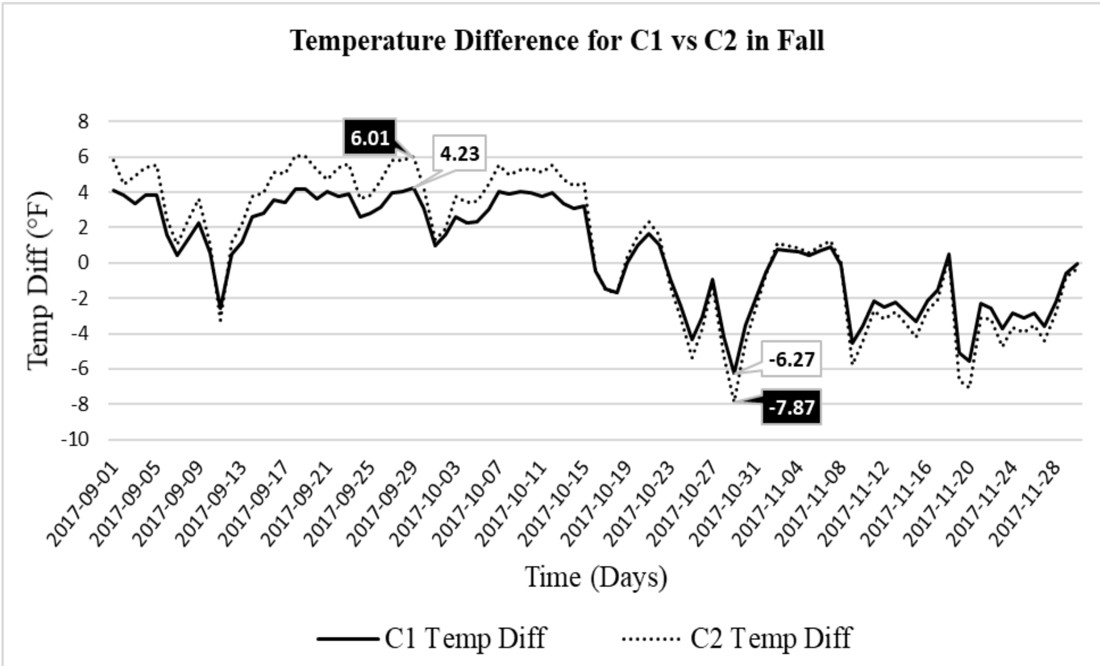

Figure 4.43: Average Temperature difference variation for C1 vs C2 in Fall

The temperature difference for C1 and C2 in the fall are presented in Figure 4.43. The records show that the temperature difference for C1 varies between -6.27 °F and 4.23 °F while C2 varies between -7.87 °F and 6.01 °F. The average temperature difference of C1 (0.52 °F) when compared to C2 (0.91 °F) was increased by about 0.39 °F. There is a statistical difference in performance between both C1 and C2 though the performance looks similar at certain points during the season as seen in the Figure 4.43. Based on the assumption that the higher the temperature difference, the better the performance in fall. The records in Figure 4.43 indicates C2 as a better performing glazing than C1.

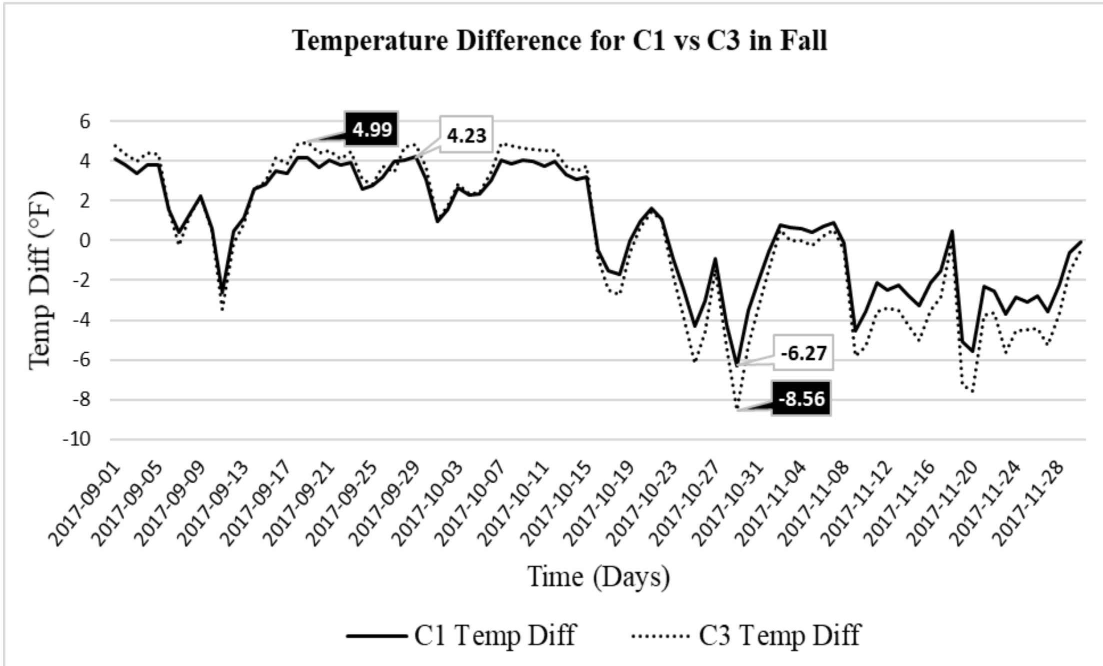

Figure 4.44: Average Temperature difference variation for C1 vs C3 in Fall

The temperature difference for C1 and C3 in the fall are presented in Figure 4.44. The records show that the temperature difference for C1 varies between -6.27 °F and 4.23 °F while C3 varies between -8.56 °F and 4.99 °F. The average temperature difference of C1 (0.52 °F) when compared to C3 (0.12 °F) was increased by about 0.41 °F. The details in Figure 4.44 show the significant difference in performance between both C1 and C3 in spite of the similar performances observed at several points during the season. Based on the assumption that the higher temperature difference means the better performance in fall, the records indicates C1 as a better performing glazing than C3.

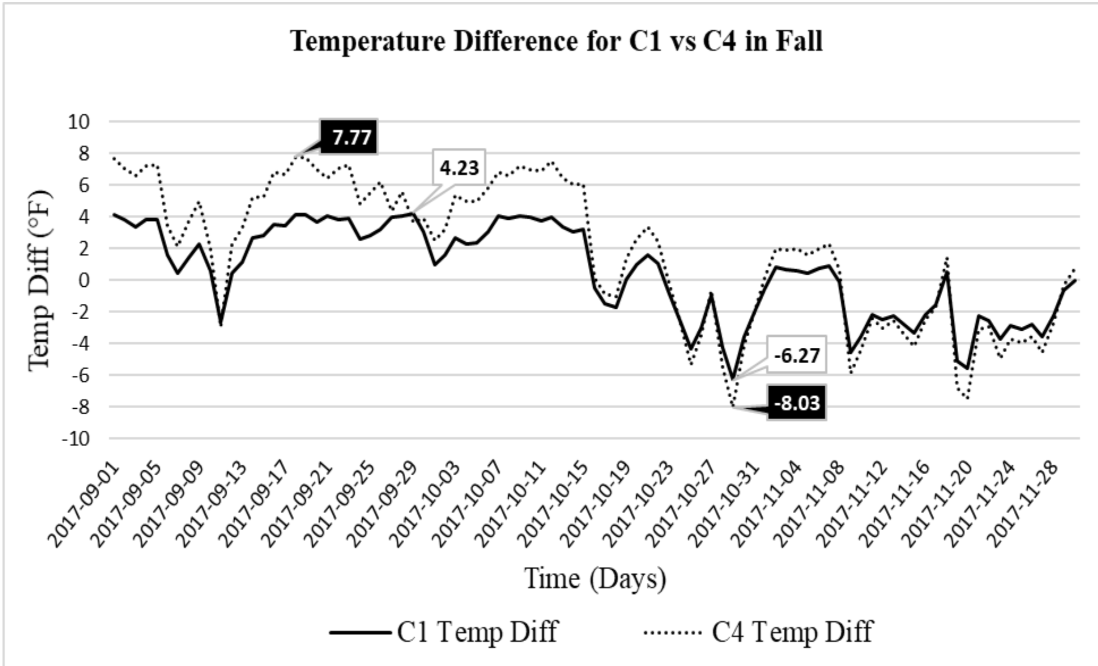

Figure 4.45: Average Temperature difference variation for C1 vs C4 in Fall

The temperature difference for C1 and C4 in the fall are presented in Figure 4.45. The records show that the temperature difference for C1 varies between -6.27 °F and 4.23 °F while C4 varies between -8.03 °F and 7.77 °F. The average temperature difference of C1 (0.52 °F) when compared to C4 (1.76 °F) was increased by about 1.23 °F. The details in Figure 4.45 show the significant difference in performance between both C1 and C4 through the fall period. Based on the assumption that the higher temperature difference means the better performance in fall, the records indicates C4 as a better performing glazing than C1.

The temperature difference for C1 and C5 in the fall are presented in Figure 4.46. The records show that the temperature difference for C1 varies between -6.27 °F and 4.23 °F while C5 varies between -8.00 °F and 7.26 °F. The average temperature difference of C1 (0.52 °F) when compared to C5 (1.59 °F) was increased by about 1.07 °F. The details in Figure 4.46 show the significant difference in performance between both C1 and C5 through the fall period. The temperature difference for C5 is consistently higher that C1 except for the period between 28-Oct and 28-Nov. The total temperature difference for C5 higher than C1 and based on the assumption that the higher temperature difference makes a better performance in fall, the records indicate C5 as a better performing glazing than C1.

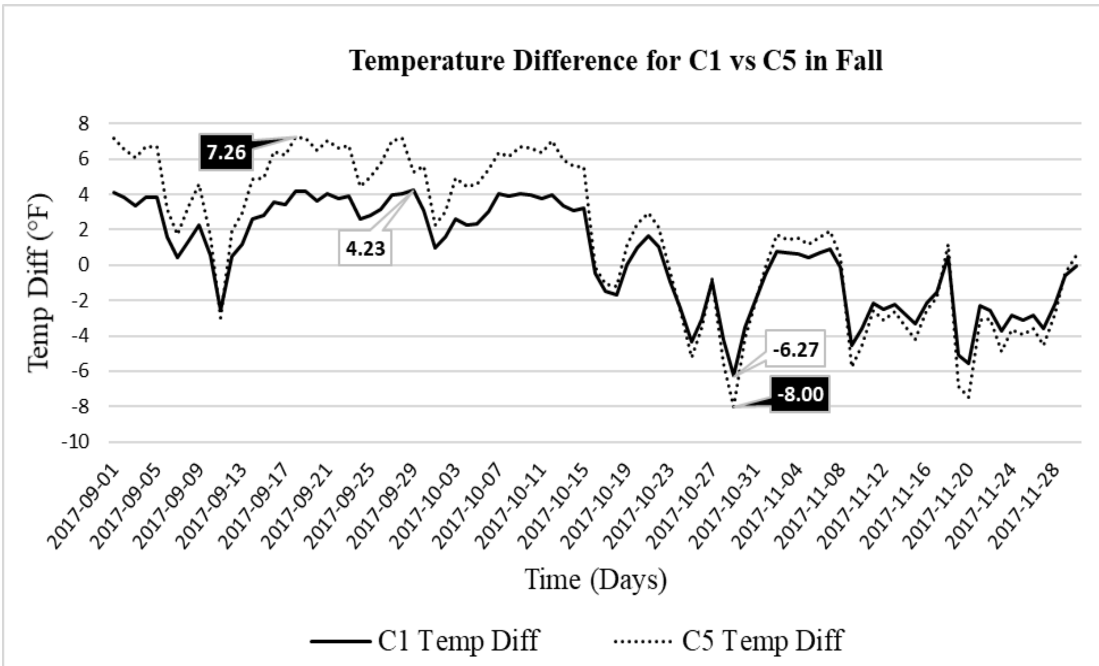

Figure 4.46: Average Temperature difference variation for C1 vs C5 in Fall

The temperature difference for C2 and C3 in the winter are presented in Figure 4.47. The records show that the temperature difference for C2 varies between -7.87 °F and 6.01 °F while C3 varies between -8.56 °F and 4.99 °F. The average temperature difference of C2 (0.91 °F) when compared to C3 (0.12 °F) was increased by about 0.79 °F. There is a significant difference in performance between both C2 and C3 as seen in Figure 4.47. The total temperature difference for the C3 is less than C2. Based on the assumption that the higher the temperature difference, the better the performance in fall, the records indicates C2 as a better performing glazing than C3.

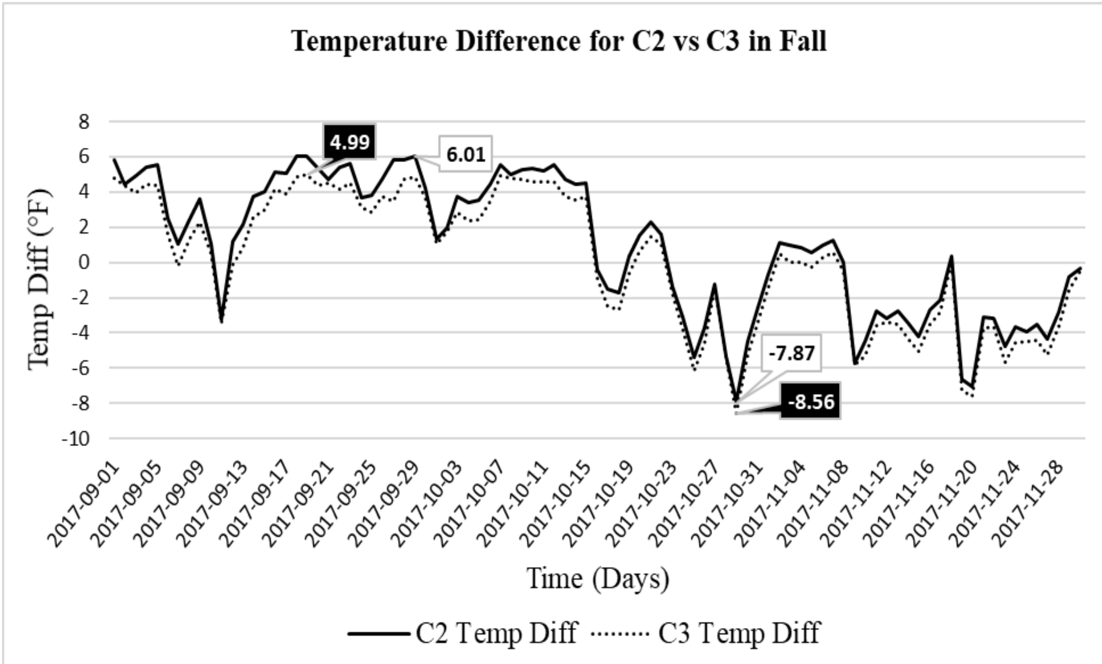

Figure 4.47: Average Temperature difference variation for C2 vs C3 in Fall

The temperature difference for C2 and C4 in the fall are presented in Figure 4.48. The records show that the temperature difference for C2 varies between -7.87 °F and 6.01 °F while C4 varies between -8.03 °F and 7.77 °F. The average temperature difference of C2 (0.91 °F) when compared to C4 (1.76 °F) was reduced by about 0.85 °F. There is a significant difference in performance between both C2 and C4 as seen in Figure 4.48. The total temperature difference for the C2 is less than C4. Based on the assumption that the higher the temperature difference, the better the performance in fall, the records indicates C4 as a better performing glazing than C2.

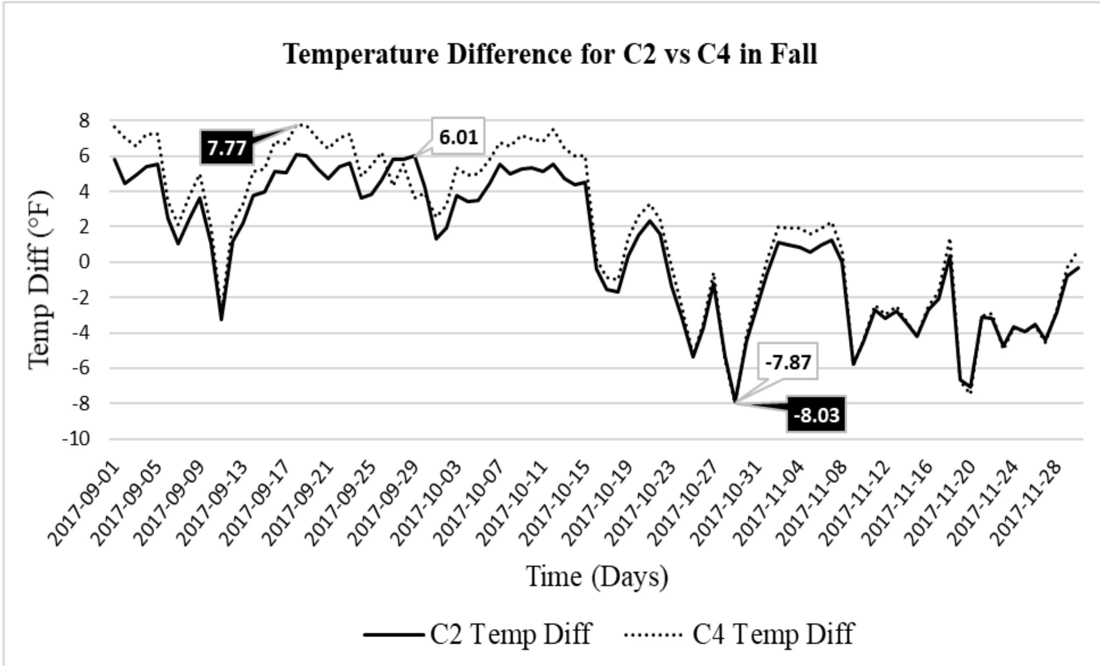

Figure 4.48: Average Temperature difference variation for C2 vs C4 in Fall

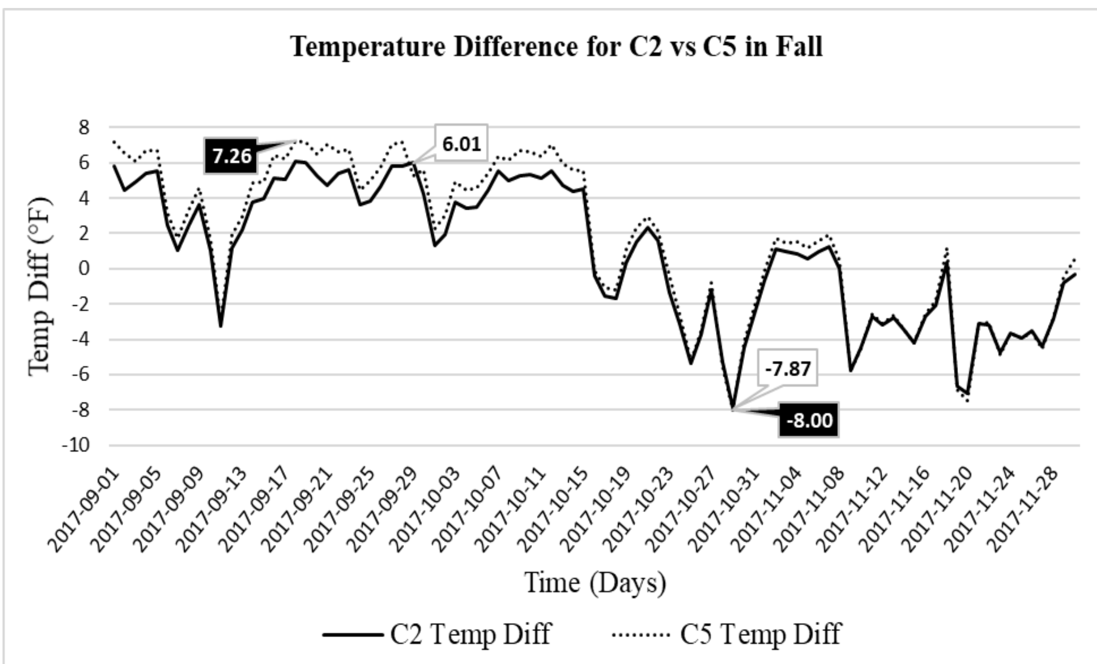

Figure 4.49: Average Temperature difference variation for C2 vs C5 in Fall

The temperature difference for C2 and C5 in the fall are presented in Figure 4.49. The records show that the temperature difference for C2 varies between -7.87 °F and 6.01 °F while C5 varies between -8.00 °F and 7.26 °F. The average temperature difference of C2 (0.91 °F) when compared to C5 (1.59 °F) was reduced by about 0.68 °F. There is a significant difference in performance between both C2 and C5 as seen in Figure 4.49. The total temperature difference for C2 is less than C5 and based on the assumption that the higher the temperature difference, the better the performance in fall, the records indicates C5 as a better performing glazing than C2.

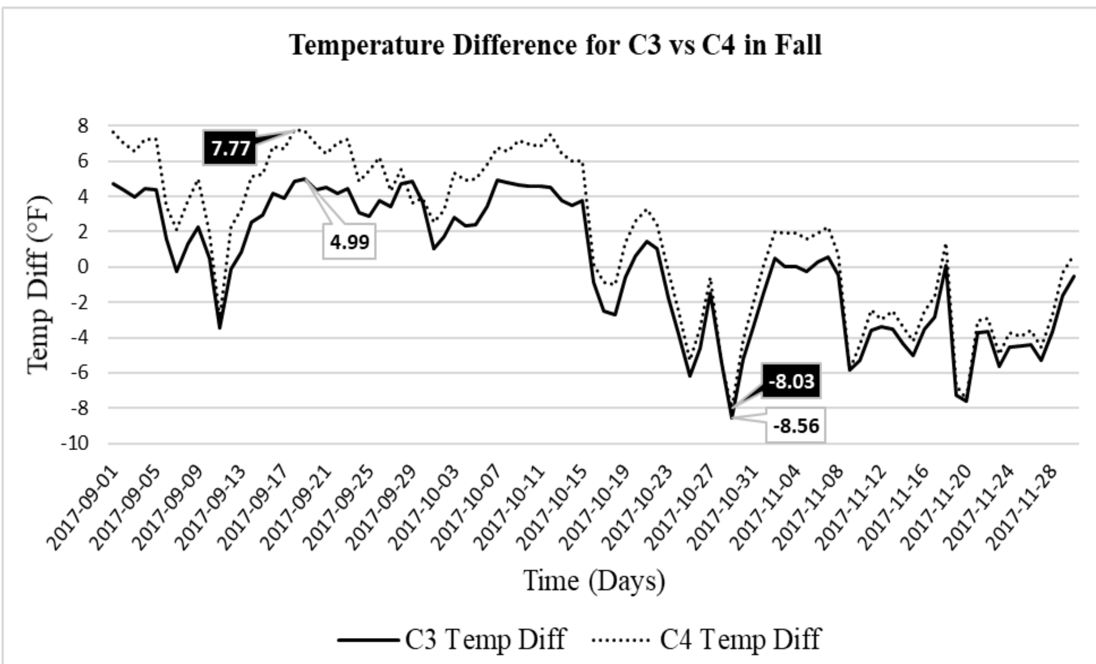

Figure 4.50: Average Temperature difference variation for C3 vs C4 in Fall

The temperature difference for C3 and C4 in the spring are presented in Figure 4.50. The records show that the temperature difference for C3 varies between -8.56 °F and 4.99 °F while C4 varies between -8.03 °F and 7.77 °F. The average temperature difference of C3 (0.12 °F) when compared to C4 (1.76 °F) was increased by about 1.64 °F. There is a significant difference in performance between both C3 and C4 as seen in Figure 4.50. The total temperature difference for the C3 is less than C4. Based on the assumption that the higher the temperature difference, the better the performance in spring, the records indicates C4 as a better performing glazing than C3.

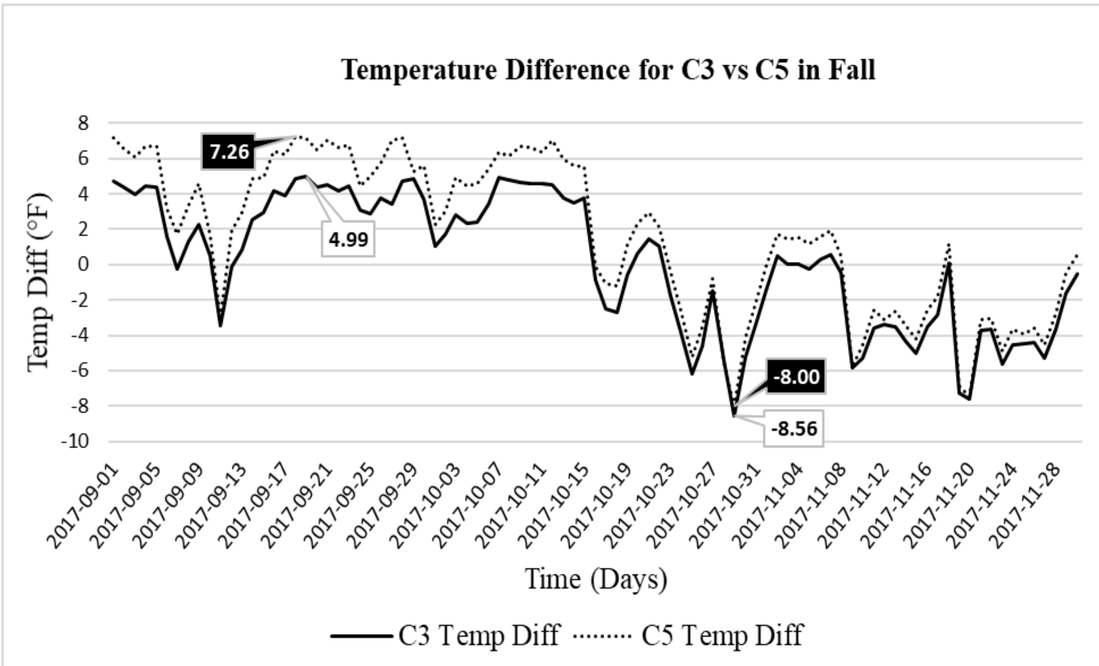

Figure 4.51: Average Temperature difference variation for C3 vs C5 in Fall

The temperature difference for C3 and C5 in the fall are presented in Figure 4.51. The records show that the temperature difference for C3 varies between -8.56 °F and 4.99 °F while C5 varies between -8.00 °F and 7.26 °F. The average temperature difference of C3 (0.12 °F) when compared to C5 (1.59 °F) was increased by about 1.48 °F. There is a significant difference in performance between both C3 and C5 as seen in Figure 4.51. The total temperature difference for the C3 is less than C5. Based on the assumption that the higher the temperature difference, the better the performance in fall, the records indicates C5 as a better performing glazing than C3.

The temperature difference for C4 and C5 in the fall are presented in Figure 4.52. The records show that the temperature difference for C4 varies between -8.03 °F and 7.77 °F while C5 varies between -8.00 °F and 7.26 °F. The average temperature difference of C4 (2.72 °F) when compared to C5 (2.27 °F) was reduced by about 0.31 °F. There is a significant difference in performance between both C4 and C5 as seen in Figure 4.52. The total temperature difference for the C4 is more than C5. Based on the assumption that the higher the temperature difference, the better the performance in spring, the records indicates C4 as a better performing glazing than C5.

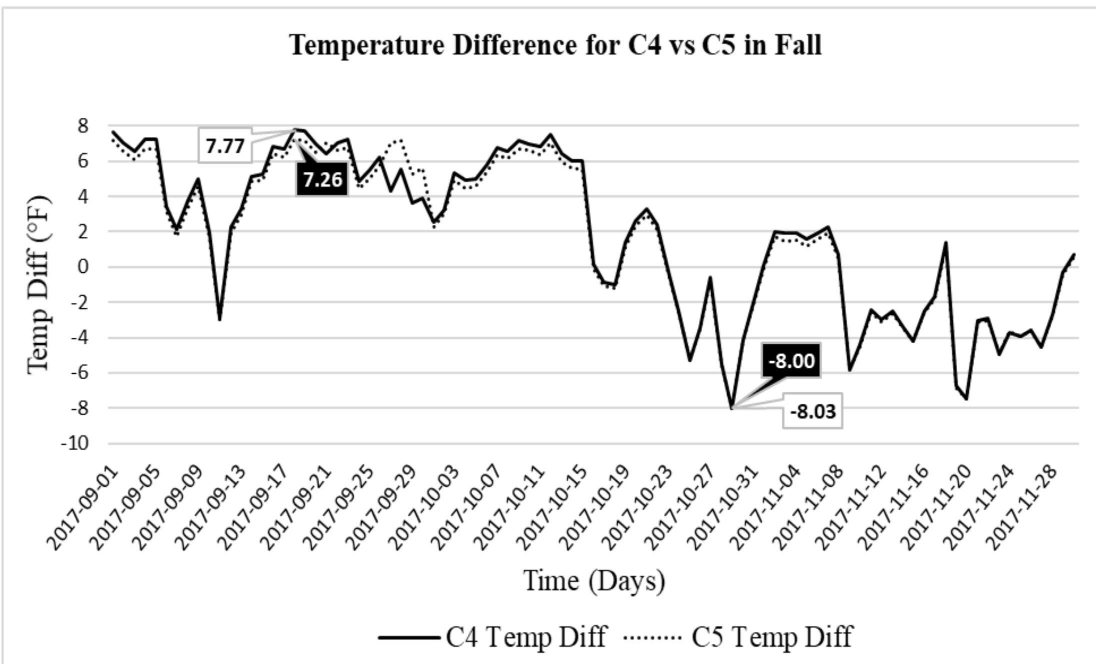

Figure 4.52: Average Temperature difference variation for C4 vs C5 in Fall

4.5 COMPARISON OF RESULTS

The results of the glazing thermal performance were compared and ranked in each season. The sum of the temperature differences between the exterior and interior surfaces for C1, C2, C3, C4 and C5 were summarized to rank the performance in each season. Generally, heat flows from warmer to cooler bodies, which means heat flows from the interior surface of a window to the exterior surface in winter and a reverse direction is summer. The U-value in glazing represents their resistance to heat transfer which means the ability to control heat loss during winter and heat gain during the summer, fall and spring. In this study, the heat transfer was represented by the difference between the interior and exterior surface temperature, where negative results in winter signifies good performance and positive results in summer fall and spring mean good performance. Hence, in the winter, a lower value of temperature difference illustrates better performance while a higher value illustrates better performance in the summer, fall and spring season as the temperature in southern climate region increases after winter. These illustrations are based on the desire to have more heat during the winter and the need to prevent heat gain during other seasons.

The overall thermal performance comparison of the glazing in winter is presented in Figure 4.53. The thermal performance was determined based on the total sum of the temperature differentials through the season. The ranking according to their thermal performance, when arranged in descending order is as follows C3, C2, C5, C4 and C1 where the C3 ranks as the best performance amongst all the glazing alternatives, as a result of its ability to control heat flow in the season of comparison. When the interior surface is warmer than the exterior surface which, is the typical scenario in winter, the C3 has the highest value of temperature difference that indicates its better performance than others.

The next performing glazing after C3 was the C2 and C5. The analysis showed that C2 and C5 perform similarly with a very close total temperature difference value in the winter. After these two glazing, C4 ranks next and finally C1 with the least performance in winter.

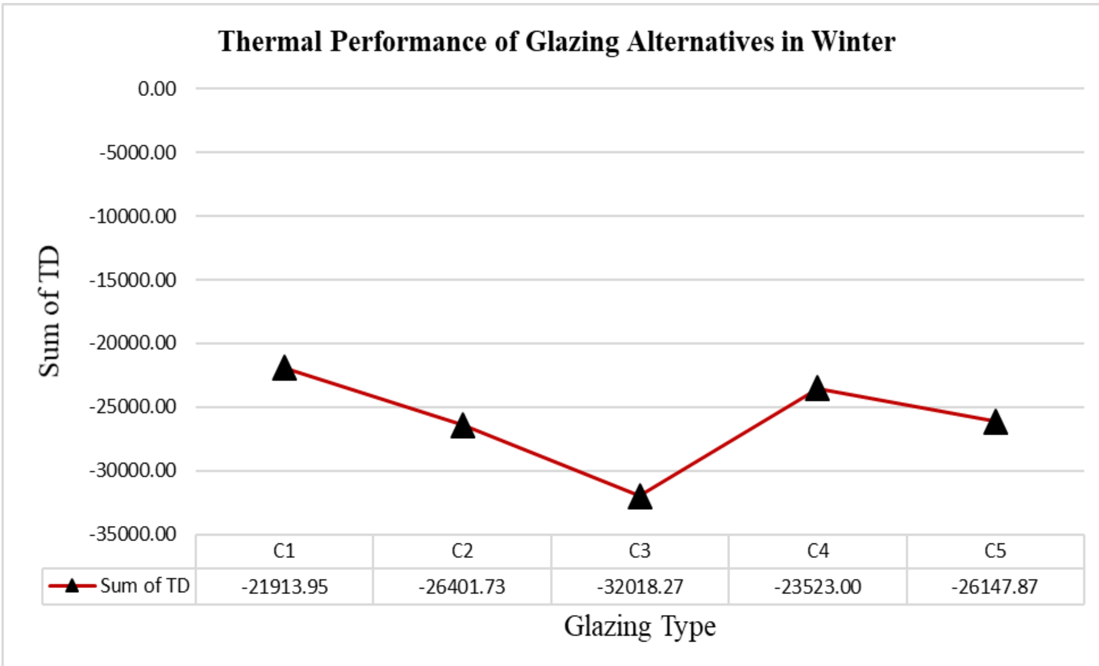

Figure 4.53: Thermal Performance of Glazing in Winter

*where TD means Temperature differentials

The performance of the glazing in winter was based on the lowest sum of the temperature differential. This is because the winter, amongst the other seasons in this location, had the longest period where exterior temperatures where lower than the interior temperatures, hence, the negative values obtained for the temperature differentials calculated. Due to the desire to reduce heat loss in the winter, the lowest differential meant the best performance as seen in Figure 4.53

The overall thermal performance comparison of the glazing in spring is presented in Figure 4.54. In contrast to the winter, the ranking according to their thermal performance when arranged in descending order is as follows C4, C5, C1, C2 and C3. The data results, rank C4 as the best in thermal performance amongst all the glazing alternatives, based on its ability to control heat flow in the season of comparison. In the spring, where temperatures begin to rise and the exterior surface is warmer than the interior surface, the C4 has the highest value of temperature difference that indicates better thermal performance than other alternatives. The next performing glazing after C4 was the C5. The analysis surprisingly showed C1 as a better performing glazing than C2 and C3. Although the C1 performed similarly to C2 as seen in Figure 4.54, C1 has a higher temperature difference value than C2 and C3. Finally, C3 ranked the least performance in spring.

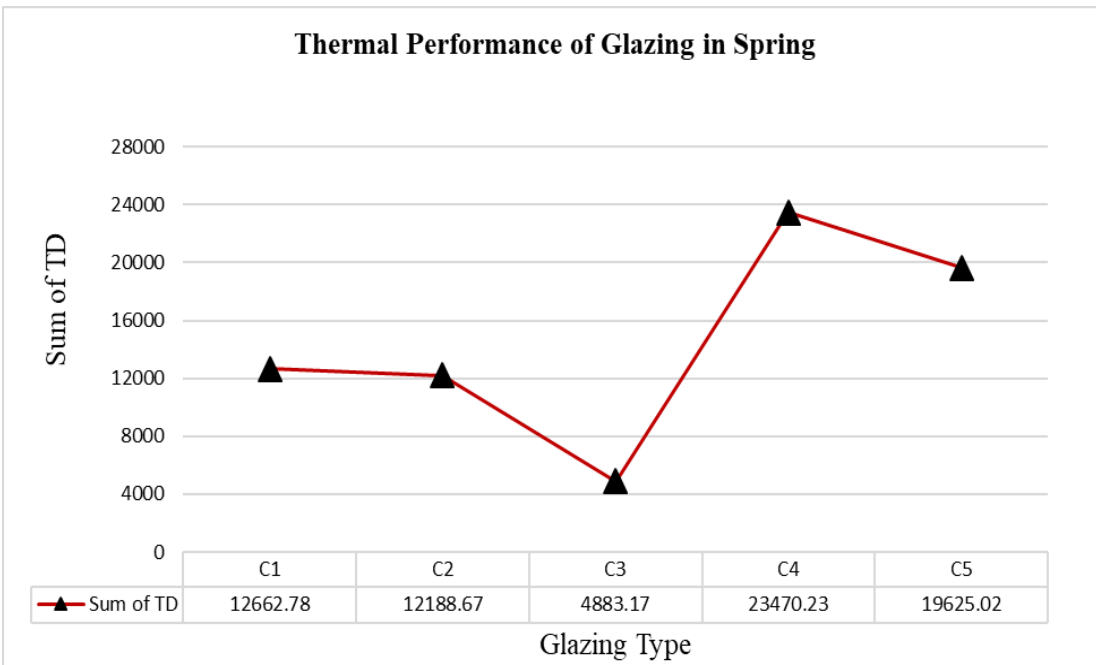

Figure 4.54: Thermal Performance of Glazing in Spring

*where TD means Temperature differentials

The overall thermal performance comparison of the glazing in summer is presented in Figure 4.55. In the summer, the ranking according to their thermal performance when arranged in descending order is as follows C4, C5, C2, C3 and C1. Just like the spring, the data results rank C4 as the best in thermal performance amongst all the glazing alternatives based on its ability to control heat flow in the season of comparison. In the summer, where temperatures attain its highest, the exterior surface is warmer than the interior surface and C4 has the highest value of temperature difference that indicates better thermal performance than other alternatives. The next performing glazing after C4 just like in spring was the C5. However, in contrast with spring, the analysis showed C2 and C3 as a better performing glazing than C1 as seen in Figure 4.55. C2 has the next higher temperature difference value then C3 and finally C1 which ranked the least performance in summer.

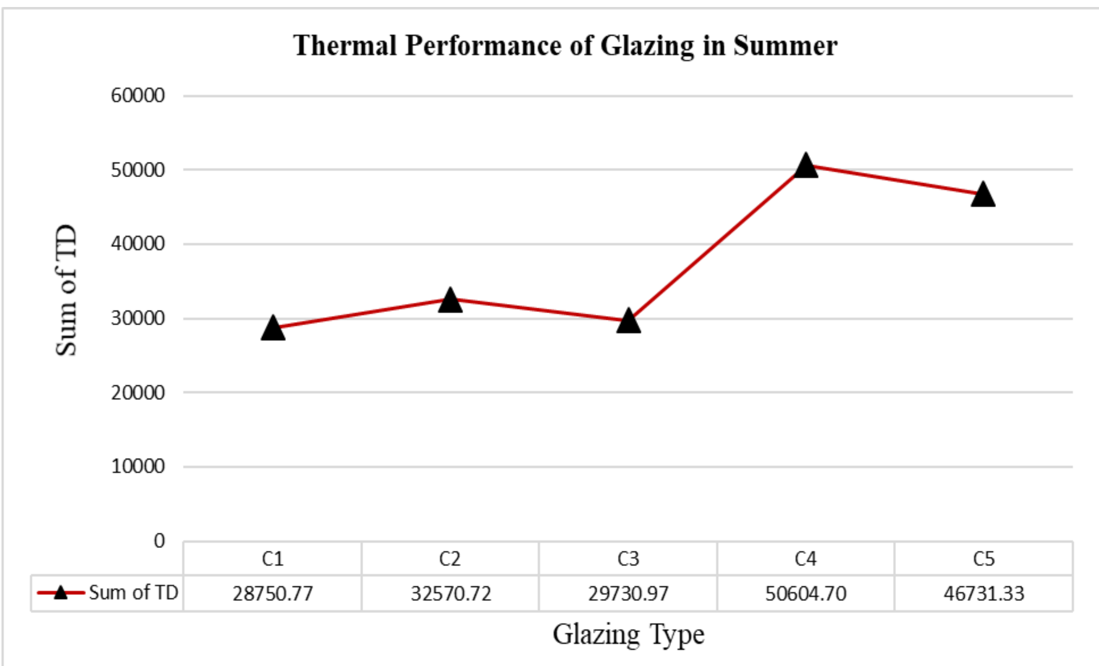

Figure 4.55: Thermal Performance of Glazing in Summer

*where TD means Temperature differentials

The overall thermal performance comparison of the glazing for fall is presented in Figure 4.56. The ranking for the fall season according to their thermal performance in descending order is as follows C4, C5, C2, C1 and C3. Just like the spring and summer, the data results rank C4 as the best in thermal performance amongst all the glazing alternatives. Although temperatures begin to drop in the fall (see Figure 4.41), the exterior surface remains warmer than the interior surface and C4 has the highest value of temperature difference that indicates better thermal performance followed by the C5. Like summer, C2 had the next higher temperature difference value that made it the next performing glazing. However, in contrast with summer, the analysis showed C1 as a better performing glazing than C3 as seen in Figure 4.56.

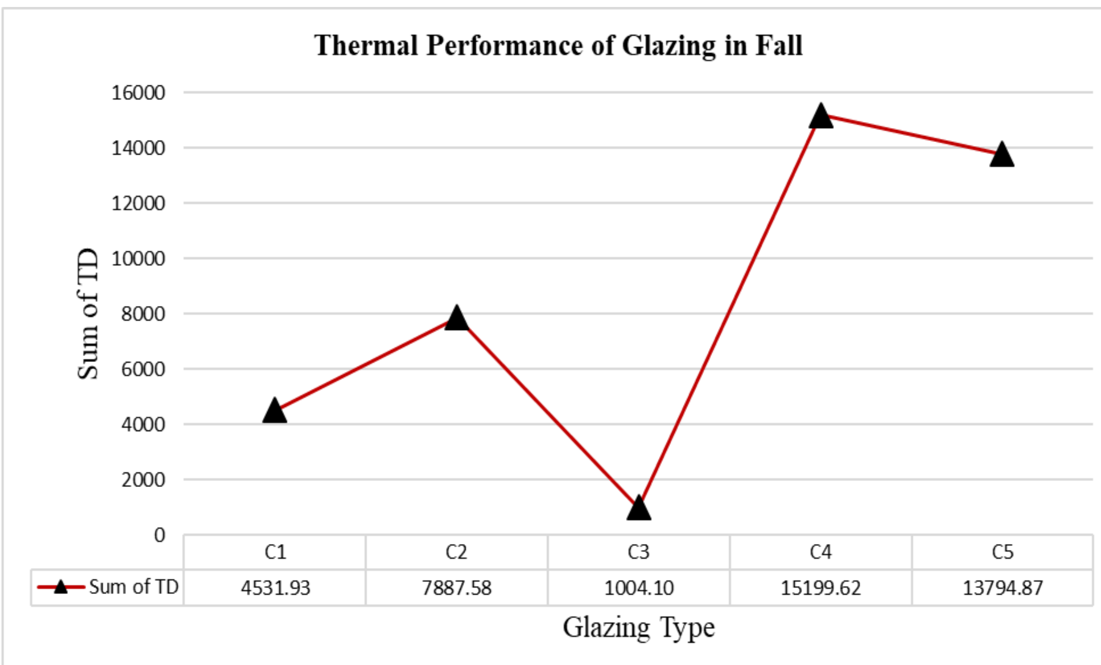

Figure 4.56: Thermal Performance of Glazing in Fall

*where TD means Temperature differentials

Unlike the winter, the spring summer and fall had a longer period where the exterior temperatures were higher than the interior temperatures which resulted in positive values for the temperature differential calculated. Hence the highest sum of temperature differential meant the highest performance in this seasons.

Table 4.13: Summary of actual performance based on the temperature difference

Glazing Type	Winter	Spring	Summer	Fall
C1				
C2				
C3				
C4				
C5				

Table 4.14: Summary of predicted performance based on the U-values

Glazing Type	Winter	Spring	Summer	Fall
C1				
C2				
C3				
C4				
C5				

Based on the results of the study, the actual thermal performance of the glazing in each season are presented in Table 4.13, from the best to the least performance using the ranking color code (see Figure 3.5). The table shows that C4 and C5 performed best when the exterior temperatures were warmer than the interior temperatures. While the C3 and C2 performed best when the interior temperatures are warmer than the exterior temperatures.

5 SUMMARY, CONCLUSION AND RECOMMENDATIONS

5.1 Summary of Findings

This research provided a comparative analysis of different selected glazing alternatives on indoor thermal performance for the different seasons of the year. For this study, the thermal performance of five glazing alternatives, carefully installed into a windowpane in a research laboratory at the University of West Florida, Pensacola, Florida were evaluated using temperature differences. The performances of the selected glazing were tested under the same weather conditions and in the same west orientation using a statistical software. The statistical analysis, repetitive measure analysis of variance (ANOVA) test was used to evaluate the thermal performance of the glazing throughout the study. The results obtained from the test revealed there was a statistical difference in performance between each glazing across different season except for C2 and C5, which had no difference in the winter. Although the selected glazing had U-values that met the manufacturer's requirement for windows in the southern region, nevertheless, the findings of the study indicated each glazing performed slightly different from the other under different seasons.

From the study, C4 had the best performance in summer fall and spring when the exterior temperatures became warmer than the interior temperatures while C3 had the best performance when the interior temperature became warmer than the exterior temperature. The tint level in C4 allowed for less heat absorption, higher temperature differential and a higher visual transmittance value when compared to the other glazing alternatives. C1 had the least performance in the study but showed slight improvement only in transition seasons. It is assumed that the poor thermal performance of the C1 characterized by high temperature differential in winter and low temperature differential in summer, was greatly influenced by its high U-value and lack of properties that enhance performance such as tints, layers to mention a few. Based on these results one can conclude that single the glazing in a heat dominated climate performs worse than the double glazing under the same climate region.

Building owners and designers can utilize this performance ranking in selecting a glazing for their facility. For instance, in a facility where visual privacy is not of high priority and daylighting is expedient, there is a need to select a glazing with high visual transmittance and this ranking provide a guide for owners to see the possible thermal potential of each glazing and be aware of the potential differences depending on the climate. Where visual privacy is pertinent and owners deem selecting a glazing with low visual transmittance more valuable, this ranking also provides the thermal performance to guide selection. Because of the heat absorbing nature of tints, an additional shading device can be installed to improve thermal performance and control heat flow into the facility.

The charts from this study are based on data collected in this particular case and it is important to note that the findings show relative performance based on differentials rather than absolute performance of the selected glazing. But through this, designers and home owners will understand what tradeoffs to expected from any of the glazing. An example is a tradeoff between visible light and solar heat gain.

5.2 Limitations and Recommendations for Future Research

Several limitations related to this study are recognized. First of all, the glazings are in a shaded area and not affected by direct sunlight. Second, temperatures were the only variable taken into consideration for the comparative analysis. It is urged to take into account other contributing factors such as the interior temperatures, humidity levels, solar radiation, wind speed and installation effects for better understanding of performances. Third, the study only considers a limited number of five glazing type with the same air space and glass pane dimensions to investigate thermal performance. It will be of utmost benefit to take into consideration newer glazing types and either north or south orientations to help identify a better combination technique that could potentially improve thermal performance. Lastly, the location of the study in the southern region also limits the resulting thermal performance recommendations to southern zones and a heat-dominated region.

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